

JACARANDA
PHYSICS **2**
VCE UNITS 3 AND 4 | FOURTH EDITION

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ABOUT THIS RESOURCE

Jacaranda Physics has been reimagined to provide students and teachers with the most comprehensive resource on the market. This engaging and purposeful suite of resources is fully aligned to the VCE Physics Study Design (2017–2021).

Formats

Jacaranda Physics is now available in print and a range of digital formats, including:

Print	learnON	eBookPLUS	PDF	eGuidePLUS
				
Printed textbook with free digital access code inside	learnON is our immersive and flexible digital learning platform	The eBookPLUS is an electronic version of the student text	Downloadable PDFs available with eBookPLUS	The eGuidePLUS includes everything from the eBookPLUS with additional resources designed for teachers

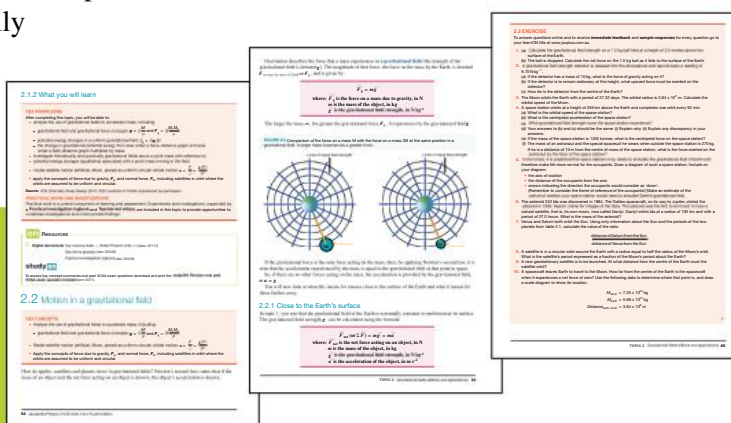
Fully aligned to the VCE Physics Study Design

Have confidence that you are covering the entire VCE Physics Study Design (2016–2021), with:

- tailored exercise sets at the end of each sub-topic
- additional background information easily distinguished from curriculum content
- practice SACs clearly linked to each outcome
- practice exams for each area of study.

Key concepts approach

Students can easily understand which aspect of the Study Design they are studying with Key Knowledge dot points highlighted at the start of each topic and broken down into Key Concepts in each sub-topic.



Engaging resources and rich media

A variety of online and offline resources to encourage students of all learning styles, including:

- videos and interactivities embedded at the point of learning
- practical investigations complete with printable logbook
- a variety of worksheets and activities allow students to apply their knowledge of the content.

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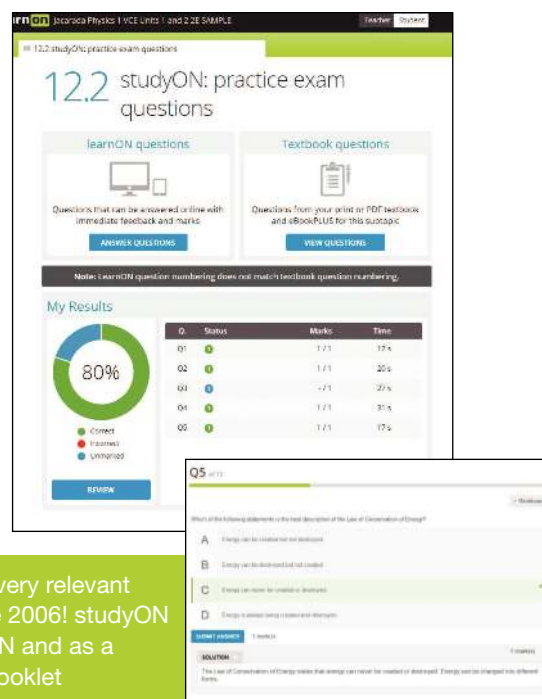
Videos of both sample problems and practical investigations led by experienced teachers allow students to better consolidate their learning.



Inspiring students to become independent learners

This resource, on the immersive digital platform learnON, encourages self-driven student learning through:

- fully worked solutions for every question providing students with immediate feedback
- progress tracked automatically in learnON allowing students to reflect on their learning, and enabling students to highlight areas of strength and weakness
- topic summary, key terms and practice questions at the end of every topic
- sample problems with fully worked solutions set out in the THINK–WRITE format.



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Prepare for exams with every relevant past exam question since 2006! studyON is now included in learnON and as a printable exam revision booklet

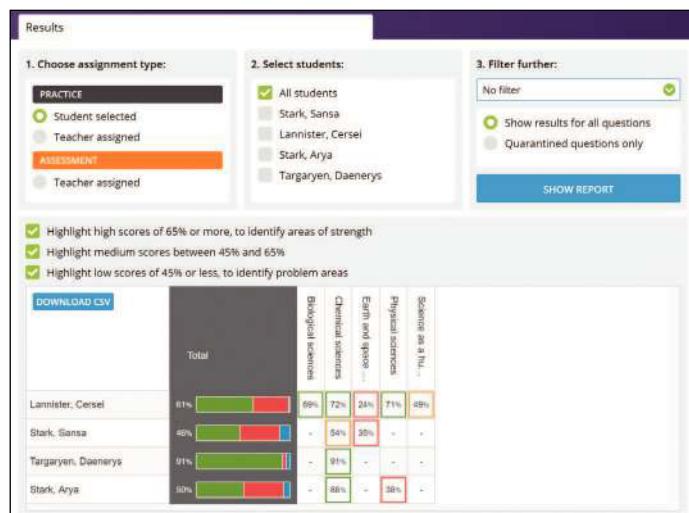
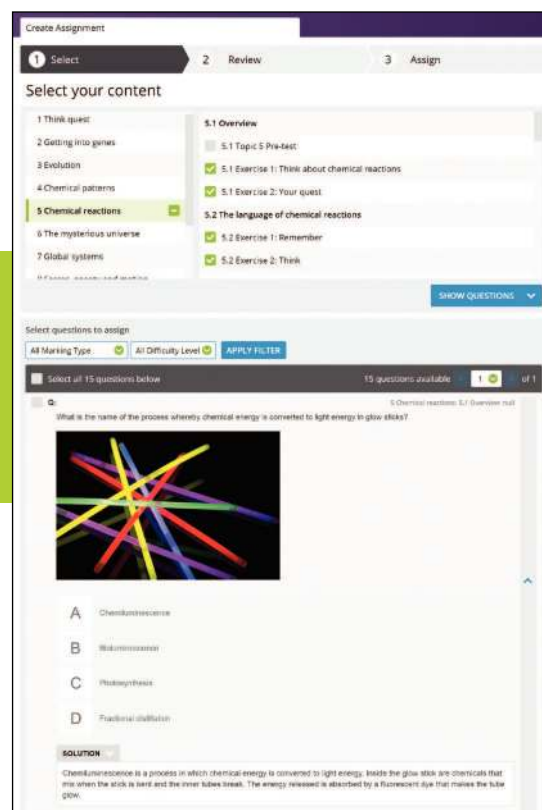
A wealth of teacher resources

Jacaranda Physics empowers teachers to teach their class their way with the extensive range of teacher resources including:

- quarantined topic tests and SACs that are easily customisable
- practical investigation support with demonstrative videos, laboratory information, expected results and risk assessments
- work programs
- curriculum grids.

Test Maker

Create custom tests for your class from the entire question pool — including all subtopic, topic review and past VCAA exam questions



Visibility of student results

Detailed breakdown of student results allows you to identify strengths and weaknesses across various topics and sub-topics.

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UNIT 3

HOW DO FIELDS EXPLAIN MOTION AND ELECTRICITY?

In this unit, you will explore energy and how it explains the phenomena of motion and electricity in the physical world. You will gain this understanding through the exploration of gravitational, electric and magnetic fields, using the field model to investigate the energy and force on an object. You will further your knowledge of electricity gained in Unit 1, exploring how electricity is both generated and transmitted. You will gain an understanding of various explanations of motion, exploring and applying both Newton's laws of motion and Einstein's Theory of Special Relativity, and the relationship between force, energy and mass.



AREA OF STUDY	OUTCOME	TOPICS
1. How do things move without contact?	Analyse gravitational, electric and magnetic fields, and use these to explain the operation of motors and particle accelerators, and the orbits of satellites.	1. Gravitational, electric and magnetic fields 2. Gravitational fields (effects and applications) 3. Electric and magnetic fields (effects and applications)
2. How are fields used to move electrical energy?	Analyse and evaluate an electricity generation and distribution system.	4. Generation of electricity 5. Transmission of power
3. How fast can things go?	Investigate motion and related energy transformations experimentally, analyse motion using Newton's laws of motion in one and two dimensions, and explain the motion of objects moving at very large speeds using Einstein's Theory of Special Relativity.	6. Newton's laws of motion 7. Force, energy and mass in collisions and other interactions 8. Special relativity

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1 Gravitational, electric and magnetic fields

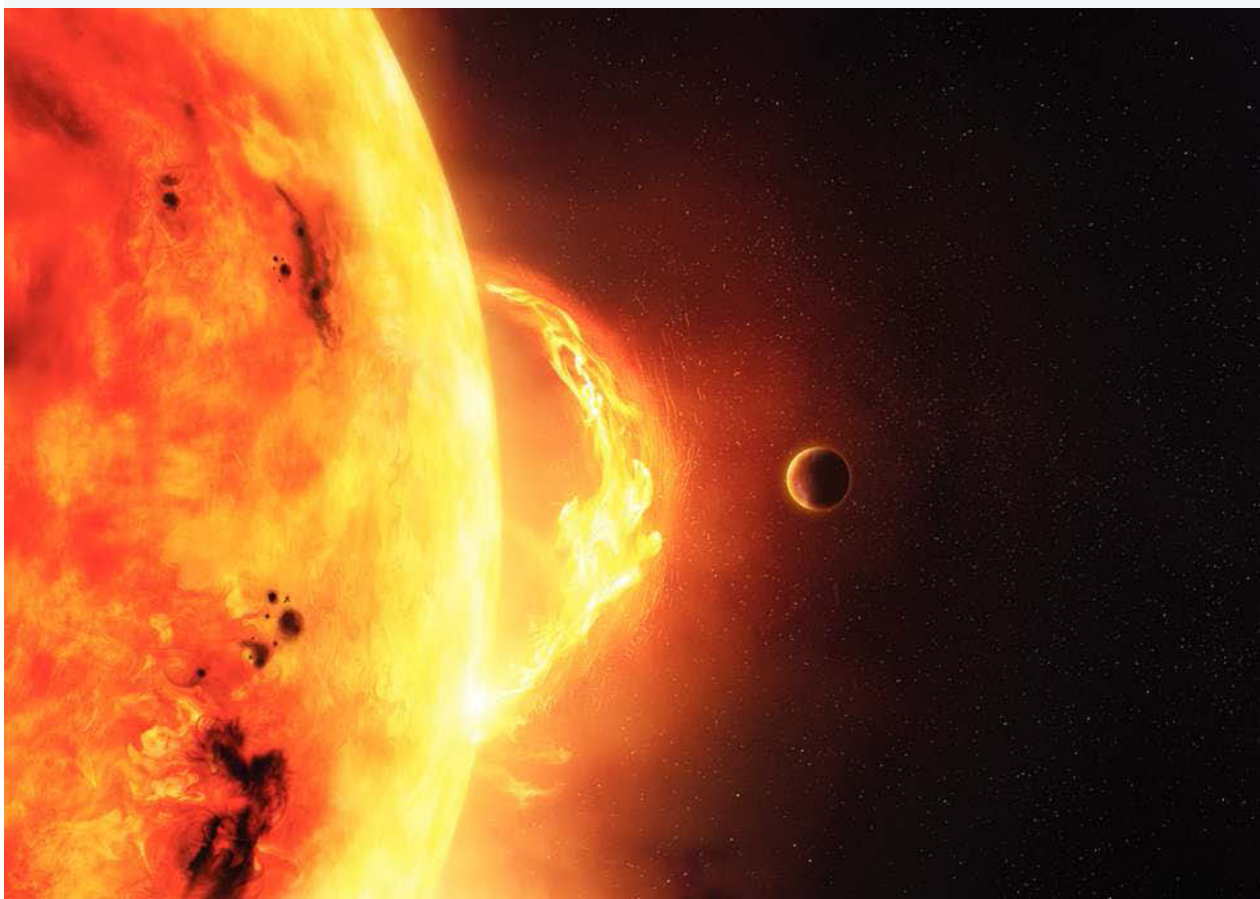
1.1 Overview

Numerous **videos** and **interactivities** are available just where you need them, at the point of learning, in your digital formats, learnON and eBookPLUS at www.jacplus.com.au.

1.1.1 Introduction

In everyday life, balls drop to the ground when they are let go. Needles in compasses spin and point to the north. Two balloons rubbed against your jumper repel and float away from one another. The motion of an object can be explained in terms of the net force experienced by the object. So, where do the forces come from in these cases? Explanations of observations might go something like this: The ball drops because of gravity. The balloons repel because they are both positively charged, and objects carrying like charges repel.

FIGURE 1.1 A solar flare at the surface of the Sun releases charged particles to stream into space where they will interact with planetary gravitational, electric and magnetic fields.



The molten iron in the centre of the Earth is like a giant bar magnet, and the small compass magnet moves to align itself with the Earth's magnetic field. In this topic, you will explore a model for how masses interact with other masses, how charges interact with other charges and how magnets interact with other magnets, even when they are not touching. In this model, the ball, balloon and compass needle are interacting with the environments created by other masses, charges and magnetic particles. These environments are called fields. The ball drops because the mass of the ball experiences the gravitational field from the mass of the Earth. The charged balloon moves because it experiences the electric field of the other charged balloon. The magnetised compass needle moves because it experiences the magnetic field of the Earth. So, what do these very different phenomena have in common? The masses, charges and magnetic objects are all able to affect other masses, charges and magnetic objects that are not touching them — so-called 'action at a distance'. The field model has been one of the great successes of modern physics. The nature of gravitational, electric and magnetic fields, their similarities and differences, is explored in this topic.

1.1.2 What you will learn

KEY KNOWLEDGE

After completing this topic, you will be able to:

- describe gravitation, magnetism and electricity using a field model
- analyse the use of gravitational fields to accelerate mass, including
 - gravitational field and gravitational force concepts: $\mathbf{g} = G \frac{M}{r^2}$ and $\mathbf{F}_g = G \frac{M_1 M_2}{r^2}$.
- analyse the use of an electric field to accelerate a charge, including
 - electric field and electric force concepts: $\mathbf{E} = \frac{kq}{r^2}$ and $\mathbf{F} = \frac{kq_1 q_2}{r^2}$
 - the magnitude of the force on a charged particle due to a uniform electric field: $\mathbf{F} = q\mathbf{E}$.
- investigate and compare theoretically and practically gravitational, magnetic and electric fields, including directions and shapes of fields, attractive and repulsive fields, and the existence of dipoles and monopoles
- investigate and compare theoretically and practically gravitational fields and electrical fields about a point mass or charge (positive or negative) with reference to
 - the direction of the field
 - the shape of the field
 - the use of the inverse square law to determine the magnitude of the field.
- investigate and apply theoretically and practically a vector field model to magnetic phenomena, including shapes and directions of fields produced by bar magnets, and by current-carrying wires, loops and solenoids
- identify fields as static or changing, and as uniform or non-uniform.

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PRACTICAL WORK AND INVESTIGATIONS

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

on Resources

-  **Digital documents** Key science skills — VCE Physics Units 1– 4 (doc-32112)
 Key terms glossary (doc-32246)
 Practical investigation logbook (doc-32247)

studyon

To access key concept summaries and past VCAA exam questions download and print the **studyON: Revision and past VCAA exam question booklet** (sonr-0050).

1.2 Gravitational forces and fields

KEY CONCEPTS

- Describe gravitation using a field model
- Analyse the use of gravitational fields to accelerate mass, including:
 - gravitational field and gravitational force concepts: $\mathbf{g} = G \frac{M}{r^2}$ and $\mathbf{F}_g = G \frac{M_1 M_2}{r^2}$
- Investigate theoretically and practically gravitational fields, including directions and shapes of fields
- Investigate theoretically and practically gravitational fields about a point mass with reference to:
 - the direction of the field
 - the shape of the field
 - the use of the inverse square law to determine the magnitude of the field
 - potential energy changes (qualitative) associated with a point mass moving in the field
- Identify fields as static or changing, and as uniform or non-uniform.

Gravitation, with the aid of field models, allows the understanding of how masses can influence other masses that are distant from them. A field model can be visualised as a map of the force experienced by a small mass placed within the environment of another mass or masses. Various factors influence gravitational fields, including the shape, direction of influence and magnitude of the field and properties of the mass (such as its radius). Later, in topic 2, this simple picture will be further applied to explain both the motion of a ball dropped close to the surface of the Earth and to the motion of satellites in orbit around the Earth.

1.2.1 Mass and gravitation

What is it about a ball that causes it to experience gravity? The answer was worked out by Isaac Newton, nearly three hundred and fifty years ago, when he was trying to explain the motion of the planets and the Moon in the solar system. Newton realised that masses are attracted to other masses and that this is universally true, not just on Earth but also between other planetary bodies. The mass of a ball is attracted to the mass of the Earth.

When a ball is dropped from a few metres above the surface of the Earth, the movement of the ball towards the Earth is easily seen. If air resistance is negligible, the ball accelerates and the acceleration of the ball is the same for balls with different masses. Newton proposed that the ball accelerates because of an attractive force from the Earth. Newton linked this to his already-established second law (in which the total force on an object equals its acceleration multiplied by its mass). Newton argued that if a ball had twice as much mass, the force of attraction to the Earth would double. A ball with three times as much mass would be three times as strongly attracted to the Earth. By applying Newton's third law — that the force on A by B must be equal in magnitude and opposite in direction to the force on B by A — it can be understood that the gravitational force of attraction must also be proportional to the other mass, in this case the mass of the Earth. Newton then concluded that the gravitational force of attraction between two masses must be proportional to the product of the two masses.

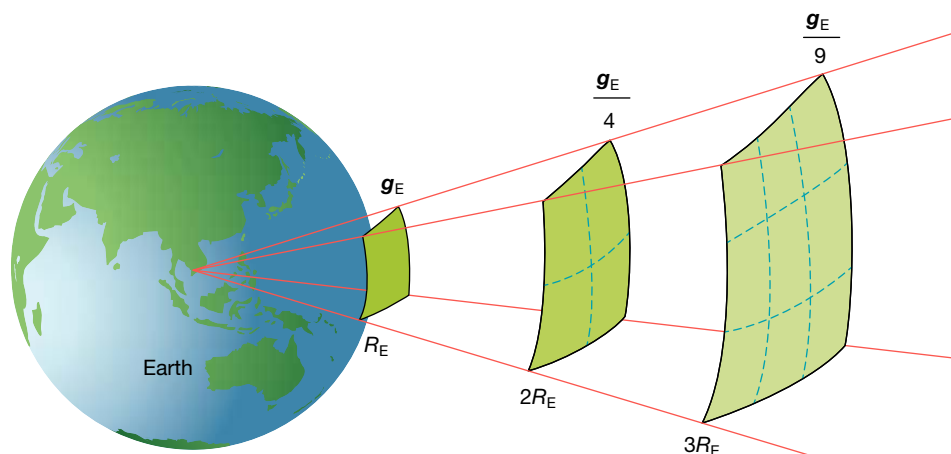
The inverse square law

The force due to gravity between two masses is not just related to the magnitudes of the masses but is also affected by the distance between them.

Imagine the Earth as a large, perfect sphere, and consider a ball placed at some point above the surface of the sphere. The radius of the Earth (R_{Earth} or R_E) is very large (approximately 6 400 000 m). Therefore, if a ball is dropped from ten metres above the surface of the Earth, the distance between the centre of a ball and the centre of the Earth is hardly any larger than the radius of the Earth. If the Earth is considered to be a perfect sphere, then the ball will have the same experience at any point 10 metres above the Earth's surface.

Now imagine the ball placed much further away from the Earth, at a distance of $2R_E$ from the Earth's centre. Although the source of the attraction of the ball (the mass of the Earth) is still the same, the area over which the 'attractiveness' is spread out is much larger.

FIGURE 1.2 The inverse square law illustrated. As the distance from the source increases, the strength of the source is spread out over an increasingly large area. As a result, the strength of the source is inversely proportional to the square of the distance.



The surface area of a perfectly spherical Earth is $4\pi R_E^2$. At a distance of $2R_E$ from the centre of the Earth, the attraction is spread out over a surface area of $4\pi(2R_E)^2 = 16\pi R_E^2$. This means that at any point $2r$ from the centre of the Earth, the attraction of the ball to the Earth is four times weaker than at point r . At a distance of $3r$ from the surface, the attraction is spread out over a surface area of $4\pi(3r)^2 = 36\pi r^2$, so the attraction of the ball at any point will be nine times weaker than at point r . You can see that the force of attraction is inversely proportional to the square of the distance between the centres of the two masses. This is called an **inverse square law**. Therefore, as you move further away from a central mass, the gravitational field is not static, but changes.

Putting it all together, Newton's Law of Universal Gravitation states that the magnitude of the force on a mass, M_1 , by another mass, M_2 , where the centres of the masses are separated by a distance r is given by:

$$F_g = G \frac{M_1 M_2}{r^2}$$

where: F_g is the gravitational force on M_1 by M_2 , in N
 G is the gravitational constant ($6.67 \times 10^{-11} \text{ N kg}^{-2} \text{ m}^2$)
 M_1 is the mass of object 1, in kg
 M_2 is the mass of object 2, in kg
 r is the distance between the masses, in m

Note that the direction of the attractive force experienced by M_1 is along an imaginary line connecting the centres of the two masses pointing towards M_2 .

The value of G could not be determined at the time of Newton because the mass of the Earth was not known. Another 130 years passed before Henry Cavendish was able to measure the gravitational attraction between two known masses and calculate the value of G .

The value of G is very small, indicating that gravitation is quite a weak force. A large mass is needed to produce a gravitational effect that is easily noticeable.

SAMPLE PROBLEM 1

Calculate the force due to gravity of the following:

- a. The Earth (with a mass of 5.98×10^{24} kg) on a 70 kg person standing on the equator
- b. a 70 kg person standing on the Earth's equator

 Teacher-led video: SP1 (tlvd-0108)

THINK

- a. Recall the formula for Newton's Law of Universal Gravitation. The distance r is the separation of the centres of the two masses.

- b. Remember Newton's third law: The force on A by B is equal in magnitude and opposite in direction to the force on B by A.

WRITE

- a. Assume that the direction towards the Earth is positive.

$$\begin{aligned} F_{\text{on person by the Earth}} &= G \frac{M_{\text{Earth}} M_{\text{person}}}{r^2} \\ &= \frac{6.67 \times 10^{-11} \times 5.98 \times 10^{24} \times 70}{(6.37 \times 10^6)^2} \\ &= 688 \text{ N} \end{aligned}$$

The force due to gravity of the Earth on a 70 kg person standing on the equator is 688 N towards the centre of the Earth.

- b. $F_{\text{on Earth by the person}} = -F_{\text{on person by the Earth}}$
 $= -688 \text{ N}$

The negative value means that the direction of the force is in the opposite direction to the force on the person by the Earth. The force due to gravity of a 70 kg person standing on the Earth's equator is 688 N towards the person.

PRACTICE PROBLEM 1

Use the following data to calculate the force due to gravity by the Earth on the Moon and the force due to gravity by the Moon on the Earth:

mass of Earth = 5.98×10^{24} kg

mass of Moon = 7.35×10^{22} kg

distance between the Earth and the Moon = 3.84×10^8 m.

1.2.2 Gravitational fields

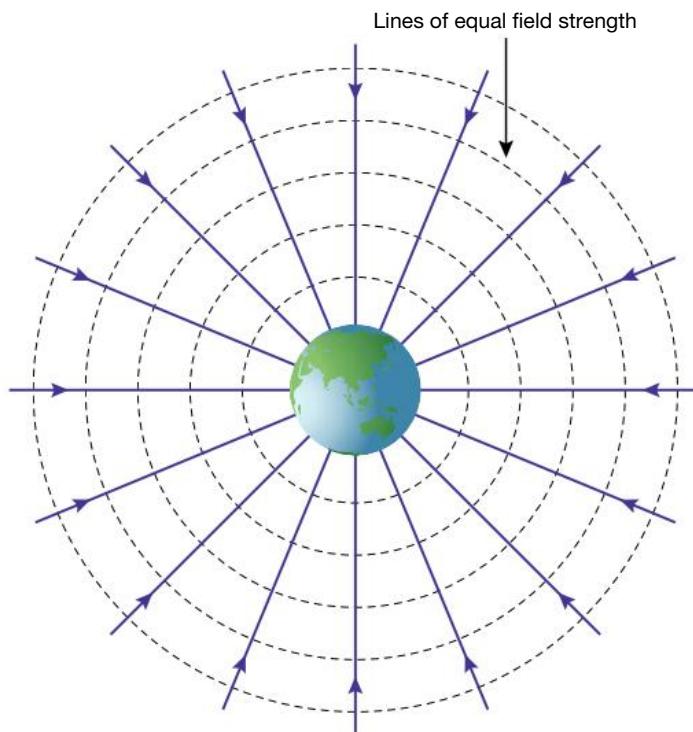
Newton's Law of Universal Gravitation describes the force between two masses. However, the solar system has many masses, each attracting one another. The Sun, the heaviest object in the solar system, determines the orbits of all the other masses, but each planet can cause minor variations in the orbital paths of the other planets. The precise calculation of the path of a planet or comet becomes a complicated exercise with many gravitational forces needing to be considered.

Physicists after Newton realised it was easier to determine, for each point in space, the total force that would be experienced by a unit mass (1 kg). This idea slowly developed and, in 1849, Michael Faraday formalised the concept, and explained the interactions between electric charges and between magnets, calling it a 'field'.

A field is more precisely defined as a physical quantity that has a value at each point in space. There are many different types of fields. For example, a weather map showing the pressure across Australia could be described as a diagram of a pressure field. This is an example of a scalar field, in which each point has a set value. In contrast, gravitational, electric and magnetic fields are vector fields; they not only give a value or magnitude to the strength of the field at each point in space, but they also give direction for that field at that point. The arrows in the diagram of the Earth's gravitational field show the direction of the field, and the density of the lines (how close together the lines are) indicates the strength of the field. The field lines become further apart as the distance from Earth increases, showing that the field is non-uniform. However, it does not change with time, so it is static.

A value for the strength of the **gravitational field** around a mass M can be determined from the value of the force on one kg of mass.

FIGURE 1.3 Diagram of the Earth's gravitational field



$$g = G \frac{M}{r^2}$$

where: g is the gravitational field strength, in N kg^{-1}
 G is the gravitational constant ($6.67 \times 10^{-11} \text{ N m}^2 \text{ kg}^{-2}$)
 M is the mass of the object (the central body), in kg
 r is the distance from the centre of the object, in m

SAMPLE PROBLEM 2

Calculate the gravitational field strength of the Moon at the surface of the Moon if its mass is $7.35 \times 10^{22} \text{ kg}$ and its radius is $1.74 \times 10^6 \text{ m}$.

 Teacher-led videos: SP2 (tlvd-0109)

THINK

Recall the formula $g = G \frac{M}{r^2}$, where:

$$G = 6.67 \times 10^{-11} \text{ N m}^2 \text{ kg}^{-2}$$

$$M = 7.35 \times 10^{22} \text{ kg and}$$

$$r = 1.74 \times 10^6 \text{ m}$$

WRITE

$$\begin{aligned} g &= G \frac{M}{r^2} \\ &= \frac{6.67 \times 10^{-11} \times 7.35 \times 10^{22}}{(1.74 \times 10^6)^2} \\ &= 1.62 \text{ N kg}^{-1} \end{aligned}$$

PRACTICE PROBLEM 2

Calculate the gravitational field strength of the Sun at the centre of the Earth, given the following:

$$M_{\text{Sun}} = 1.99 \times 10^{30} \text{ kg}$$

distance from the centre of the Earth to the centre of the Sun = $1.50 \times 10^{11} \text{ m}$.

The strength of the gravitational field at the Earth's surface can be calculated using the values for the mass and radius of the Earth, $M = 5.98 \times 10^{24} \text{ kg}$; $R_E = 6.38 \times 10^6 \text{ m}$:

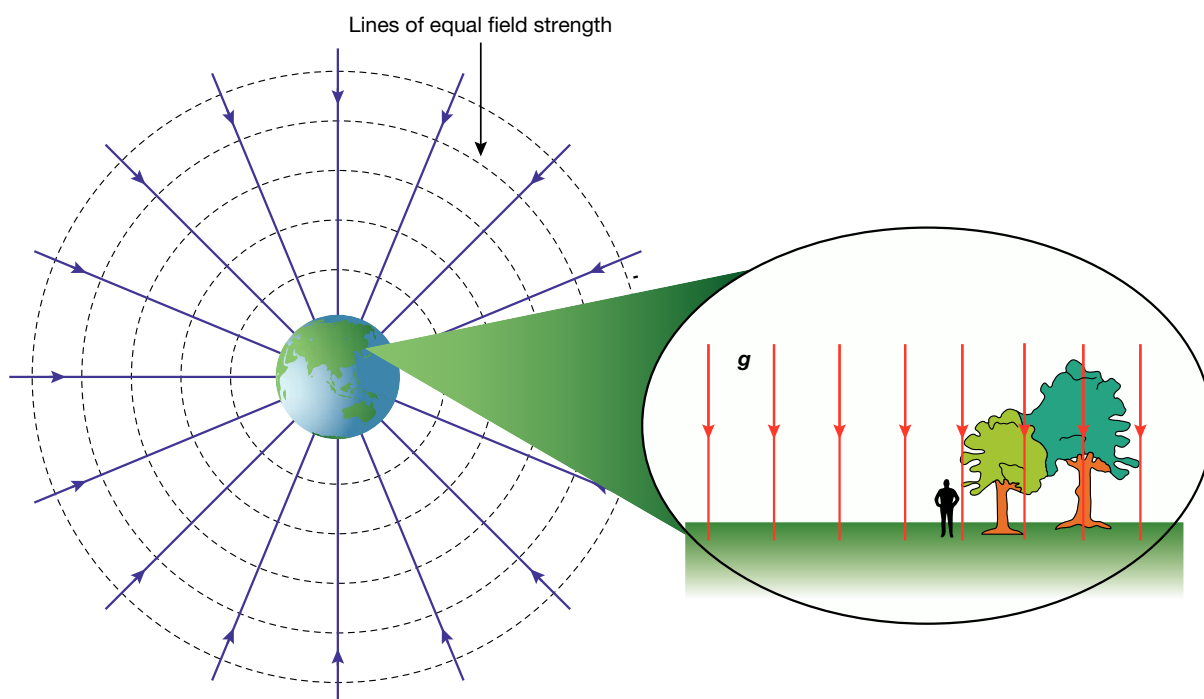
$$\begin{aligned} g &= \frac{6.67 \times 10^{-11} \times 5.98 \times 10^{24}}{(6.38 \times 10^6)^2} \\ &= 9.80 \text{ N kg}^{-1} \end{aligned}$$

(This is usually rounded to 9.8 N kg^{-1} .)

The gravitational field close to the surface of the Earth

You have just learned that the gravitational field of the Earth decreases as the square of the distance from the centre of the Earth. However, the Earth is huge compared to the scale of ordinary human actions. For a distance of 1000 m from the surface of the Earth, the gravitational field has decreased by a mere 0.03%, from 9.805 N kg^{-1} to 9.802 N kg^{-1} . The gravitational field strength experienced by a ball dropping from an initial height of a couple of metres above the surface of the Earth, is effectively constant or uniform.

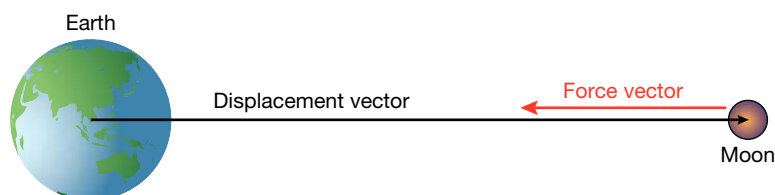
FIGURE 1.4 Zooming in on the gravitational field very close to the surface of the Earth, from a human perspective, the gravitational field appears to be constant and uniform. A mass placed at any point in this field would experience the same magnitude and direction of force: $F = mg$.



Graphing the gravitational field

The gravitational force is an attractive force — masses are attracted to each other.

FIGURE 1.5 The Earth exerts gravitational force on the Moon back towards the Earth.

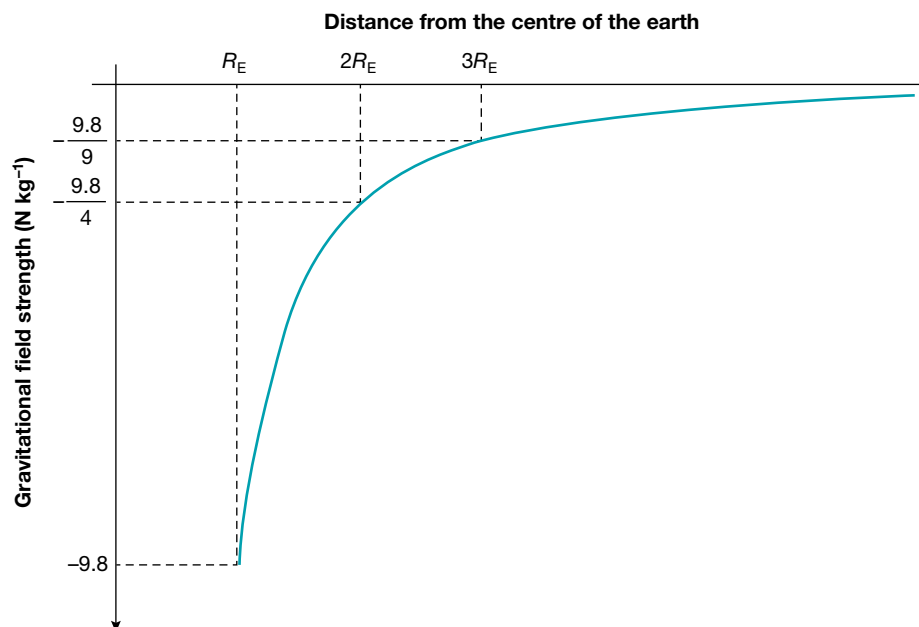


Picturing the force that the Earth exerts on the Moon, it is not hard to see that this force is in the opposite direction to the displacement of the Moon from the Earth. As a result, Newton's Law of Universal Gravitation and the complete expression for the gravitational field from a point mass should have a negative sign:

$$F_g = -G \frac{M_1 M_2}{r^2}, \quad g = -G \frac{M}{r^2}$$

Graphing the gravitational field shows clearly that the field strength is inversely proportional to the square of the distance from the mass. Therefore, as the distance increases, the gravitational field becomes non-uniform and changing.

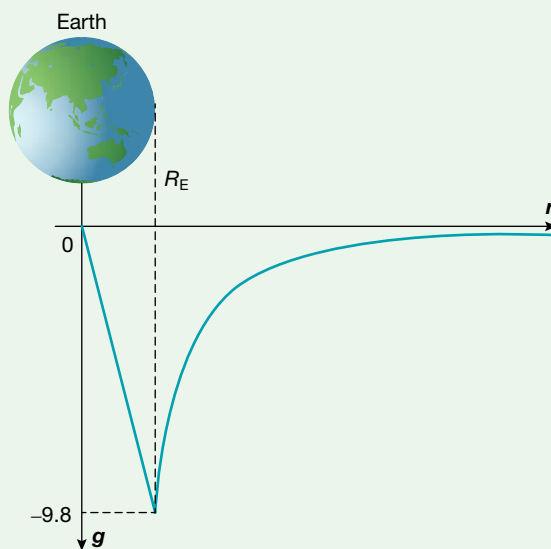
FIGURE 1.6 Graph of the Earth's gravitational field versus distance from the centre of the Earth



THE GRAVITATIONAL FIELD INSIDE THE EARTH

What does the gravitational field look like inside the Earth? Newton showed that the gravitational field inside a hollow spherical shell is in fact zero. This means that, closer to the centre of the Earth, the amount of mass that contributes to the Earth's gravitational field decreases. The overall effect is that the gravitational field decreases linearly from the outside of the Earth towards the centre.

FIGURE 1.7 Graph of the gravitational field of the Earth, including the strength inside the Earth



1.2 EXERCISE

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

- Sketch the gravitational field of the Earth.
 - Draw a vector indicating the force on an object that is positioned one Earth radius above the surface of the Earth, and a vector indicating the force on an object that is positioned two Earth radii above the surface of the Earth.
 - Compare the magnitude and direction of the two vectors.
 - Is the gravitational field uniform or non-uniform? Explain how this is indicated in your sketch.
- The gravitational force experienced by an object is known as the force due to gravity. Calculate (i) the gravitational field strength and (ii) the force due to gravity of a 70 kg person at the surface of:
 - Earth (mass = 5.98×10^{24} kg, radius = 6.37×10^6 m)
 - Mars (mass = 6.42×10^{23} kg, radius = 3.39×10^6 m)
 - Venus (mass = 4.87×10^{24} kg, radius = 6.05×10^6 m)
 - Pluto (mass = 1.31×10^{22} kg, radius = 1.15×10^6 m).
- Explain why the gravitational field lines for a mass always point radially inwards towards the centre of the mass.
- Calculate the gravitational field strength at distances of (i) 10 000 km, (ii) 20 000 km and (iii) 30 000 km from the centre of the Earth.
 - Calculate the ratios of the field strengths for (i) and (ii), (i) and (iii), and (ii) and (iii)
 - Compare the ratios and explain your findings.
- Calculate the force of attraction between the Earth and the Sun.
- If the Earth expanded to twice its radius without any change in its mass, what would happen to the force due to gravity on an individual on the surface of the Earth?
- The Moon is 3.84×10^5 km from the Earth and an average distance of 1.50×10^8 km from the Sun. Compare the gravitational field strength experienced by the Moon from the Sun with that from the Earth.

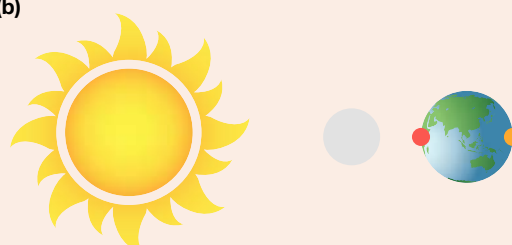
8. One of the simplest reasons tides occur is because of the difference in the gravitational pull on the opposite sides of the Earth.

Consider the following two situations (not drawn to scale):

(a)



(b)



The centre of the Earth is 1.496×10^{11} m from the Sun and 3.84×10^8 m from the Moon, and the radius of the Earth is 6.14×10^6 m. The mass of the Sun is 1.99×10^{30} kg and the mass of the Moon is 7.35×10^{22} kg. Calculate the combined gravitational field from the Sun and the Moon at the point on the surface of the Earth indicated by the red and orange dots at the times A and B.

9. How many Earth radii from the centre of the Earth must an object be positioned for the gravitational force by the Earth on the object to equal the gravitational force that would be exerted by the Moon on the object if the object was on the Moon's surface? The Moon has a radius of 1.74×10^6 m and a mass of 7.35×10^{22} kg. The radius of the Earth is 6.14×10^6 m.

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1.3 Electric forces and fields

KEY CONCEPTS

- Describe electricity using a field model
- Analyse the use of an electric field to accelerate a charge, including:
 - electric field and electric force concepts: $E = \frac{kq}{r^2}$ and $F = \frac{kq_1q_2}{r^2}$
 - the magnitude of the force on a charged particle due to a uniform electric field: $F = qE$.
- Investigate theoretically and practically electric fields, including directions and shapes of fields, attractive and repulsive fields, and the existence of dipoles and monopoles
- Investigate theoretically and practically electrical fields about a point charge (positive or negative) with reference to:
 - the direction of the field
 - the shape of the field
 - the use of the inverse square law to determine the magnitude of the field.
- Identify fields as static or changing, and as uniform or non-uniform.

The interaction between electric charges can also be described using a field model, but with an added degree of complexity. Electric charges can be either positive or negative. Like charges repel each other and unlike charges attract each other. This means that the value for an electric force can be positive or negative.

1.3.1 Coulomb's Law

Coulomb's Law states that the force between two point charges at rest is directly proportional to the product of the magnitudes of the charges and inversely proportional to the square of the distance between them. This is shown using the formula:

$$F = \frac{kq_1q_2}{r^2}$$

where: F is the force on each charged particle, in N
 k is Coulomb's constant ($8.99 \times 10^9 \text{ N m}^2 \text{ C}^{-2}$)
 q_1 and q_2 are the signed magnitudes of the two charges, in C
 r is the distance between the two charges, in m

In fact, k only has a value of $8.99 \times 10^9 \text{ N m}^2 \text{ C}^{-2}$ if there is a vacuum between the charges. Air has a similar value, but if the charges are immersed in any other substance, the force is reduced.

This constant has no special name, unlike the constant in Newton's Law of Universal Gravitation. It is often referred by various names, such as 'the electric force constant' and 'Coulomb's constant'.

Because the signs of the charges are included in the formula expressing Coulomb's Law, the sign of the force value, F , indicates whether the force is attractive or repulsive: a positive force value indicates repulsion and a negative force value indicates attraction.

SAMPLE PROBLEM 3

Two balloons are rubbed on a woollen jumper and each gain a charge of 2.0 nC. What force does one balloon exert on the other when they are 10.0 cm apart? Is this an attractive or repulsive force?

 Teacher-led video: SP3 (tlvd-0110)

THINK

Recall Coulomb's Law: $F = k \frac{q_1q_2}{r^2}$.

where:

$$k = 8.99 \times 10^9 \text{ N m}^2 \text{ C}^{-2}$$

$$q_1 \text{ and } q_2 = 2.0 \times 10^{-9} \text{ C and}$$

$$r = 0.100 \text{ m}$$

WRITE

$$F_{B1 \text{ on } B2} = \frac{8.99 \times 10^9 \times 2.0 \times 10^{-9} \times 2.0 \times 10^{-9}}{(0.100)^2}$$
$$= 3.6 \times 10^{-6} \text{ N}$$

The force has a positive sign, so the two balloons repel each other. (This can also be determined by the fact both charges are the same, and will therefore repel.)

PRACTICE PROBLEM 3

In the hydrogen atom, the electron and proton are on average $5.3 \times 10^{-11} \text{ m}$ apart. An electron has a charge of $-1.6 \times 10^{-19} \text{ C}$, and a proton has a charge of $+1.6 \times 10^{-19} \text{ C}$. Find the magnitude of the electrical force between the electron and proton. Is it attractive or repulsive?

THE LONG ROAD TO COULOMB'S LAW

You will probably have experienced a small electric shock when you touched a metal rail after walking across carpet. This phenomenon has been observed for thousands of years. Objects such as glass, gemstones and amber (petrified tree resin) can become 'electrified' by friction when they are rubbed with materials such as animal fur and fabrics, producing a little spark. The Ancient Greek word for amber is *elektron*.

Investigators tried to explain the various manifestations of electricity, but an understanding of the phenomenon was elusive. Both attraction and repulsion were observed, but initially repulsion was considered less important. In 1551, Girolamo Cardano realised that this electrical attraction was different from magnetic attraction. In 1600, William Gilbert, the physician to Elizabeth I, found that other substances such as glass and wax could be ‘electrified’, but he concluded that metals could not. In 1729, Stephen Gray discovered that electric charge could pass through materials such as the human body and metals. He concluded that some objects are **conductors** and others are **insulators**. In 1734, Charles du Fay showed that Gilbert was wrong about metals: they could be charged as long as the metal was in a handle of glass. However, du Fay thought there were two fluids, to explain the two types of charge, whereas Benjamin Franklin in 1746 suggested there was only one fluid. Objects with an excess of this fluid were designated positively charged, while negatively charged objects were deficient in the fluid.

In 1766, Franklin tried an experiment involving a hollow metal sphere with a small hole. He charged up the sphere and then lowered a small cork carrying an electric charge inside the sphere. Nothing happened to it — the cork was not pushed around, no matter where he placed the test charge. He wrote about this to his friend Joseph Priestley in England. Priestley was aware of Newton’s Law of Universal Gravitation, which is an inverse square law. He also knew that Newton had proved mathematically that, because of the inverse square law, no net gravitational force exists inside a hollow sphere. That is, at every point inside the sphere, the gravitational force from the mass on one side is balanced by the force from the mass on the other side.

Priestley confirmed Franklin’s results and realised that this was strong evidence that the inverse square law applied to electricity. In 1767, he published his finding that electric force was an inverse square law. Unfortunately, his paper went unnoticed by other scientists of his time.

If the force between two charges was an inverse square law, that is, $F \propto \frac{1}{r^n}$ where $n = 2$, could the value of n be experimentally confirmed?

In 1769, John Robison investigated how the force between charges changed with separation. He determined the value of the power n to be 2.06, very close to 2. In the 1770s, Henry Cavendish measured the value as between 1.96 and 2.04, but he never published his results.

In 1788 and 1789, Charles-Augustin de Coulomb published a series of eight papers on different aspects of his electrical experiments, showing that the electric force satisfied the inverse square law.

TABLE 1.1 The results of some of Coulomb’s experiments

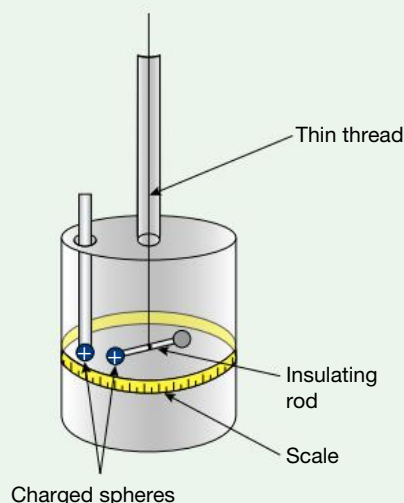
Observed force (in units)	Distance	
	Observed (in units)	Calculated (in units)
36	36	36
144	18	18
576	8.5	9

Coulomb’s papers were excellent examples of scientific writing. He described his apparatus in detail, and he discussed possible sources of error in his measurements. He also used two different methods to determine the value of n , obtaining the same result with each. Hence, Coulomb’s Law was named after him.

To investigate the force between two charges, Coulomb designed a torsion balance. His torsion balance had a long silk thread hanging vertically with a horizontal rod attached at the end. On one end of the rod was a small metal-coated sphere. On the other end was a sphere of identical mass to keep the rod level. The metal sphere was given a quantity of charge and a second metal sphere, charged with the same type of charge, was lowered to be in line with the first sphere. The electrical repulsion caused the silk thread to twist slightly. The angle of twist or deflection of the rod was a measure of the strength of the repulsive force.

Coulomb was able to measure the force to an accuracy of less than a millionth of a newton.

FIGURE 1.8 Coulomb’s torsion balance



Coulomb found that the force between two point charges at rest is directly proportional to the product of the magnitudes of the charges and inversely proportional to the square of the distance between them:

$$F \propto \frac{q_1 q_2}{r^2}$$

This expression has no equals sign; it is not an equation or formula. Coulomb was able to measure the force and separation very accurately, but charge was such a new concept that there were no units to measure it. Coulomb was only able to show that halving the size of each charge reduced the size of the force by a quarter.

It was not until the unit for current, the ampere, was defined and precisely measured that a unit for charge could be defined and calculated:

$$\text{charge} = \text{current} \times \text{time} \quad (Q = I \times t)$$

This unit was called the coulomb (represented by the symbol C) after Charles-Augustin de Coulomb. One coulomb of charge (1.0 C) equals the amount of charge that is transferred by one ampere of current in one second.

A coulomb of charge is a large quantity of charge. For example, the amount of charge transferred when fur is rubbed against a glass rod is a few millionths of a coulomb. In a typical lightning strike, about 20 coulombs of charge is transferred, whereas in the lifetime of an AA battery, about 5000 coulombs passes through the battery.

When the electron was discovered, its charge was determined to be 1.602×10^{-19} coulombs, which means that the total charge of 6.241×10^{18} electrons would equal one coulomb.

Once a unit to measure charge was available, the above relationship for the force between charges could be written as an equation with a proportionality constant, k .

on Resources

 **Interactivity** Doing the twist (int-6608)

1.3.2 The electric field from a charged particle

Attraction and repulsion between charges occurs without the need for contact — therefore, ‘action at a distance’ occurs. To explain such interactions, Michael Faraday (1791–1867) proposed the concept of a ‘field’. In the case of an electric charge, there was an **electric field** in the space around the charge such that if a second charge was placed in that space, it would experience an **electrical force**. The electric field at that point interacts directly with this second charge to produce a force.

If the first charge is represented by q_1 and the second charge is a small test charge q_2 , then the force on each charge is given by $F = \frac{kq_1 q_2}{r^2}$. The strength of the electric field, E , is defined by the force on the small test charge divided by the size of the test charge, or force per unit charge, and the unit for electric field is Newtons per coulomb or N C^{-1} :

$$E = \frac{F}{q_2} = \frac{\left(\frac{kq_1 q_2}{r^2}\right)}{q_2}$$

Cancelling q_2 gives:

$$\vec{E} = \frac{kq}{r^2}$$

where: $\vec{E}$ is the strength of the electric field due to a point charge, in N C^{-1}
 q is the charge of the point charge (that is causing the electric field), in C
 r is the distance from the point charge, in m
 k is Coulomb’s constant ($8.99 \times 10^9 \text{ N m}^2 \text{ C}^{-2}$)

This is a similar situation to the expressions for gravitational field.

TABLE 1.2 Comparison between expressions for electric and gravitational fields

Force and field between masses	Force and field between charges
$F_g = G \frac{M_1 M_2}{r^2}$	$F = \frac{kq_1 q_2}{r^2}$
$F_g = mg$	$F = qE$
$g = G \frac{M}{r^2}$	$E = \frac{kq}{r^2}$

However, electrical interactions are different from gravitational interactions in that electric charges can attract and repel. There are two types of charge, positive and negative, with **like charges** repelling each other and **unlike charges** attracting.

SAMPLE PROBLEM 4

What is the magnitude of the electric field at a point 50 cm to the left of a point charge of $+2.0 \times 10^{-7} \text{ C}$?

 **Teacher-led video:** SP4 (tlvd-0111)

THINK

Recall the formula for an electric field:

Ensure the distance is in metres and the charge is in coulombs. In this case, the distance of 50 cm needs to be converted to 0.5 m.

WRITE

$$E = \frac{kq}{r^2}$$

$$E = \frac{8.99 \times 10^9 \times 2.0 \times 10^{-7}}{(0.5)^2}$$

$$= 7.2 \times 10^3 \text{ N}$$

PRACTICE PROBLEM 4

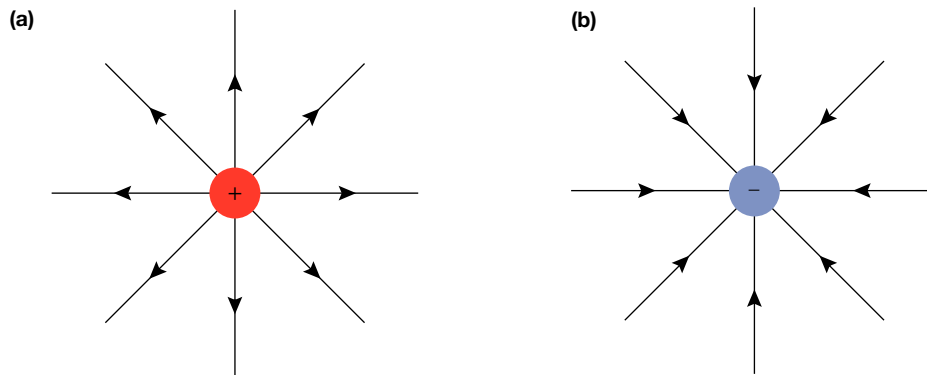
What is the magnitude of the electric field at a point 30 cm to the right of a point charge of $-3.0 \times 10^{-6} \text{ C}$?

Drawing an electric field diagram

When you draw a gravitational field, the field lines indicate the direction in which a mass would move. But for an electric field, because there are two types of charge, a convention is needed so that you can correctly interpret field diagrams.

In an electric field diagram, the direction of the field is the direction in which a positive charge would move.

FIGURE 1.9 Fields around (a) a positive charge and (b) a negative charge



Remember that the changes in the density of the field lines give an indication of changes in the strength of the field. For the source charges in figure 1.9, the fields lines spread out from the centre. The increased spacing between field lines further away from the centre is an indication of the decreasing strength of the field, illustrating the non-uniform nature of the field. Like the gravitational field of a point mass, the field from the point charge is static or unchanging as time passes.

SAMPLE PROBLEM 5

Consider a particle with a charge of $1.0 \mu\text{C}$.

- Draw a diagram of the field of the particle.
- Draw a vector showing the force on a 1.0 nC charge placed 2.0 cm to the right of the particle.
- Draw a vector showing the force on a -1.0 nC charge placed 2.0 cm to the right of the particle.
- Draw a vector showing the force on a 1.0 nC charge placed 4.0 cm to the right of the particle.

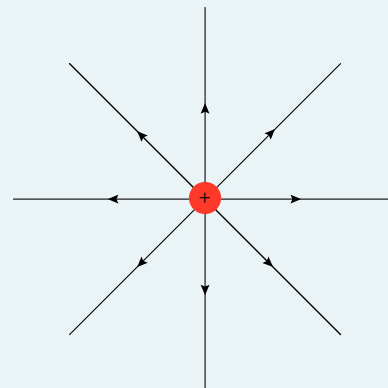
 **Teacher-led video:** SP5 (tlvd-0112)

THINK

- Recall the shape of the electric field around a point charge, remembering that the direction of the field is the way in which a positive charge would flow (away from the charge).

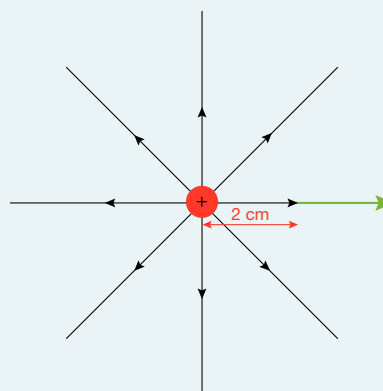
WRITE

a.



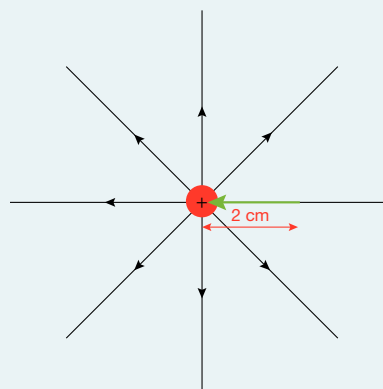
- b. As the charges are both positive, they will repel each other.

b.



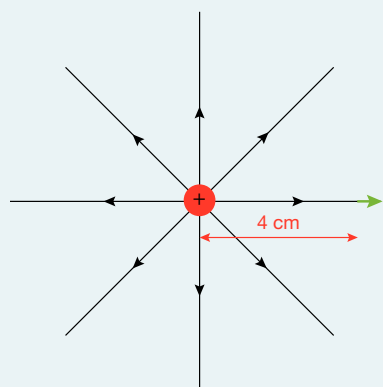
- c. As the charges are opposite, they will attract each other.

c.



- d. As the charges are both positive, they will repel each other. As the distance between the charges has doubled, the force between them has reduced to $\frac{1}{4}$ of the original force.

d.



PRACTICE PROBLEM 5

Consider a particle with a charge of $-1.0 \mu\text{C}$.

- Draw a diagram of the field of the particle.
- Draw a vector showing the force on a 1.0 nC charge placed 2.0 cm to the left of the particle.
- Draw a vector showing the force on a -1.0 nC charge placed 2.0 cm south-east of the particle.
- Draw a vector showing the force on a 1.0 nC charge placed 4.0 cm north-east of the particle.

Graphing the electric field

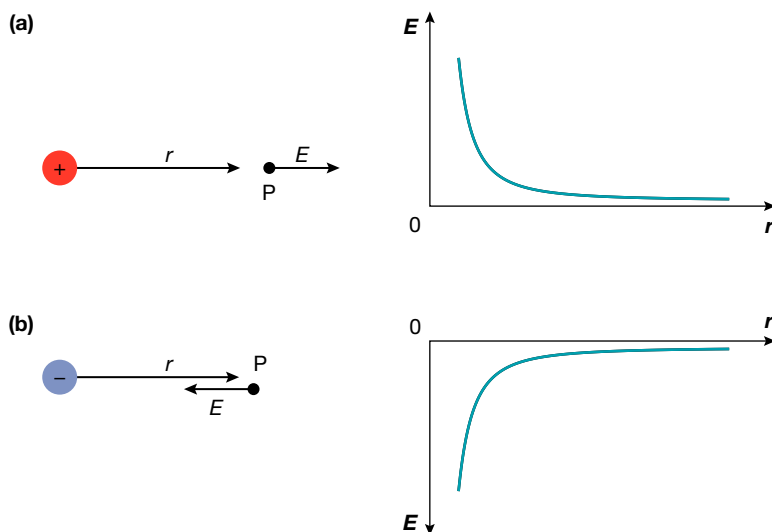
The direction of the electric field is the direction in which a positive test charge would move.

For a central positive charge, the direction of the electric field vector at a point P is in the same direction as the position vector of P. This means that the graph of the electric field is above the distance axis. This can be further understood when you consider the formula for an electric field, where

$E = \frac{kq}{r^2}$. If the value of q (the charge) is positive, the strength of the electric field (E) is also positive.

For a central negative charge, the direction of the electric field vector is in the opposite direction to the position vector, so the graph of the electric field around a negative charge will be below the distance axis. This can be further understood when you consider the formula for an electric field, where $E = \frac{kq}{r^2}$. If the value of q (the charge) is negative, the strength of the electric field (E) is also negative.

FIGURE 1.10 The electric field at an increasing distance from (a) a positive charge, (b) a negative charge

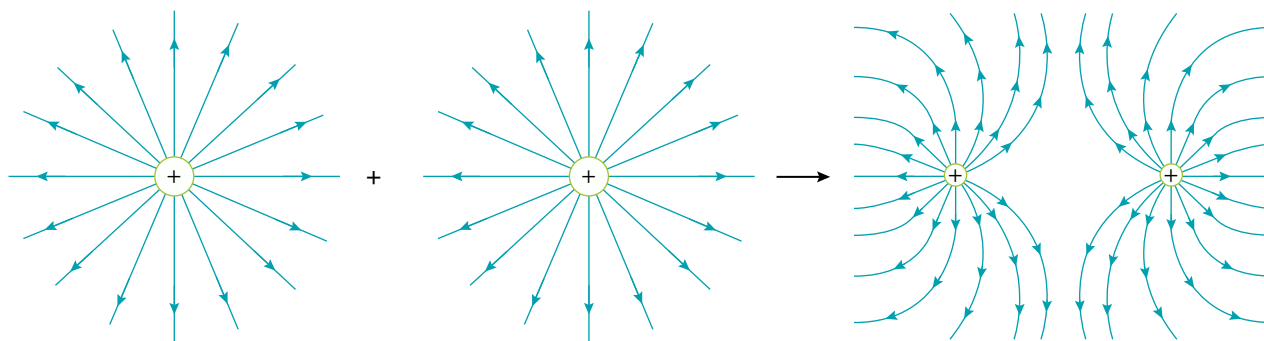


1.3.3 Electric fields from two or more charges: dipoles and parallel charged plates

When two or more charged sources are present, the fields from each of the individual sources are added together to give the total field. Remember that fields are vectors and obey vector addition laws.

Consider the following diagram of the electric field for two positive charges:

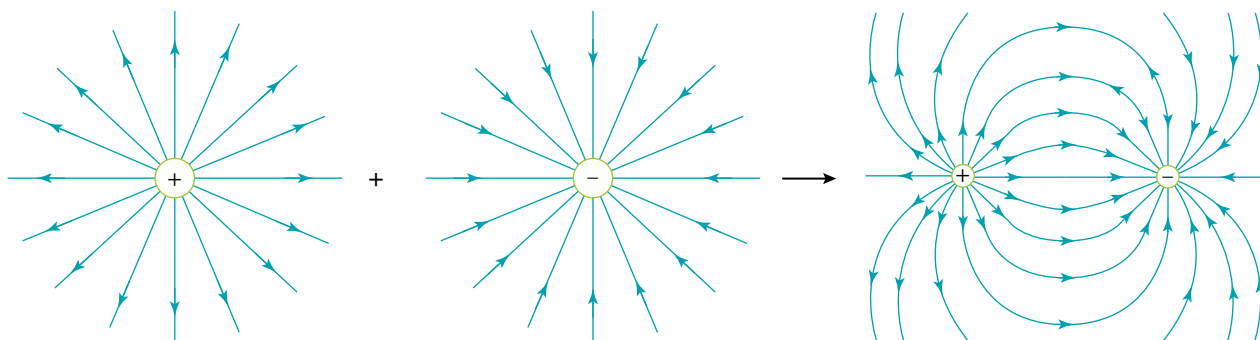
FIGURE 1.11 The field from two positive charges



At the point halfway between the two charges, the fields from the two charges completely cancel, resulting in a field of zero. Notice that at large distances from the charges, the field lines look very similar to the field lines from a point with twice as much charge.

If you look at the situation of a positive charge near a negative charge of equal size, known as an **electric dipole**, you obtain a very different pattern:

FIGURE 1.12 The field from a positive and a negative charge, known as an electric dipole



The field pattern from the electric dipole cannot be confused with the field from a single charge. It has a definite attractive end and a definite repulsive end. The field from an electric dipole is also clearly non-uniform.

When a positive charge and a negative charge are separated by a short distance, the electric field around them is called a **dipole field**. This concept is also relevant to magnetic fields, where the ends of a bar magnet have different polarities (north and south).

Electric dipoles play a very important role in atoms and molecules. For example, in a molecule of water, H_2O , the oxygen atom more strongly attracts the shared electrons than do each of the hydrogen atoms, as shown in figure 1.13. This makes the oxygen end of the molecule more negatively charged and the hydrogen end more positively charged. Because of this, the water molecule is called a polar molecule. It is this polarity that makes water so good at dissolving substances.

An antenna can be described as a varying electric dipole. To produce a radio or a TV signal, electrons are accelerated up and down the antenna. At one moment, the top may be negative and the bottom positive, then, a moment later, the reverse is the case.

FIGURE 1.13 A water molecule (H_2O) displays polarity.

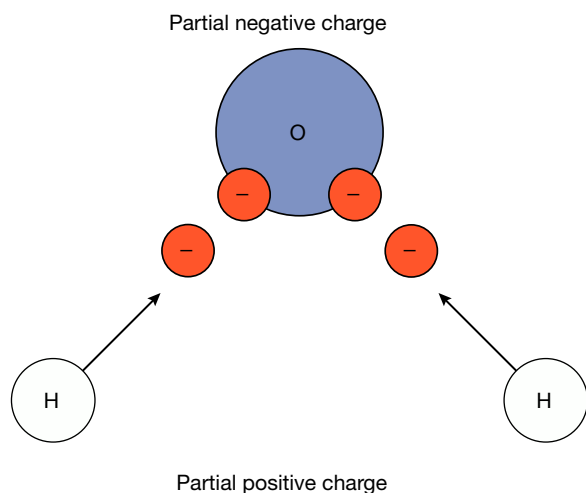
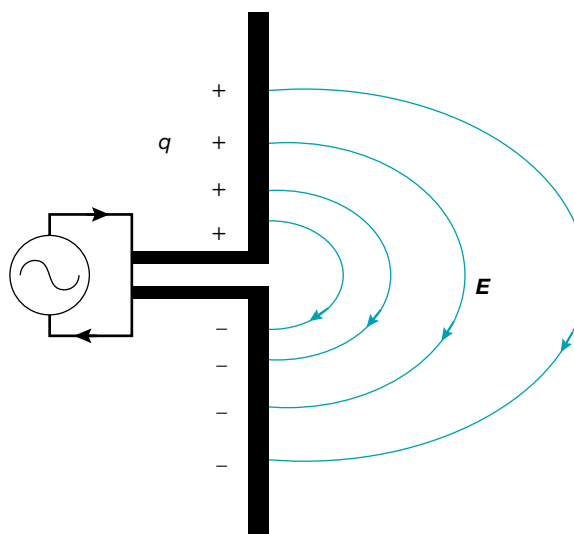


FIGURE 1.14 Partial circuit diagram of an antenna



SAMPLE PROBLEM 6

- a. Sketch the field due to the two particles shown in the following diagram, each with a charge of $-1.0 \mu\text{C}$ separated by 4.0 cm .



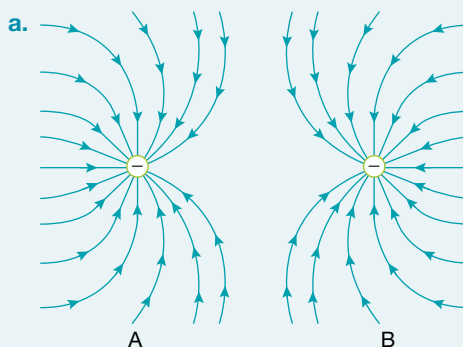
- b. Draw a vector indicating the direction of the force on a 1.0 nC charge placed to the left of particle A.
 c. Describe how the direction of the force on the 1.0 nC charge changes as it is moved along an imaginary line connecting particles A and B.

 **Teacher-led video:** SP6 (tlvd-0113)

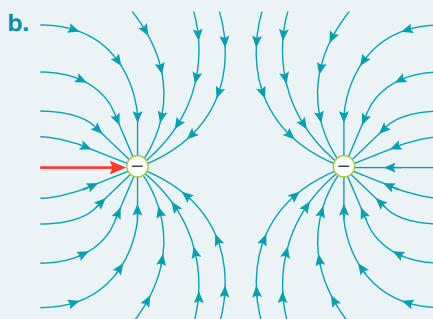
THINK

- a. Recall the shape of the electric field around two negative charges.

WRITE



- b. As the charge is positive, it is attracted to the negative particles A and B, which are directly to the right of the 1.0 nC charge.



- c. The positive charge is attracted to both negative point charges A and B. The overall net force on the charge is the sum of the forces acting on it from particles A and B.

- c. When the 1 nC charge moves past particle A to the right-hand side, it experiences an attractive force to the left from particle A and also an attractive force to the right from particle B. Because the charge is closer to particle A than particle B, the force acting to the left is stronger than the force to the right, so the net (or overall) force on the 1 nC charge at this point is to the left (but it is smaller in magnitude than the force it experienced in part b). As the charge is moved closer to particle B, the magnitude of the leftwards net force decreases to zero at the point halfway between the two particles. When the charge moves closer to particle B than particle A, the net force acts to the right and becomes stronger as the charge moves closer to particle B.

PRACTICE PROBLEM 6

Sketch the electric field that would result from particle A having a negative charge of $1\ \mu\text{C}$ and particle B (which is placed to the right of particle A) having a positive charge of $1\ \mu\text{C}$.

- Compare the force on a $1\ \text{nC}$ charge placed to the left of particle A with one placed to the right of particle A.
- Describe how the force changes on the $1\ \text{nC}$ charge as it is moved along an imaginary line between A and B.

THE STRUCTURE OF DNA AND ELECTRICAL ATTRACTION

A DNA molecule is a long chain molecule built from four small molecules: adenine (A), cytosine (C), guanine (G) and thymine (T). These are arranged along the DNA molecule according to a code called the genetic code. Different sequences of A, C, G and T code for different amino acids, which are combined one after the other to produce different protein molecules. Two DNA molecules wrap around each other in a spiral to produce a double-helix chromosome.

The two DNA molecules in the helix are held together by electrical attraction between the polar ends of the four small molecules A, C, G, and T. The chromosome is able to replicate itself because A and T can only pair up with each other, and likewise C and G can only pair up with each other. If there is an A on one strand, there must be a T immediately opposite on the other strand, and so on.

Figure 1.16 shows that one of the oxygen atoms in the thymine molecule is slightly negative, and one of the hydrogen atoms in the adenine molecule is slightly positive. Similarly, a hydrogen atom in the thymine molecule is slightly positive, and a nitrogen atom in the adenine molecule is slightly negative. These two slight electrical attractions are enough to hold these two molecules together, and the separations across these weak bonds are comparable in length.

FIGURE 1.15 A section of a DNA molecule

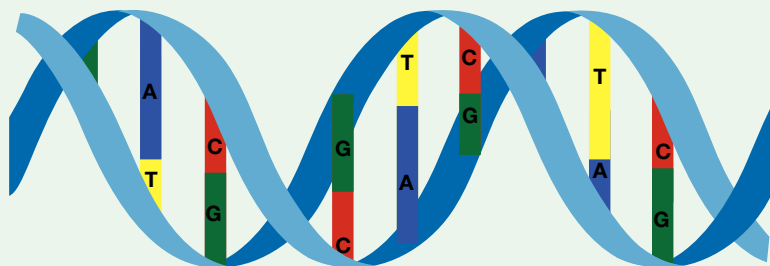
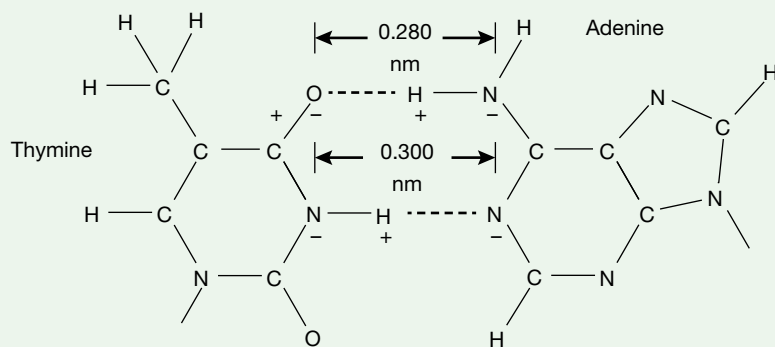
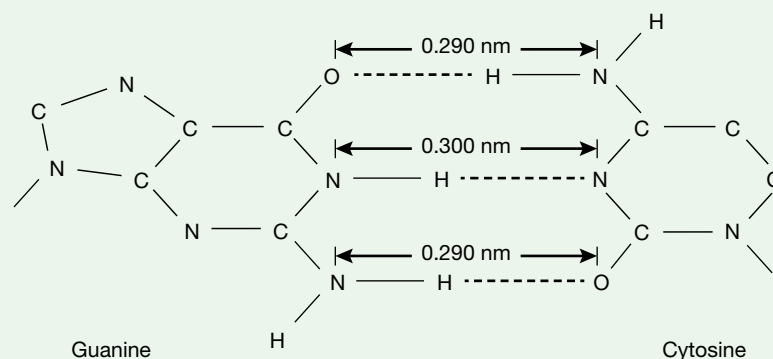


FIGURE 1.16 Electrical attraction between thymine and adenine molecules



Guanine and cytosine have a similar arrangement, except that there are three pairs of electrical attraction. Most importantly, the separations of the weak bonds between guanine and cytosine are comparable to each other and also to those of adenine and thymine. Without this matchup of separations, a chromosome could not hold together, nor could it form a double helix.

FIGURE 1.17 Electrical attraction between guanine and cytosine molecules



The electric field between parallel charged plates

If a set of positive and negative charges were lined up in two rows facing each other, the lines of electric field in the space between the rows would be evenly spaced, that is, the value of the strength of the field would be constant. This is called a **uniform electric field**.

It is also very easy to set up. Just set two metal plates a few centimetres apart, then connect one plate to the positive terminal of a battery and connect the other plate to the negative terminal of the battery. The battery will transfer electrons from one plate, making it positive, and put them on the other, making that one negative. The battery will keep on doing this until the positive plate is so positive that the battery's voltage, or the energy it gives to each coulomb of electrons, is insufficient to overcome the attraction of the positively charged plate. Similarly, the negatively charged plate will become so negative that the repulsion from this plate prevents further electrons being added.

FIGURE 1.18 A uniform electric field

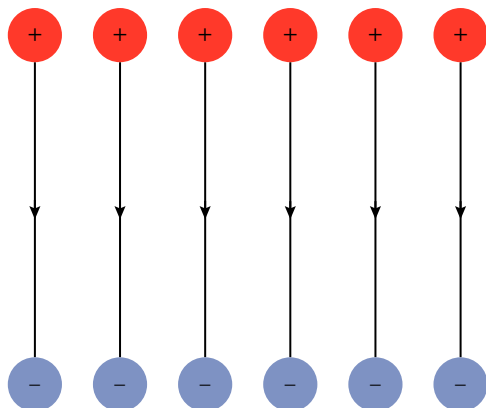
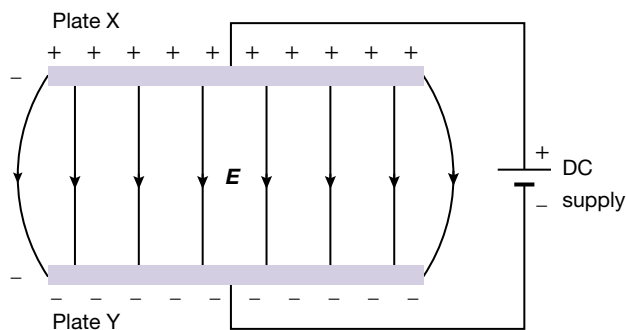


FIGURE 1.19 An electric field between two plates



The uniform field between the plates means that the force experienced by a charged particle placed at any position between the plates is the same, and the magnitude of this force can be calculated using the following formula:

$$\vec{F} = q\vec{E}$$

where: $\vec{F}$ is the force on the charged particle, in N
 q is the charge of the particle experiencing the force, in C
 $\vec{E}$ is the strength of the electric field, in N C^{-1}

The field remains static, or unchanging for as long as the parallel plates remain charged. You will see in topic 3 that this has many important applications and is the basic building block of a particle accelerator.

SAMPLE PROBLEM 7

The electric field strength between two parallel plates separated by 2.0 cm is 10 N C^{-1} . An electron (with a charge of $-1.6 \times 10^{-19} \text{ C}$) enters the space between the plates.

- Calculate the magnitude of the force on the electron.
- Describe the direction of the force on the electron.
- Calculate the change in velocity of an electron that starts at rest halfway between the two plates.

 Teacher-led video: SP7 (tlvd-0114)

THINK

- Recall that $F = qE$ and that the charge on the electron is $-1.6 \times 10^{-19} \text{ C}$.
- Remember that the electron has a negative charge.
- The electron experiences a constant force, so it undergoes constant acceleration. Apply Newton's Second Law, $F = ma$, to determine the acceleration. Use your formula sheet to find that the mass of an electron is equal to $9.1 \times 10^{-31} \text{ kg}$.
 - The values of the initial velocity, acceleration and distance travelled are known, so these can be used in the equation $v^2 = u^2 + 2as$ to calculate the final velocity. For the distance, remember that the electron is halfway between the two plates, so the distance is 1.0 cm (converted to 0.01 m for use in the formula). You also need to ensure you use your non-rounded value for acceleration during your calculations.

WRITE

- $$F = qE$$

$$= -1.6 \times 10^{-19} \times 10$$

Hence, the magnitude of the force is $1.6 \times 10^{-18} \text{ N}$.
- The sign of the force is opposite to the sign of the field, so the electron experiences a force in the opposite direction to the electric field and will be accelerated towards the positive plate.
- $$a = \frac{F_{\text{net}}}{m}$$

$$= \frac{1.6 \times 10^{-18}}{9.1 \times 10^{-31}}$$

$$= 1.8 \times 10^{12} \text{ m s}^{-2}$$

$$v^2 = u^2 + 2as$$

$$v^2 = 0 + 2 \times 1.8 \times 10^{12} \times 0.01$$

$$= 3.5 \times 10^{10}$$

$$\Rightarrow v = 1.9 \times 10^5 \text{ m s}^{-1}$$

As the initial velocity was 0 m s^{-1} and the final velocity was $1.9 \times 10^5 \text{ m s}^{-1}$, the change in velocity was $1.9 \times 10^5 \text{ m s}^{-1}$

PRACTICE PROBLEM 7

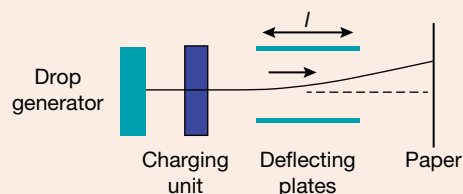
The electric field strength between two parallel plates separated by 2.0 cm is 20 N C^{-1} . A proton is placed halfway between the plates. The proton has a charge of $1.6 \times 10^{-19} \text{ C}$ and a mass of $1.67 \times 10^{-27} \text{ kg}$.

- What is the magnitude of the force on the proton?
- Describe the direction of the force on the proton.
- Calculate the final velocity of a proton that starts at rest halfway between the two plates.

1.3 EXERCISE

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

- A negative test charge is placed at a point in an electric field. It experiences a force in an easterly direction. What is the direction of the electric field at that point?
- (a) Determine the strength of the electric field 30 cm from a charge of $120\ \mu\text{C}$.
(b) Determine the direction and magnitude of the electric force on a $10\ \mu\text{C}$ charge placed 30 cm to the right of the $120\ \mu\text{C}$ charge.
- An electric force of 1.5 N acts upwards on a charge of $+3.0\ \mu\text{C}$. What is the strength and direction of the electric field?
- A and B are metal spheres x metres apart. Each has a charge of $+q$ coulombs. The force they exert on each other is 5.0×10^{-4} newtons. Determine the magnitude of the force in each of the following situations. (Consider the situations separately.)
(a) The separation of A and B is increased to $2x$ metres.
(b) A charge of $+2q$ coulombs is added to B. Are the forces on A by B and on B by A still equal in magnitude?
(c) A charge of $-3q$ coulombs is added to A.
(d) The distance is halved and the charges are changed to $+0.5q$ on A and $4q$ on B.
- Sketch the electric field around two positive charges, A and B, where the charge on A is twice that on B.
- Two small spheres, A and B, are placed with their centres 10 cm apart. P is placed between A and B, at a position 2.5 cm from A. What is the direction of the electric field at P in the following situations?
(a) A and B have the same positive charge.
(b) A has a positive charge, B has a negative charge and the magnitudes are the same.
- Two small spheres are placed with their centres 20 cm apart. The charges on each are $+4.0 \times 10^{-8}\ \text{C}$ and $+9.0 \times 10^{-8}\ \text{C}$. Where between the two spheres would a test charge experience zero net force?
- Two metal plates, X and Y, are set up 10 cm apart. The X plate is connected to the positive terminal of a 60 V battery and the Y plate is connected to the negative terminal. A small positively charged sphere is suspended midway between the plates and it experiences a force of $4.0 \times 10^{-3}\ \text{N}$. What would be the size of the force on the sphere if it was placed 7.5 cm from plate X?
(a) Calculate the acceleration of an electron in a uniform electric field of strength $1.0 \times 10^6\ \text{N C}^{-1}$.
(b) Starting from rest, how long would it take for the speed of the electron to reach 10% of the speed of light? (Ignore relativistic effects.)
(c) What distance would the electron travel in that time?
- In an inkjet printer, small drops of ink are given a controlled charge and fired between two charged plates. The electric field deflects each drop and thus controls where the drop lands on the page, as outlined in the diagram.
Let m = the mass of the drop, q = the charge of the drop, v = the speed of the drop, l = the horizontal length of the plate crossed by the drop, and E = electric field strength.
(a) Develop an expression for the deflection of the drop. *Hint:* This is like a projectile motion question.
(b) With the values $m = 1.0 \times 10^{-10}\ \text{kg}$, $v = 20\ \text{m s}^{-1}$, $l = 1.0\ \text{cm}$ and $E = 1.2 \times 10^6\ \text{N C}^{-1}$, calculate the charge required on the drop to produce a deflection of 1.2 mm.



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1.4 Magnetic forces and fields

KEY CONCEPTS

- Describe magnetism using a field model
- Investigate theoretically and practically magnetic fields, including directions and shapes of fields, and attractive and repulsive fields
- Investigate and apply theoretically and practically a vector field model to magnetic phenomena, including shapes and directions of fields produced by bar magnets, and by current-carrying wires, loops and solenoids
- Identify fields as static or changing, and as uniform or non-uniform.

Unlike for gravitational and electric fields, the sources of magnetic fields are grouped into two classes: intrinsically magnetic materials and magnetic fields arising from moving charged particles. The interrelation of electric and magnetic fields will be revisited later when you study electromagnetic radiation, otherwise known as light.

1.4.1 Early ideas about magnetism

Magnetism has been known of since the beginning of recorded history. The ancient Athenians (600 BC) observed that a stone could attract pieces of iron. They called this stone ‘magnet’ because it was found in an area that was then called Magnesia (now in Turkey). They noticed that the pieces of iron attracted to this stone could also then attract other pieces. The magnet had ‘magnetised’ the iron it was in contact with. This process is called **magnetic induction**.

MAGNETITE

The stone called ‘magnet’ is an iron oxide called magnetite. It has the chemical formula Fe_3O_4 . It is black, metallic and quite hard. The stone has also been called a lodestone, which comes from ‘leading stone’. This refers to the fact that a magnet, if free to move, orients itself along a north–south line.

In trying to explain their observations of magnetism, the Greeks and Romans concentrated on the fact that magnets attract iron.

In his book, *De Rerum Natura* (On the Nature of Things), Lucretius said the following:

At this point, I will set out to explain what law of nature causes iron to be attracted by that stone which the Greeks call from its place of origin, ‘magnet’, because it occurs in the territory of Magnesia. Men look upon this stone as miraculous. They are amazed to see it form a chain of little rings hanging from it. Sometimes you may see as many as five or more in pendant succession swaying in the light puffs of air; one hangs from another, clinging to it underneath, and one derives from another the cohesive force of the stone. Such is the permeative power of this force.

...

So much by way of preface... it will be easy to lay bare... the cause of the attraction of the iron. First, this stone must emit a dense stream of atoms which dispels by a process of bombardment all the air that lies between the stone and the iron. When this space is emptied and a large tract in the middle is left void, then atoms of the iron all tangled together immediately slide and tumble into the vacuum. The consequence is that the ring itself follows and so moves in with its whole mass. No other substance is so rigidly held together by the entanglement of its elemental atoms as cold iron, that stubborn and benumbing metal.

...

Summing up in a few brief words, when the textures of two substances are mutually contrary, so that the hollows in the one correspond to the projections in the other... then connection between them is most perfect. It is even possible for some things to be coupled together, as though interlinked by hooks and eyes. And such, it would seem is the linkage between iron and magnet.

While Lucretius provides a picturesque model of a magnet's attraction for iron, it does not explain later observations. From about 800 AD onwards, most cultures discovered that magnets always point in the same direction if free to spin. The magnetic compass became a necessary tool for navigation and exploration. The end of the magnet that pointed towards the north was called the north-seeking end, or north end for short. The other end was called the south end.

FIGURE 1.20 A magnet will line up with a line from north to south if it is allowed to spin freely.

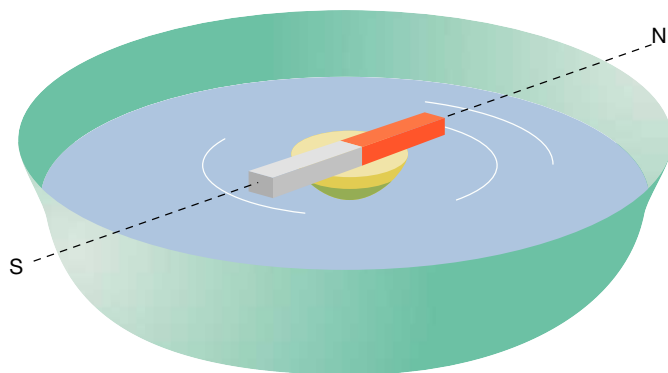
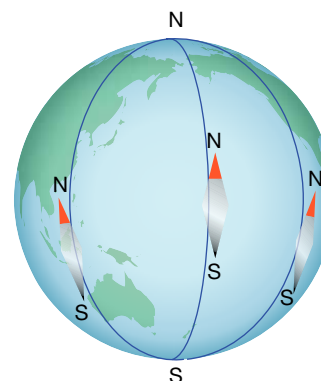


FIGURE 1.21 The south end of the magnet points generally towards geographic south.

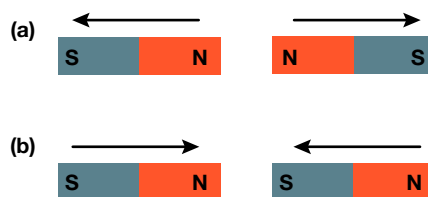


In ancient times, while the attraction of magnets for iron was an obvious phenomenon, the repulsion between magnets was either not observed or not considered as important as the attraction. The early ideas do not explain repulsion.

It was only much later that attraction and the repulsion between two magnets were treated equally. This appreciation led Peter Peregrinus, a French soldier living in the thirteenth century, to propose three ideas:

1. The ends of the magnet, where the strongest attraction for iron occurred, were different from each other.
2. When the ends were brought together, the two like ends repelled each other.
3. The two unlike ends attracted each other.

FIGURE 1.22 (a) Like ends repel (b) unlike ends attract.



These simple ideas were forgotten during the Middle Ages. In the sixteenth century, Dr Gilbert, a physician to Queen Elizabeth I, developed the same ideas. He also found that a freely suspended magnet dipped down at an angle to the horizontal and that this angle varied with latitude. He explained these observations by suggesting that Earth contained a magnet.

Today, Gilbert's idea of a solid magnet inside Earth is rejected because Earth's crust does not contain sufficient iron for the measured strength of Earth's magnetism. Also, much of Earth's core is molten liquid. A satisfactory explanation is still being sought for the origin of Earth's magnetism.

FIGURE 1.23 A magnet compass not only aligns itself along a line from north to south, it also dips downwards at an angle that varies with latitude.

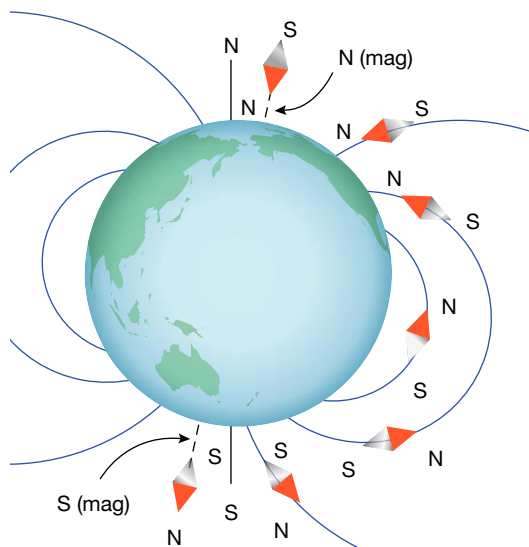
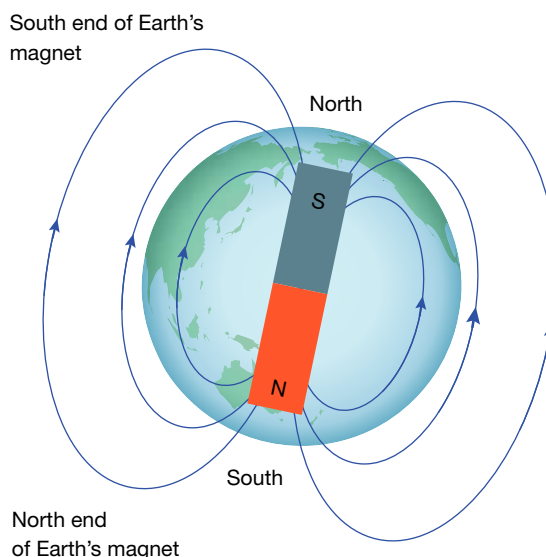


FIGURE 1.24 The south-seeking end of the needle points towards geographic south. But because unlike ends attract, this end of Earth's magnet must be a magnetic north end.



Although Gilbert's work was a major breakthrough, his concept of how magnets attracted the iron was very similar to that of Lucretius:

Magnetic force is something animate, it imitates a soul, nay, it surpasses the human soul. It sends forth its energy without error . . . quick, definite, constant, directive, imperant, harmonious. The magnet emits an effluvium which reaches out to the attracted body as a clasping arm and draws it to itself.

1.4.2 Magnetic fields and magnetic materials

It was only when Michael Faraday (1791–1867) suggested the concept of a **magnetic field** that a useful model appeared. The magnetic field was described as a property of the space around a magnet, so that if a piece of iron was in that space it would experience a force. The lines typically drawn around a magnet represent the direction of this field, and their closeness indicates its strength. The lines are imaginary; they help to visualise a very abstract but useful concept. A picture (or diagram) of iron filings around a magnet is an effective representation of a magnetic field.

There are rules for drawing field lines:

- Each field line is a continuous loop that leaves the north end of the magnet, enters at the south end and passes through the magnet back to the north end.
- Field lines do not intersect.
- The direction of the magnetic field at a point is along the tangent to the field line.
- The closeness of the lines represents the strength of the magnetic field. When the distance between the lines is the same, this field is known as uniform. If the distance changes, the field is referred to as non-uniform (as seen in figure 1.25).

Magnets can be designed to produce fields of different shapes. A horseshoe magnet with adjacent ends produces a strong and even field between the ends. A circular magnet with a north end in the middle produces a radial field that points outward all the way around. This design is used in loudspeakers.

Some magnets have stronger fields than others. The strength of a magnetic field is measured in tesla. The strength of Earth's magnetic field at its surface is quite small, about 10^{-4} tesla or 0.1 millitesla (0.1 mT). The strength of a typical school magnet is about 0.1 T. A fridge magnet is about 30 mT. The strongest permanent magnetic fields typically produced have field strengths of about 1.0 T.

FIGURE 1.25 (a) A magnetic field can be represented by the direction and closeness of field lines on a page. (b) Closer lines represent increased strength. Note the non-uniform nature of the field.

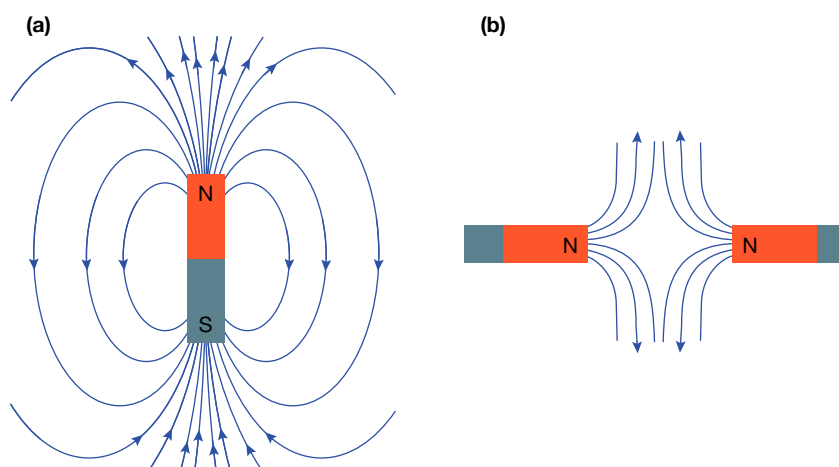
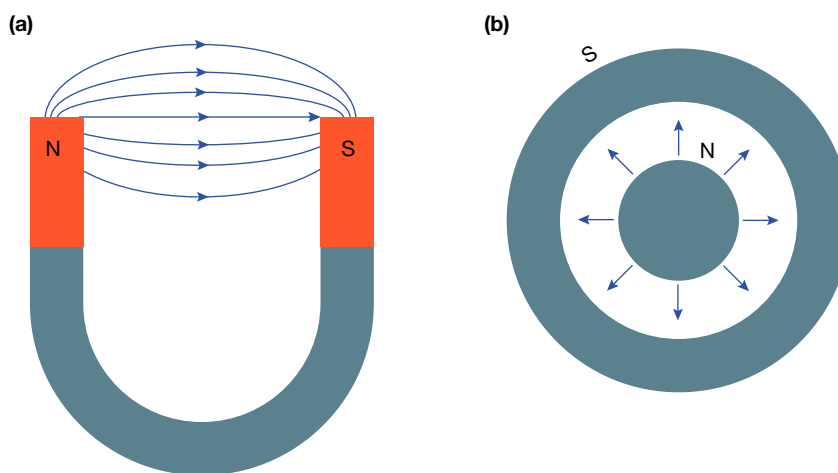


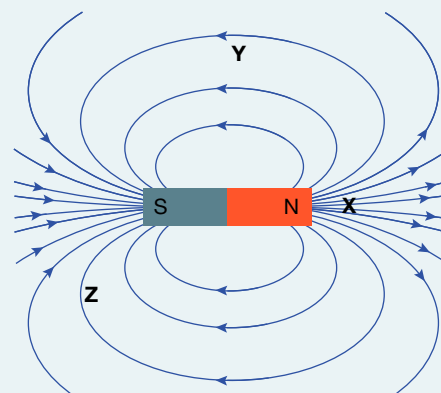
FIGURE 1.26 Differently shaped magnetic fields can be created by arranging the north and south ends of the magnet, as shown by (a) a horseshoe magnet and (b) a circular magnet.



SAMPLE PROBLEM 8

Consider the following diagram of the magnetic field of a bar magnet.

- In what direction would the north end of a compass point if placed at points X, Y and Z?
- Rank the points in order of increasing field strength.



 **Teacher-led video:** SP8 (tlvd-0115)

THINK

- a. Remember that the field lines indicate the direction that a magnetic compass would point.
- b. Remember that the density of the field lines indicates the relative strength of the field.

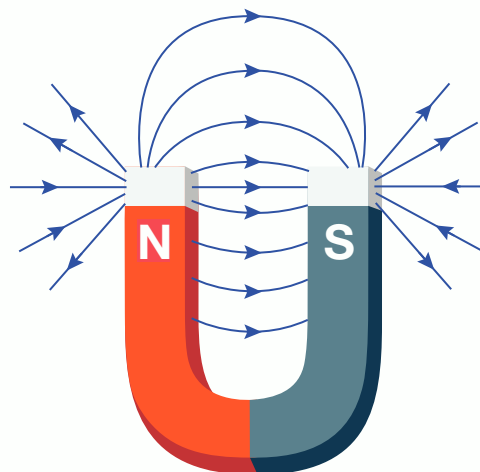
WRITE

- a. At X, the field lines point away from the north pole of the bar magnet, so a compass placed there would point towards the right, away from the north pole.
At Y, the field lines point towards the left, so the compass needle would point towards the left.
At Z, the field lines curve, so the compass would follow the tangent to the curve and would point to the right at an angle of approximately 45° upwards.
- b. The field lines are most dense at X and least dense at Y, so the points in order of increasing field strength would be Y, Z, X.

PRACTICE PROBLEM 8

Consider the magnetic field of a horseshoe magnet.

- a. In what direction would the north end of a compass point if placed just to the left of the north pole?
- b. In what direction would the north end of a compass point if placed halfway between the north and south pole?
- c. In which position would the field be strongest?



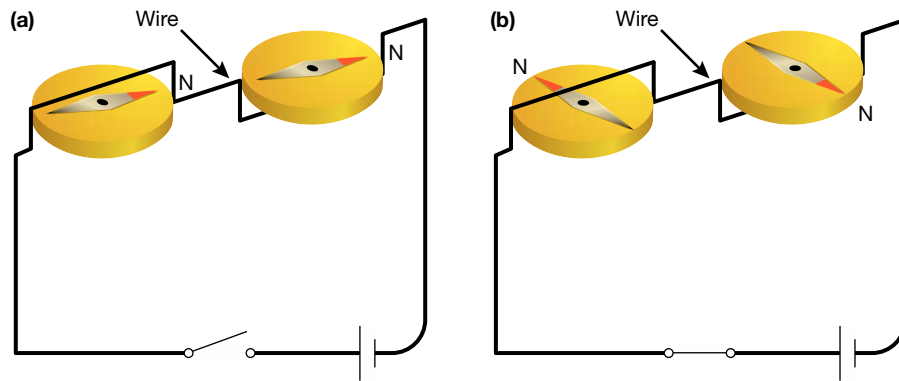
on Resources

 **Digital document** Investigation 1.2 Magnetic field mapping (doc-31586)

1.4.3 Magnetic fields from moving charges

Hans Christian Oersted, like many others at the time (1820), thought there was a connection between electricity and magnetism. He placed a wire carrying a current over a magnetic compass and saw that the needle deflected. He then placed the wire under the compass and the needle deflected in the opposite direction.

FIGURE 1.27 (a) Switch open in circuit, and (b) switch closed in circuit. To achieve maximum deflection, the wire should be placed in line with the magnetic needle before the current is turned on.



Deflection of a compass needle means there is a magnetic field associated with the current, which causes the needle to line up with it. So, though charged particles have their own associated electric field, they also produce a magnetic field when the charge is moving, as seen in this investigation. In this case, the charge is moving through a current-carrying wire. Using a compass, the field around a current in a wire can be mapped.

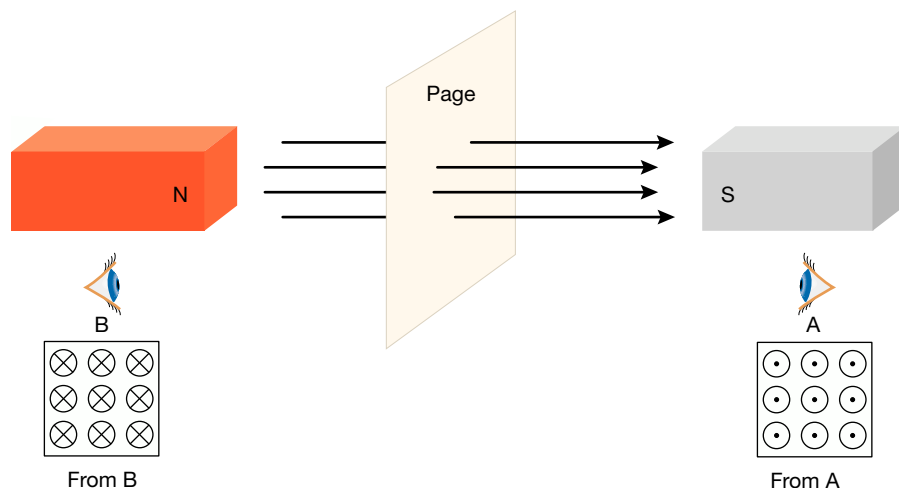
Representing current and its magnetic field often requires a three-dimensional view. To achieve this on a flat two-dimensional page, a convention is adopted.

The symbol of a circle with a dot in the middle is used to represent a magnetic field coming *out* of a page. A circle with a diagonal cross is used to represent a magnetic field going *into* the page.

The magnetic field due to a straight current-carrying wire is non-uniform, decreasing in strength at increased distance for the wire.

The symbols shown in figure 1.28 are designed to suggest, in the instance on the right, the point of an arrow coming towards the reader and, in the instance on the left, the feathers of the arrow going away from the reader.

FIGURE 1.28 Magnetic fields going into the page (from B) and coming out of the page (from A)



Current-carrying wire and the right-hand-grip rule

Oersted's observation that a wire carrying a current exerts force on a compass needle led to the understanding that moving charges are a source of magnetic field. When this current is constant and unchanging, the magnetic field is static. The right-hand-grip rule is a useful aid for relating the direction of the current flow to the direction of the associated magnetic field.

The right-hand-grip rule: The wire carrying the current is gripped by the right hand, with the thumb pointing in the direction that conventional current (the direction a positive charge would move) flows. The fingers wrap around the wire in the direction of the magnetic field.

FIGURE 1.29 The compasses around the wire show a circular magnetic field.

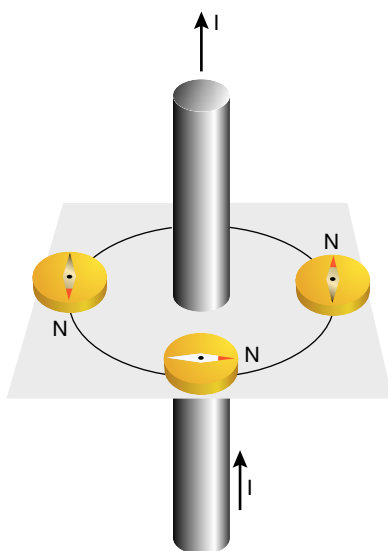
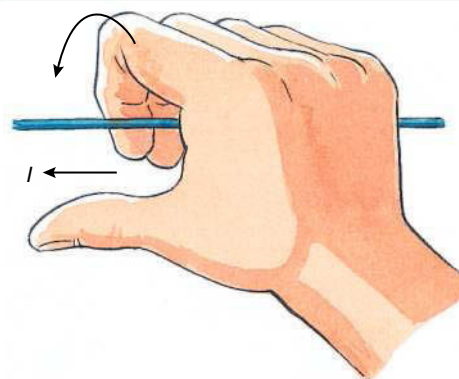


FIGURE 1.30 If a person's right hand holds the wire with the thumb pointing in the direction of the conventional current, the fingers curl around the wire in the direction of the magnetic field.



SAMPLE PROBLEM 9

Use the right-hand-grip rule to determine the direction of the magnetic field at point P in the following diagrams.

(a)



(b)



 **Teacher-led video:** SP9 (tlvd-0116)

THINK

Point your thumb in the direction of the current so that the curl of your fingers shows the direction of the field.

WRITE

- a. The current points upwards, so, by applying the right-hand-grip rule, the magnetic field circulates around the wire pointing into the page at P .

- b. The current points downwards, so, by applying the right-hand-grip rule, the magnetic field circulates around the wire, pointing out of the page at P .

PRACTICE PROBLEM 9

Use the right-hand-grip rule to determine the direction of the magnetic field at point Z in the following diagrams.



Loops and solenoids

Applying the right-hand-grip rule to a loop of wire shows that the magnetic field enters at one side of the loop and exits from the other side, all the way around the loop. Joining loops together results in a **solenoid**. The magnetic fields from each loop add together to produce a stronger magnetic field.

If the loops are very close together, the field lines within the coil are parallel to the axis of the coil. Inside the coil, the field is approximately uniform. The field lines then emerge from one end of the solenoid, curve around and enter the other end of the solenoid, completing the path for the field lines. The shape of this field is similar to that of a bar magnet and is non-uniform. The ends of the solenoid can be labelled north and south. The field emerges from the north end. Looking from this end along the axis, the current is seen to be travelling anticlockwise. The other end is opposite.

FIGURE 1.31 Applying the right-hand-grip rule to each part of the loop reveals that, at all points of the loop, the magnetic field is curving in the same direction.

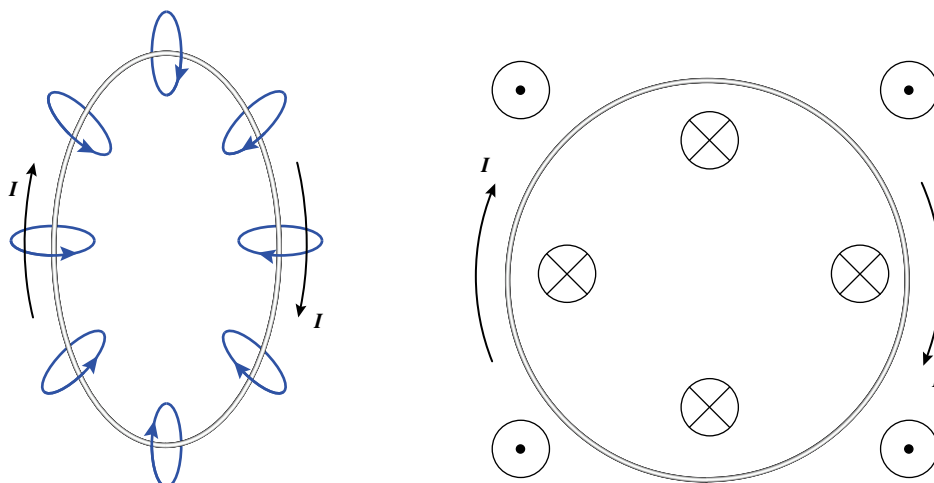
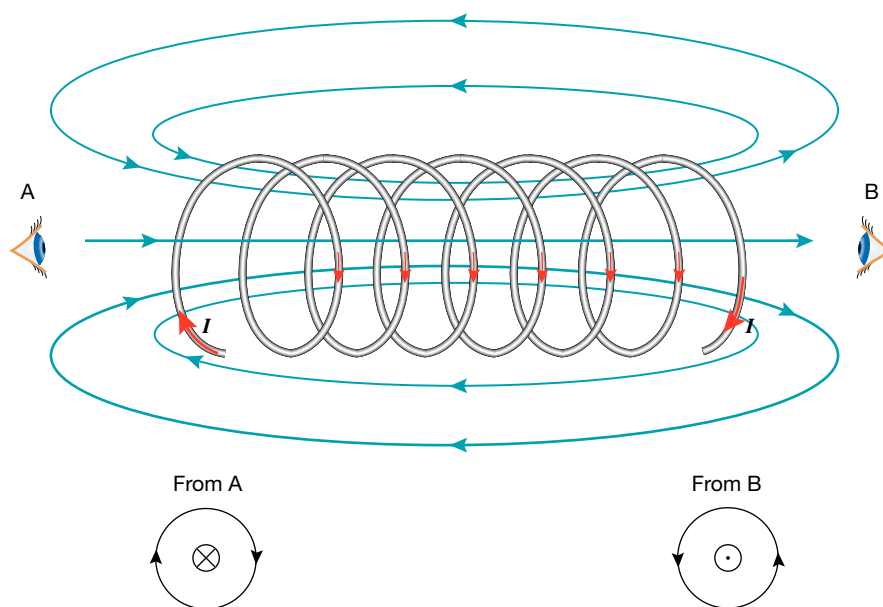
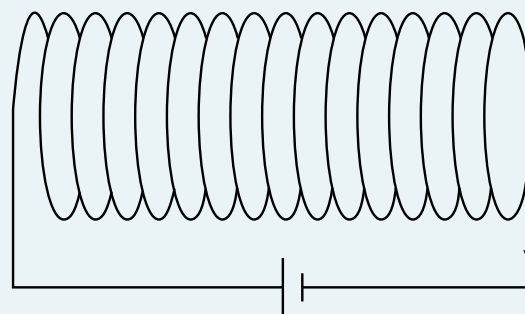


FIGURE 1.32 Using the right-hand-grip rule with a solenoid



SAMPLE PROBLEM 10

The following solenoid has a current passing through it in the direction shown. Draw five field lines representing the resultant magnetic field.



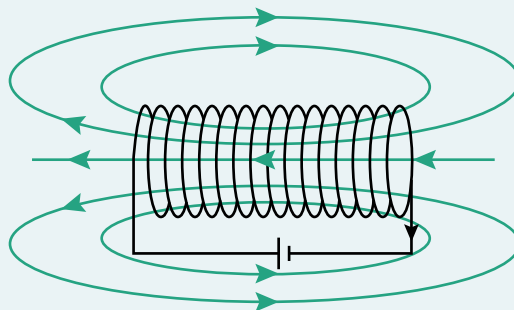
 **Teacher-led video:** SP10 (tlvd-0117)

THINK

Use the right-hand-grip rule.

WRITE

Applying the right-hand-grip rule, you can see that the magnetic field passes through the centre of the coil from right to left. Because magnetic field lines must form closed loops, the field outside the coil is in the opposite direction. Inside the coil, the magnetic field is approximately uniform. Outside the coil, the strength of the magnetic field decreases away from the coil.



PRACTICE PROBLEM 10

Consider the magnetic field of the solenoid in sample problem 10. How would the field change if the direction of the current in the solenoid were reversed?

Creating an electromagnet

In 1823, an English electrical engineer, William Sturgeon, found that when he placed an iron rod inside a solenoid, it greatly increased the strength of the magnetic field of the electric current to the point where it could support more than its own weight. Sturgeon had invented the **electromagnet**. He ultimately built a 200 g electromagnet with 18 turns of copper wire that was able to hold 4 kg of iron with current supplied by one battery.

By placing an iron core inside a solenoid, Sturgeon had made a magnet that could be turned on and off at the flick of a switch, and made stronger by increasing the current. His invention has many applications. In a wrecking yard, for example, electromagnets are used to separate metals containing iron from other metals. Electromagnets do not need to have an iron core inside the solenoid. A solenoid on its own can have a magnetic field that is produced by an electrical current.

The difficulty with using iron in an electromagnet is that when the current is turned off, the iron loses its magnetism. However, by adding carbon to the iron to produce an alloy, the magnetism is not lost when the current is turned off — a permanent magnet has been made. Stronger and more long-lasting magnets are made with different combinations of elements. The common ‘alnico’ magnets in schools are made from iron (54%), nickel (18%), cobalt (12%), aluminium (10%) and copper (6%).

Explaining magnetism in atoms

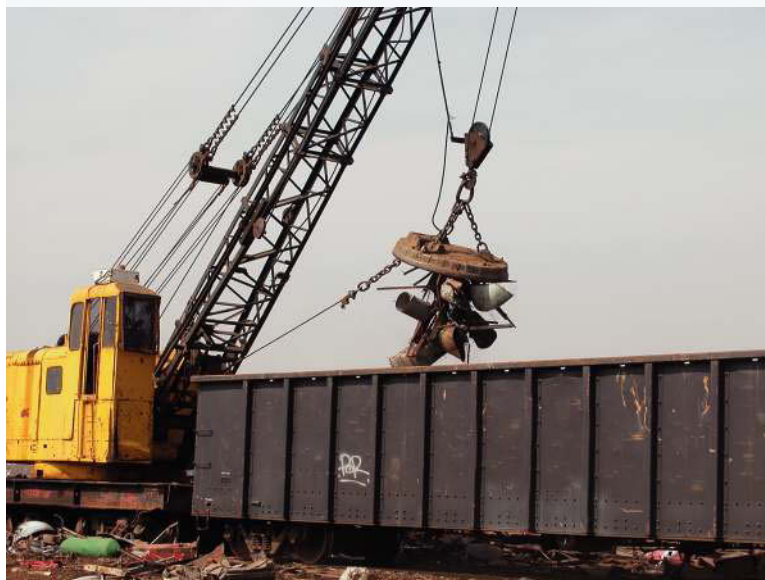
The solenoid provides a model for the magnetism in a magnet and the iron rod. The shapes of the magnetic fields of a solenoid and of a magnet are identical. The magnetic field in the solenoid is produced by a current travelling in a circle, and the magnetic field is at right angles to the plane of the circle.

Electrons travel around the nucleus of an atom in circle-like paths, so each electron must produce its own magnetic field. In most atoms, the paths of the electrons are randomly oriented, so their magnetic fields cancel out. However, the paths of a few electrons in an iron atom always line up. These are shielded by outer electrons, so they are not disturbed by other atoms. In this way, each iron atom can act as a little magnet.

When there is a current flowing through a solenoid with an iron core, the magnetic field lines up all the atoms in the iron core so their magnetic fields all point in the same direction. This creates a very strong field. However, when the current is turned off, the motion of the atoms rapidly produces a random rearrangement due to their temperature.

In artificial magnets (e.g. fridge magnets), other elements are added to iron to hold the iron atoms in place while they are lined up by another magnetic field so they stay lined up. This produces a permanent magnet. The crystal structure of magnetite (or the iron oxide in the magnet) forces its atoms to line up.

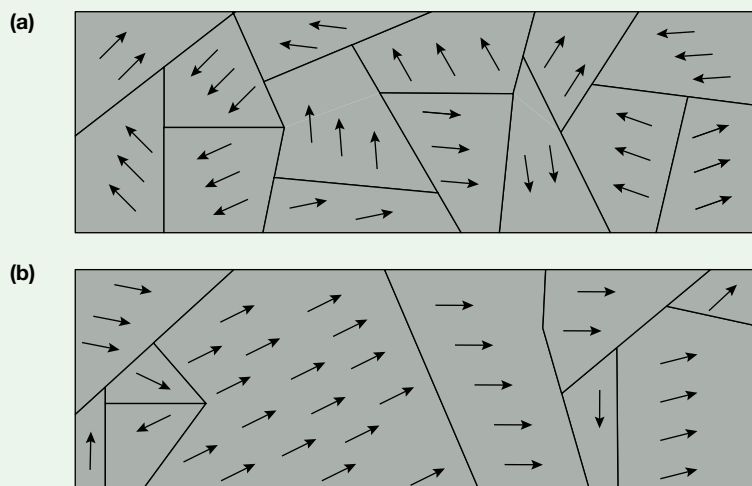
FIGURE 1.33 Car parts being lifted by an electromagnet in a car wrecking yard



MAGNETIC DOMAINS IN IRON

In a piece of iron, groups of nearby atoms line up together throughout the metal into regions called magnetic domains. When the iron is placed in a magnetic field, the domains that are already lined up with the external field increase in size as other domains shrink.

FIGURE 1.34 (a) The magnetic fields of adjacent iron atoms align themselves in local areas called domains. (b) Domains in a piece of iron exposed to a magnetic field, acting to the right



on Resources

 **Digital document** Investigation 1.3 Making an electromagnet (doc-31588)

1.4.4 Fields from multiple magnetic sources

Like the gravitational field and electric field, the magnetic field is also a vector field. When more than one magnetic source is present, the total magnetic field is the vector sum of the original fields. By drawing the vectors of each of the original fields head to tail, the direction of the resultant field can be determined by drawing a vector from the start of the first vector to the end of the second vector. Pythagoras's theorem may be used to determine the magnitude of this vector if a right-angled triangle is formed.

FIGURE 1.35 The magnetic field from two bar magnets

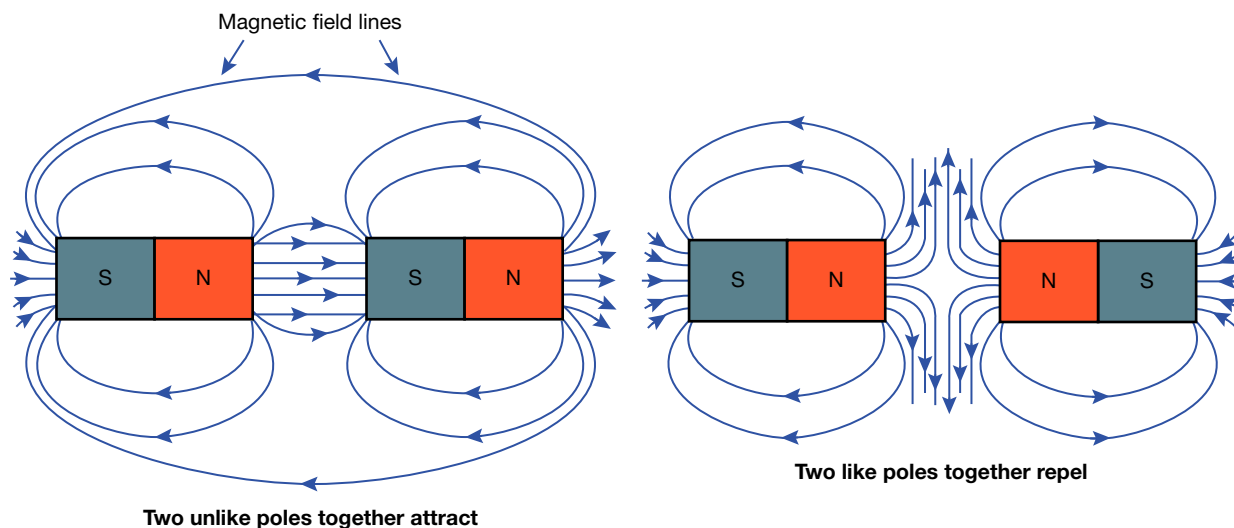
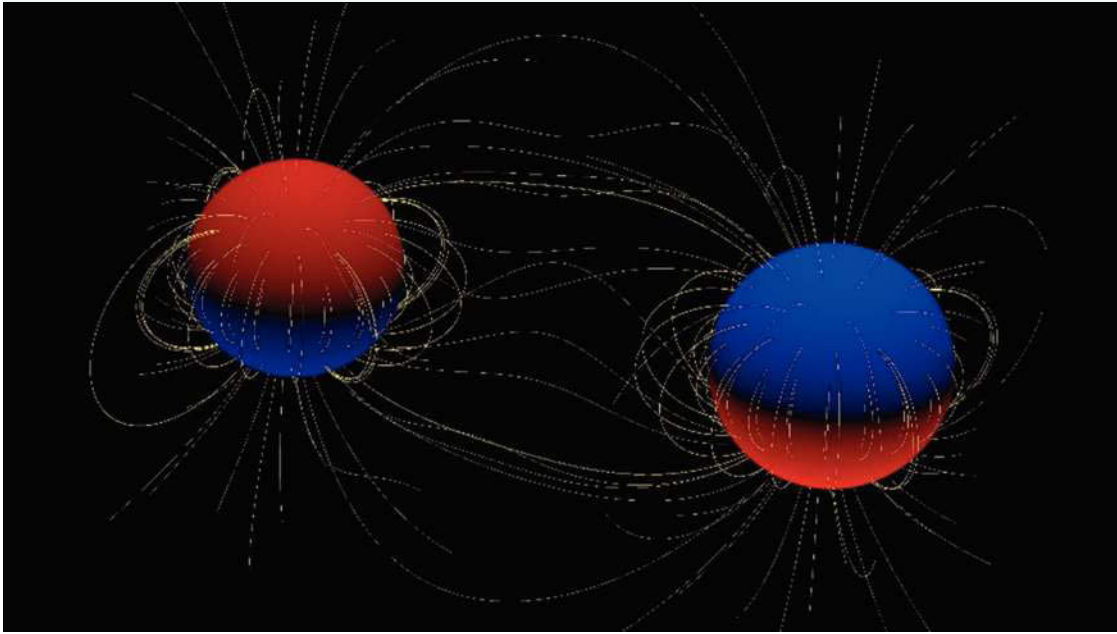


FIGURE 1.36 The magnetic field from a binary star system in which each star has a magnetic field



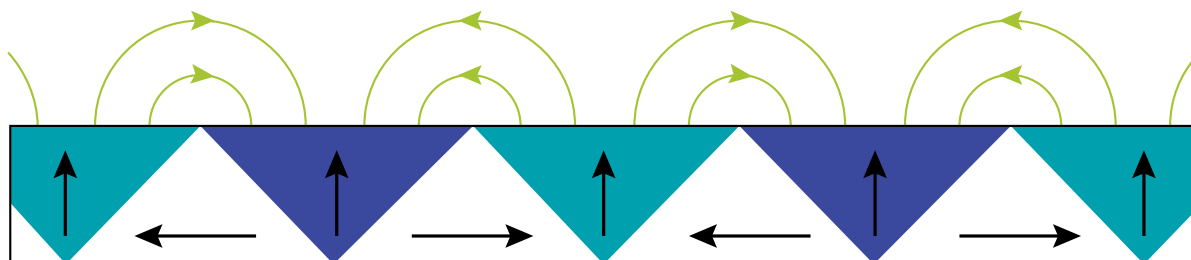
The effect of the Earth's magnetic field can be seen in the orientation of the compass needles in figure 1.37, particularly in those to the left and right of the wire. The compass needles are not perfectly perpendicular to the wire, but slightly tilted to the left-hand side of the page, indicating that the Earth's magnetic field points towards the left-hand side of the page in this experiment.

You may have noticed that fridge magnets are magnetic on one side only, which seems to contradict our understanding of magnetic field lines. This is because a fridge magnet is a composition of magnets arranged in a Halbach array. The superposition of the Halbach array of alternating horizontal and vertical magnetic fields results in magnetic field on one side of the array only. During manufacture, a rubber sheet embedded with ferromagnetic particles is exposed to an alternating magnetic field so that the sheet acquires a magnetic field that alternates vertically and horizontally, as shown in figure 1.38. The resultant field is zero on one side of the sheet.

FIGURE 1.37 Magnetic field measurements around a current-carrying wire



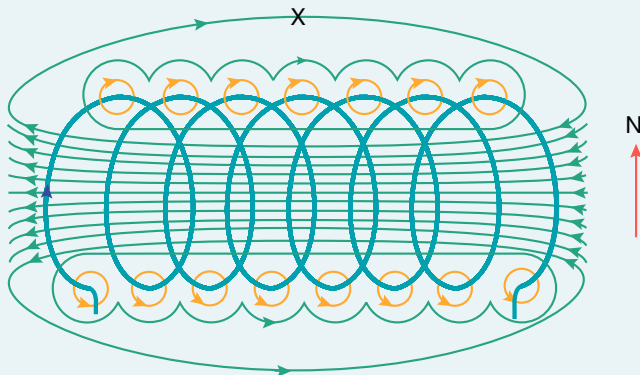
FIGURE 1.38 Fridge magnets arranged in a Halbach array



SAMPLE PROBLEM 11

The magnetic field at point X from the current-carrying solenoid shown in the following illustration is $25 \mu\text{T}$. The Earth's magnetic field is $25 \mu\text{T}$.

- What direction would a compass point if it were placed at point X?
- Calculate the strength of the resultant magnetic field at X.



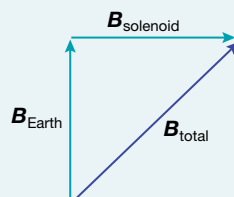
Teacher-led video: SP11 (tlvd-0118)

THINK

- At point X, the compass would point along the direction of the sum of the magnetic fields of the solenoid and the Earth. The Earth's magnetic field is pointed up and, at point X, the magnetic field in the solenoid is to the right.
- The strength can be calculated using Pythagoras's theorem.

WRITE

- The combined vector sum is



The diagram shows that the resultant would point in a north-east direction.

$$\begin{aligned}
 \text{b. } B &= \sqrt{(B_{\text{solenoid}}^2 + B_{\text{Earth}}^2)} \\
 &= \sqrt{(25^2 + 25^2)} \mu\text{T} \\
 &= 35 \mu\text{T}
 \end{aligned}$$

PRACTICE PROBLEM 11

A neodymium iron boron magnet is placed 1.0 cm to the left of a magnetic probe (located at point X). The field strength due to the magnet is 0.01 T . A second identical magnet is also placed 1.0 cm below a magnetic probe, but at right angles to the first magnet.

- What is the resultant strength of the magnetic field at point X?
- What are the possible directions of the magnetic field at point X?



Resources

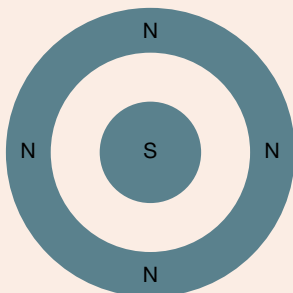
- Digital document** Investigation 1.4 Vector model of magnetic fields (doc-31587)
- Teacher-led video** Investigation 1.4 Vector model of magnetic fields (tlvd-0224)
- Weblink** Magnetic field around a wire applet
- Video eLesson** Magnetic fields (med-0195)

1.4 EXERCISE

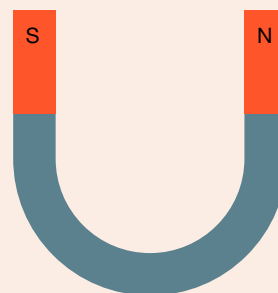
To answer questions online and to receive **immediate feedback** and **sample responses** for every question go to your learnON title at www.jacplus.com.au.

- How would you use a magnet to test whether a piece of metal was magnetic?
- How could naturally occurring magnets have been formed?
- Why do both ends of a magnet attract an iron nail?
- What is the polarity of Earth's magnetic field at the magnetic pole in the southern hemisphere?
- Draw the magnetic field lines for the following items:
 - a loudspeaker magnet
 - a horseshoe magnet.

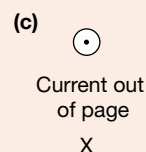
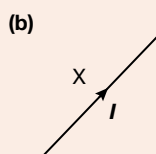
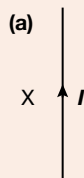
(a)



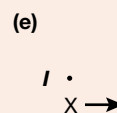
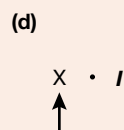
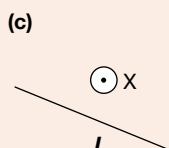
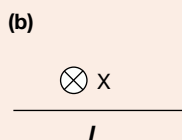
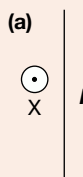
(b)



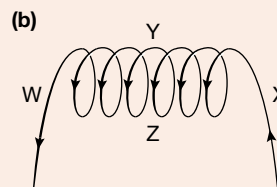
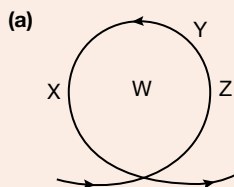
- Use the right-hand-grip rule to determine the direction of the magnetic field at point X in the following diagrams.



- Copy the following diagrams and use the right-hand-grip rule and the direction of the magnetic field at X to determine the direction of the current in the wire in each case.



- Use the right-hand-grip rule to determine the direction of the magnetic field at W, X, Y and Z in the following diagrams. Figure (a) represents a circular loop of wire with a current and figure (b) represents a solenoid.



- When current is connected to a solenoid that is wrapped around two iron rods that have been placed in a line, the two rods move apart. Explain why this happens.
- In Oersted's experiment, the compass needle initially points north-south. What would happen if the current in the wire above the needle ran:
 - west-east
 - east-west?

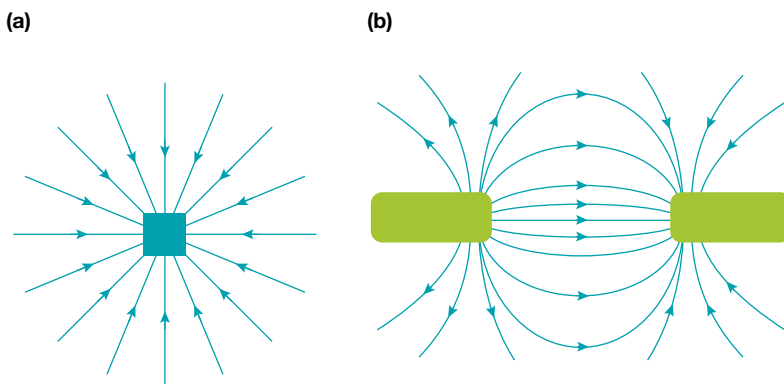
1.5 Comparing gravitational, magnetic and electric fields

KEY CONCEPTS

- Compare theoretically and practically gravitational, magnetic and electric fields, including directions and shapes of fields, attractive and repulsive fields, and the existence of dipoles and monopoles
- Compare theoretically and practically gravitational fields and electrical fields about a point mass or charge (positive or negative) with reference to:
 - the direction of the field
 - the shape of the field
 - the use of the inverse square law to determine the magnitude of the field.
- Identify fields as static or changing, and as uniform or non-uniform.

Gravitational, electric and magnetic fields are all properties of the space around an object, whether the object is a mass, a charge or a magnetic pole. Lines are used to show the direction of the field, that is, the direction a test object would move; the strength of the field is shown by the density of the lines. For some field diagrams, it is not possible to tell the type of field simply by looking at the diagram.

FIGURE 1.39 Field diagrams



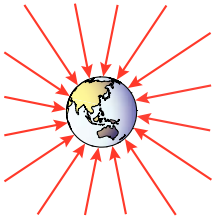
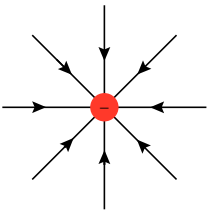
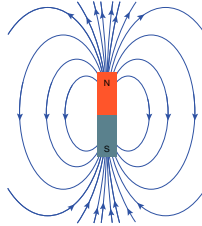
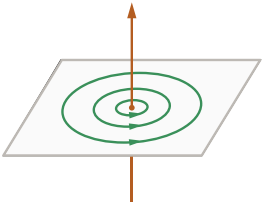
For example, field diagram (a) in figure 1.39 could show either a gravitational field around a mass or an electric field around a negative point charge. It could not be a magnetic field as, even though it might look like the field near the south pole of a magnet, there would be a north pole not too far away.

Similarly, field diagram (b) in figure 1.39 could show either an electric field around two opposite charges or a magnetic field around north and south poles. However, it could not be a gravitational field, because mass does not come in two opposite versions.

The fields described in this topic are all vector fields, and they share the property that fields from multiple sources can be added to find the total field at any point.

The essential features of gravitational, electric and magnetic fields are summarised in table 1.3.

TABLE 1.3 Summary of gravitational, electric and magnetic fields

	Gravitational field	Electric field	Magnetic field	
Surrounds	a mass	a charge	(i) a magnet	(ii) a moving charge
Diagram				
Affects:	other masses	other charges	other magnetic materials and/or moving charges	
Field strength symbol and units	$\mathbf{g}$ N kg ⁻¹ (or m s ⁻²)	$\mathbf{E}$ N C ⁻¹ (or V m ⁻¹)	$\mathbf{B}$ T (or N mA ⁻¹)	
Magnitude of field from a point source	$g = G \frac{M}{r^2}$	$E = \frac{kq}{r^2}$	A magnetic north or south pole cannot be isolated to make a point source (monopole). Calculating the magnetic field strength due to a bar magnet or current-carrying wire is beyond the scope of this course.	
Direction of the field is defined by:	the direction of the force on a test mass placed in the field.	the direction of the force on a positive test charge placed in the field.	the direction of the orientation of the north pole of a compass placed in the field.	
Force in the field	A mass m placed in the field experiences a force $m\mathbf{g}$ in the direction of $\mathbf{g}$.	A charge q placed in the field experiences a force $q\mathbf{E}$ in the direction of $\mathbf{E}$.	The quantitative force on a magnet by a magnetic field $\mathbf{B}$ is beyond the scope of this course.	The force on a moving charge in the presence of a magnetic field $\mathbf{B}$ is $q\mathbf{vB}$ and the force on a current-carrying wire in the presence of a magnetic field $\mathbf{B}$ is $nI\mathbf{B}$, as described in topic 3.
Polarity of the field	Unipolar	Positive or negative monopoles. A dipole field is the field from a separated positive and negative charge.	The north or south pole cannot be isolated to create a magnetic monopole.	
A uniform field exists:	on the Earth's surface.	between two oppositely charged parallel conducting plates.	between the poles of a large horseshoe magnet.	inside a current carrying coil.
A static field exists:	around a mass.	around charges that are not moving.	around magnetised materials.	around a wire carrying a constant current.

SAMPLE PROBLEM 12

Identify similarities and differences between the gravitational field generated from a point mass and the electric field generated from a positive charge.

 **Teacher-led video:** SP12 (tlvd-0119)

THINK

Recall that fields are described by whether they are uniform or non-uniform, their shape and direction, and the nature of their source.

WRITE

Similarities:

1. The gravitational field generated from a point mass and the electric field generated from a positive charge both obey an inverse square law.
2. The gravitational field and electric field are both non-uniform and static.
3. The point mass and positive charge can both be described as monopoles.

Differences:

1. The direction of the gravitational field is inwards towards the point mass, whereas the electric field generated from a positive charge is outwards, away from the point charge.
2. The gravitational field is attractive for all other masses, whereas the electric field generated from a positive charge repels other positive charges and attracts negative charges.

PRACTICE PROBLEM 12

Identify similarities and differences between the electric field of a dipole and the magnetic field of a bar magnet.

You can see in table 1.3 that there are circumstances in which each type of field can be uniform. There are also circumstances in which each type of field is non-uniform, particularly as the distance away from the source (such as an object with mass, a magnet or a point charge) increases. Gravitational sources can only attract, whereas electric and magnetic sources can attract or repel. Gravitational and electric monopoles exist, which can be seen by the way that field lines can begin from a single point, whereas magnetic field lines can never have a beginning and an end but must instead form closed loops. The intriguing similarity between the electric dipole field and the magnetic field from a bar magnet or solenoid hints at the fundamental connection between electric and magnetic phenomena, a connection that was elegantly and brilliantly captured by James Clarke Maxwell at the end of the nineteenth century.

Ultimately, the field model is a pathway to describing the forces experienced by objects and to understanding and predicting the motion of objects and the transfer of energy in gravitational, electric and magnetic fields. In the next few topics, you will be able to apply the simple model previously outlined to explain dynamic phenomena as diverse as the motion of satellites around the Earth, and the operations of a DC motor and AC electrical generator.

1.5 EXERCISE

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

1. What is the experimental evidence for there being two types of charge?
2. Coulomb's Law is very similar to Newton's Law of Universal Gravitation. How do these two laws differ? Compare electric charge and gravitational mass.
3. Give an example of a source of a uniform and a non-uniform magnetic field. Sketch the field in each case.
4. Identify similarities and differences between the electric field due to two positive charges separated by 1.0 cm and the magnetic field due to two bar magnets with the north poles facing each other, but separated by 1.0 cm.
5. Compare the magnitude of the electric and gravitational forces of attraction between an electron and a proton that are a distance 5.3×10^{-11} m apart in a hydrogen atom. (Given data: $m_e = 9.11 \times 10^{-31}$ kg; $m_p = 1.67 \times 10^{-27}$ kg)
6. A proton is suspended so that it is stationary in an electric field. Using the value of $g = 9.8 \text{ m s}^{-2}$, determine the strength of the electric field.
7. One of the units for a gravitational field is that of acceleration. Is that also true for an electric field? If not, why not?
8. Millikan observed charged oil drops falling at a constant speed in an electric field provided by two charged plates. In a simplified version of the experiment, the oil drops are in a vacuum, so that when they fall at a constant speed, the electric force on the drop is equal and opposite to the gravitational force on the drop. If the mass of an oil drop is $10 \mu\text{g}$ and the charge of the oil drop is $10e^-$, how large does the electric field provided by the plates need to be for the gravitational and electric forces to balance?
9. What equal positive charge would the Earth and the Moon need to have for the electrical repulsion to balance the gravitational attraction? Why don't you need to know the distance of separation of the two objects? The mass of the Moon is 7.35×10^{22} kg.
10. The strength of the magnetic field can be determined using the following formula:

$$B = \frac{\mu_0 I}{2\pi r},$$

where r is the distance from a wire, and μ_0 is the vacuum permeability constant ($4\pi \times 10^{-7} \text{ T m A}^{-1}$). The strength of the Earth's magnetic field at the surface is approximately $50 \mu\text{T}$. Calculate how much current needs to flow through the wire for the magnetic field at a distance of 2.0 cm from the wire to be equal in magnitude to the Earth's magnetic field at that point.

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1.6 Review

1.6.1 Summary

- A vector field model can be applied to gravitational, electric and magnetic fields.
- The force, $\mathbf{F}$, on a mass, m , in a gravitational field, $\mathbf{g}$, is given by $\mathbf{F} = m\mathbf{g}$. The force, $\mathbf{F}$, on a charge, q , in an electric field, $\mathbf{E}$, is given by $\mathbf{F} = q\mathbf{E}$.
- The magnitude of the gravitational field from a point mass and the electric field from a point charge both decrease by an amount inversely proportional to the square of the distance from the point source.
- The magnitude of the gravitational field, g , from a point mass, M , is given by $g = G\frac{M}{r^2}$. The force of gravity on an object of mass M_1 at a distance r from a body of mass M_2 is given by $\mathbf{F} = G\frac{M_1M_2}{r^2}$, which is called Newton's Law of Universal Gravitation.
- The magnitude of the electric field, E , from a point charge, q , decreases by an amount inversely proportional to the square of the distance from the point source, such that $E = \frac{kq}{r^2}$. The electric force on a charge q_1 at a distance r from another charge q_2 is given by $\mathbf{F} = \frac{kq_1q_2}{r^2}$, which is known as Coulomb's Law.
- The force exerted by magnets on other magnets and ferromagnetic materials such as iron can be explained in terms of a magnetic field; however, there is no magnetic point source or monopole.
- The gravitational field from a point mass, M , is attractive and non-uniform.
- At the surface of the Earth, because the Earth is so large compared to the scale of human actions, the gravitational field can be modelled as uniform.
- The electric field around a point charge is non-uniform and can be attractive or repulsive for a positive charge placed in the field depending on whether the source charge is negative or positive.
- The electric field arising from a separated positive and negative charge is called a dipole field and is also non-uniform. It is similar in shape to the magnetic field around a bar magnet or the magnetic field due to a current-carrying loop.
- The electric field between two oppositely charged conducting plates is uniform, allowing charges placed between the plates to experience constant acceleration.
- An electric current in a wire produces a magnetic field. The direction of the magnetic field around a long straight current-carrying wire is given by the right-hand-grip rule.
- The magnetic field inside a current-carrying solenoid and between the poles of a large horseshoe magnet is uniform. The magnitude of the field inside a solenoid is proportional to the size of the current and the number of loops in the solenoid.

on Resources

studyon

To access key concept summaries and past VCAA exam questions download and print the **studyON: Revision and past VACC exam question booklet** (sonr-0050).

1.6.2 Key terms

A **conductor** is a material that allows electrical currents to flow.

A **dipole field** is the electric field surrounding a positive charge and a negative charge that are separated by a short distance.

An **electric dipole** is the separation of a pair of oppositely charged or magnetised poles.

An **electric field** is a vector field describing the property of the space around a charge that causes a second charge in that space to experience a force due only to the presence of the first charge.

An **electrical force** is the force experienced by a charged particle if it is placed within the electric field of a second charged particle.

An **electromagnet** is a temporary magnet produced in the presence of a current-carrying wire.

A **gravitational field** is a vector field describing the property of the space around an object with mass that causes a second object with mass to experience a gravitational force towards the object.

The **magnetic induction** process is the creation of magnetic properties in an object as the result of the presence of a second, nearby object with magnetic properties.

An **insulator** is a material that does not allow electrical current to flow.

The **inverse square law** describes a relationship in which one variable is proportional to the reciprocal of the square of another variable.

The term **like charges** indicates charges with the same polarity.

A **magnetic field** is a vector field describing the property of the space around a magnet that causes an object in that space to experience a force due only to the presence of the magnet.

A **solenoid** is a coil of wire wound into a cylindrical shape.

A **uniform electric field** is an electrical field in which the strength and direction are constant at every point.

The term **unlike charges** indicates charges with opposite polarity.



Resources



Digital document Key terms glossary (doc-32246)

1.6.3 Practical work and investigations

Investigation 1.1

Investigating the electric field using an electric compass

Aim: To investigate the electric field from positive and negative sources of charge, both singly and in combination

Digital document: doc-31585

Investigation 1.2

Magnetic field mapping

Aim: To explore the magnetic fields of different arrangements of permanent magnets

Digital document: doc-31586

Investigation 1.3

Making an electromagnet

Aim: To investigate the properties of the magnetic field produced by a solenoid, in particular the dependence of the magnitude and direction of the magnetic field on the current carried by the solenoid, the number of turns in the solenoid and the presence of an iron core

Digital document: doc-31588

Investigation 1.4

Vector model of magnetic fields

Aim: To observe the effect of the Earth's magnetic field upon the magnetic field from a current-carrying wire

Digital document: doc-31587

Teacher-led video: tlvd-0224





1.6 Exercises

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

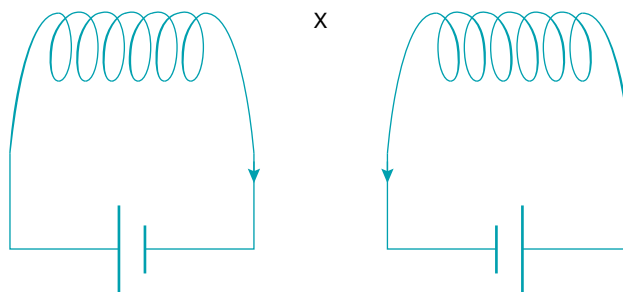
1.6 Exercise 1: Multiple choice questions

- Which of the following correctly describes the gravitational field of the Earth at large distances from the surface of the Earth?
 - The shape of the field is uniform, it attracts other masses, and the strength of the field is inversely proportional to the square of the distance from the surface of the Earth.
 - The shape of the field is non-uniform, it attracts other masses, and the strength of the field is inversely proportional to the square of the distance from the surface of the Earth.
 - The shape of the field is uniform, it attracts other masses, and the strength of the field is inversely proportional to the square of the distance from the centre of the Earth.
 - The shape of the field is non-uniform, it attracts other masses, and the strength of the field is inversely proportional to the square of the distance from the centre of the Earth.
- An astronaut arriving on the Moon feels lighter than on Earth. Which of the following gives the correct reason for this?
 - The gravitational field strength of the Moon is smaller than that of the Earth; therefore, the force experienced by the astronaut is less than on Earth.
 - The astronaut is a long way from the Earth, so the force due to gravity is smaller.
 - The diameter of the Moon is smaller than the diameter of the Earth, so the gravitational field strength is smaller.
 - The gravitational field strength of the Moon is smaller than that of the Earth; therefore, the masses are smaller on the Moon.
- Which of the following statements is **incorrect**?
 - Electric fields can attract or repel charges, depending on the type of charge and nature of the field.
 - Electric fields can be uniform or non-uniform.
 - The source of an electric field can be a monopole.
 - Electric field lines must always form closed loops.
- Which of the following statements is **incorrect**?
 - Magnetic fields can attract or repel other magnets, depending on the type of magnet and nature of the field.
 - Magnetic fields can be uniform or non-uniform.
 - The source of a magnetic field can be a monopole.
 - Magnetic field lines must always form closed loops.
- A moving charged particle:
 - creates a magnetic field
 - is not affected by other magnetic fields
 - creates a moving electric field
 - is not affected by other electric fields.

6. The force experienced by a charge q_1 that is a distance r from a charge q_2 has the value F . Then, the charge q_1 and the distance r from q_2 are both doubled. From the following choices, determine the new force on q_1 .

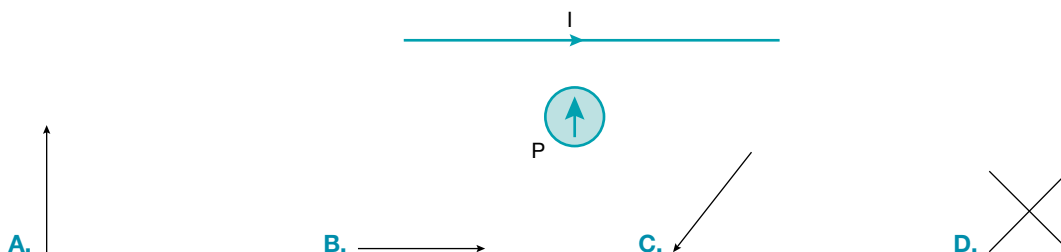
A. $\frac{1}{2}F$
 B. F
 C. $2F$
 D. $4F$

7. Two solenoids are placed as shown in the following diagram. Each solenoid contributes a magnetic field strength of 0.010 T at the point X. What is the total value of the magnetic field strength at X?



A. 0.000 T
 B. 0.005 T
 C. 0.010 T
 D. 0.020 T

8. A current-carrying wire is oriented as shown in the following diagram. A compass placed at point P has the orientation shown. What is the direction of the Earth's magnetic field at that point?



9. A charged particle is placed between two oppositely charged conducting plates. If the strength of the electric field is doubled (and ignoring gravitational effects), which of the following is true?
- A. The net force experienced by the charge doubles.
 B. The acceleration experienced by the charge doubles.
 C. The final velocity of the particle doubles.
 D. The charged particle does not move.
10. A particle is moved along an imaginary line between two masses, M_1 and M_2 . Each mass has a charge, q_1 and q_2 . The charge on the particle is $+1$ nC. As the particle is moved along the line, the force experienced by the particle changes. Which of the following statements is **not** true?
- A. If q_1 and q_2 are both positive, there will be a point somewhere on the line where the net electric force experienced by the $+1$ nC charge will be zero.
 B. If q_1 and q_2 are both negative, there will be a point somewhere on the line where the net electric force experienced by the $+1$ nC charge will be zero.
 C. If q_1 is positive and q_2 is negative, there will be a point on the line where the net electric force experienced by the $+1$ nC charge will be zero.
 D. There will be a point on the line where the gravitational attraction of the $+1$ nC charge to M_1 is equal and opposite to the gravitational attraction of the $+1$ nC charge to M_2

1.6 Exercise 2: Short answer questions

1. Calculate the gravitational field strength at the surface of Mercury (mass: 3.30×10^{23} kg; diameter: 4879 km). Find the ratio of the gravitational force on a ball at the surface of Mercury to the gravitational force on a ball on the surface of the Earth.
2. What is the strength of the electric field 1.0 mm from a proton?
3. Find the force of repulsion between two point charges with charges of 5.0 microcoulombs (μC) and 7.0 microcoulombs (μC) if they are 20 cm apart.
4. If the force between two charges was 400 mN, how far apart would they need to be moved for the force to reduce by one-eighth?
5. An electric force of 3.0 N acts downwards on a charge of $-1.5 \mu\text{C}$. What is the strength and direction of the electric field?
6. A wire pointing into the page carries a 5.0 A current.
 - a. Sketch the magnetic field from the wire, ensuring that the magnetic field passes through points P and Q.
 - b. The Earth's magnetic field is in the direction shown in the following diagram and has a uniform magnitude of $10 \mu\text{T}$. At the points P and Q, the value of the magnetic field from the wire is $20 \mu\text{T}$. Calculate the resulting magnitude and direction of the total magnetic field at P and Q.



7. Sketch the magnetic field from a solenoid and the electric field from an electric dipole. Identify similarities and differences between the two fields.
8. Calculate the magnitude of the electric field required to levitate a 1.0 g mass with a charge of 10 nC between two oppositely charged plates.
9.
 - a. Field lines can never cross. Why?
 - b. If a particle is free to move, will it move along a field line?
10.
 - a. Sketch the electric field around a positively charged straight plastic rod. Assume the charge is distributed evenly.
 - b. Sketch the electric field as if the rod had a curve in it. If the plastic rod was bent into a closed circle, what would be the strength of the electric field in the middle?

1.6 Exercise 3: Exam practice questions

Question 1 (2 marks)

The Parker Solar Probe travels in a highly elliptical orbit around the Sun and, at its point of closest approach, it will be 9.5 solar radii away. Calculate the magnitude of the Sun's gravitational field at this point. (Given data: $G = 6.67 \times 10^{-11} \text{ N m}^2 \text{ kg}^{-2}$; $M_{\text{SUN}} = 1.99 \times 10^{30} \text{ kg}$; $R_{\text{SUN}} = 6.96 \times 10^5 \text{ km}$)

2 marks

Question 2 (8 marks)

A particle acquires a 15.0 nC charge.

- a. Sketch the electric field due to the 15.0 nC charge.

2 marks

A second particle with a charge of -10.0 nC is placed 2.0 cm to the right of the 15.0 nC charge.

- b. Calculate the magnitude of the force on the -10.0 nC charge due to the 15.0 nC charge.

2 marks

- c. Is there any point at which the combined electric field from the two charges will have a value of zero?

Explain your response.

4 marks

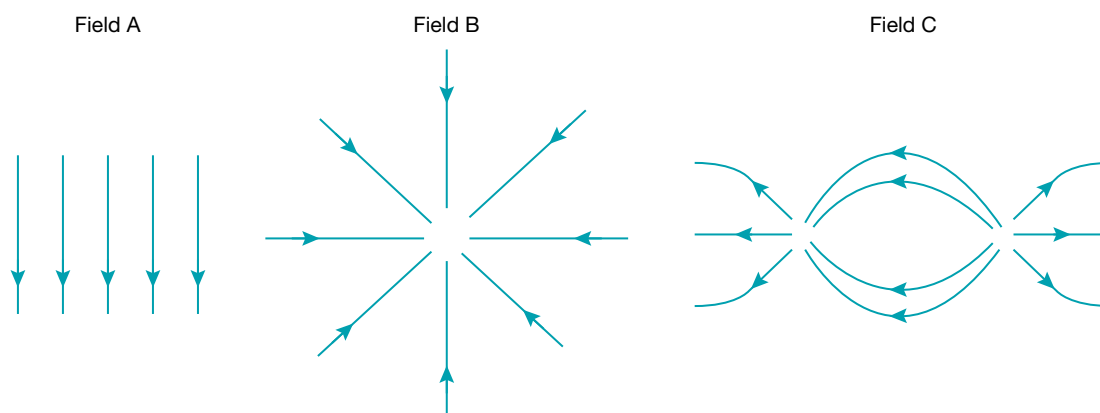
Question 3 (4 marks)

A 100 kg satellite S_1 orbits the Earth at a distance of one Earth radius above the Earth's surface. A 200 kg satellite S_2 orbits the Earth at a distance of two Earth radii above the Earth's surface.

- Calculate the ratio of the gravitational field experienced by satellite S_1 to S_2 . **2 marks**
- Where should S_2 be placed so that the gravitational force experienced by satellite S_1 is two times larger than that experienced by S_2 ? **2 marks**

Question 4 (6 marks)

When making notes on field shapes, a student records the following unlabelled sets of field lines in their notebook:



The student returns to their work and tries to identify the type of field and a possible source of field for each set of data.

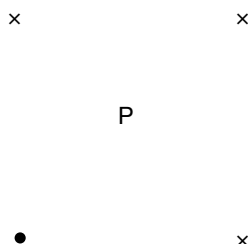
Data Set	Gravitational	Electric	Magnetic
Field A			
Field B			
Field C	Not possible	–ve and +ve charge, electric dipole	Not possible (similar to electric dipole, but not identical)

Complete the table for the remaining data sets.

6 marks

Question 5 (5 marks)

Four identical wires are arranged as shown, when viewed from above. Each wire carries the same current. The point P is equidistant from all four wires. The effect of the Earth's magnetic field can be ignored in this problem.



- Sketch the magnetic field due to the top-left wire. **2 marks**
- The magnitude of the field due to the top-left wire at the point P is 0.05 T. Calculate the total magnetic field at P and give the direction. **3 marks**

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2 Gravitational fields (effects and applications)

2.1 Overview

Numerous **videos** and **interactivities** are available just where you need them, at the point of learning, in your digital formats, learnON and eBookPLUS at www.jacplus.com.au.

2.1.1 Introduction

Everyone's lives are profoundly affected by their interaction with the gravitational field of the Earth. Your muscles are constantly working against the pull of your body towards the centre of the Earth and your heart must pump your blood so that it can circulate around your body. When you throw a ball, the path followed by the ball through the air is dictated by the pull of the ball towards the Earth. Upon observing the night sky, you may see the Moon, which orbits the Earth every 27 days. The constant gravitational pull on the Moon and artificial satellites by the Earth causes them to move in approximately circular orbits around the Earth. Indeed, gravitational attractions are at the heart of explaining the motion of the whole solar system. Knowledge of the gravitational field can also be applied to finding the energy changes experienced by objects moving through gravitational fields, allowing humans to successfully launch rockets and send probes to other planets.

FIGURE 2.1 Understanding gravitational forces has allowed humans to put satellites in orbit around the Earth.



2.1.2 What you will learn

KEY KNOWLEDGE

After completing this topic, you will be able to:

- analyse the use of gravitational fields to accelerate mass, including
 - gravitational field and gravitational force concepts: $\mathbf{g} = G \frac{M}{r^2}$ and $\mathbf{F}_g = G \frac{M_1 M_2}{r^2}$
 - potential energy changes in a uniform gravitational field: $E_g = mg\Delta h$
 - the change in gravitational potential energy from area under a force–distance graph and area under a field–distance graph multiplied by mass.
- investigate theoretically and practically gravitational fields about a point mass with reference to:
- potential energy changes (qualitative) associated with a point mass moving in the field
- model satellite motion (artificial, Moon, planet) as uniform circular orbital motion: $\mathbf{a} = \frac{v^2}{r} = \frac{4\pi^2 r}{T^2}$
- apply the concepts of force due to gravity, $\mathbf{F}_g$, and normal force, $\mathbf{F}_N$, including satellites in orbit where the orbits are assumed to be uniform and circular.

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PRACTICAL WORK AND INVESTIGATIONS

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



Resources



Digital documents Key science skills — VCE Physics Units 1–4 (doc-32112)
Key terms glossary (doc-32248)
Practical investigation logbook (doc-32249)



To access key concept summaries and past VCAA exam questions download and print the **studyON: Revision and past VCAA exam question booklet** (sonr-0051).

2.2 Motion in a gravitational field

KEY CONCEPTS

- Analyse the use of gravitational fields to accelerate mass, including:
 - gravitational field and gravitational force concepts: $\mathbf{g} = G \frac{M}{r^2}$ and $\mathbf{F}_g = G \frac{M_1 M_2}{r^2}$
- Model satellite motion (artificial, Moon, planet) as uniform circular orbital motion: $\mathbf{a} = \frac{v^2}{r} = \frac{4\pi^2 r}{T^2}$
- Apply the concepts of force due to gravity, $\mathbf{F}_g$, and normal force, $\mathbf{F}_N$, including satellites in orbit where the orbits are assumed to be uniform and circular.

How do apples, satellites and planets move in gravitational fields? Newton's second laws states that if the mass of an object and the net force acting on an object is known, the object's acceleration is known.

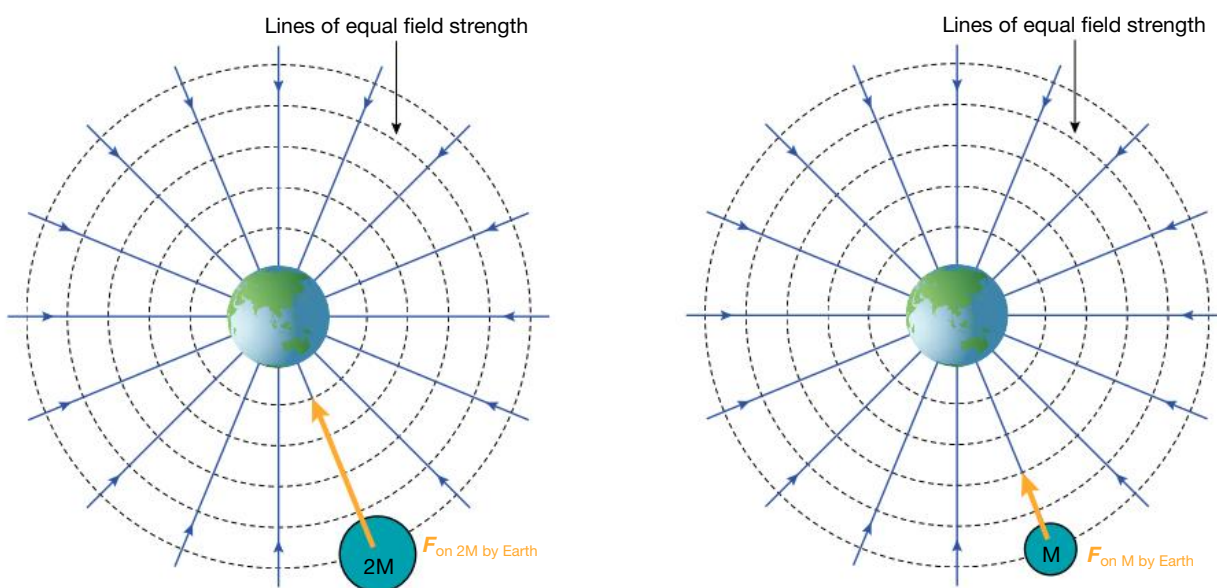
Gravitation describes the force that a mass experiences in a **gravitational field** (the strength of the gravitational field is denoted g). The magnitude of that force, the force on the mass by the Earth, is denoted $F_{\text{on mass by mass of Earth}}$ or F_g , and is given by:

$$\vec{F}_g = m\vec{g}$$

where: $\vec{F}_g$ is the force on a mass due to gravity, in N
 m is the mass of the object, in kg
 $\vec{g}$ is the gravitational field strength, in N kg^{-1}

The larger the mass, m , the greater the gravitational force, F_g , it experiences by the gravitational field g .

FIGURE 2.2 Comparison of the force on a mass M with the force on a mass $2M$ at the same position in a gravitational field. A larger mass experiences a greater force.



If the gravitational force is the only force acting on the mass, then, by applying Newton's second law, it is seen that the acceleration experienced by the mass is equal to the gravitational field at that point in space.

So, if there are no other forces acting on the mass, the acceleration is provided by the gravitational field, or $a = g$.

You will now look at what this means for masses close to the surface of the Earth and what it means for those further away.

2.2.1 Close to the Earth's surface

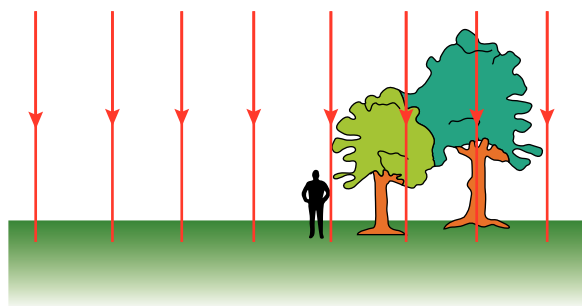
In topic 1, you saw that the gravitational field of the Earth is essentially constant or uniform near its surface. The gravitational field strength, g , can be calculated using the formula:

$$\vec{F}_{\text{net}} (\text{or } \Sigma \vec{F}) = m\vec{g} = m\vec{a}$$

where: $\vec{F}_{\text{net}}$ is the net force acting on an object, in N
 m is the mass of the object, in kg
 $\vec{g}$ is the gravitational field strength, in N kg^{-1}
 $\vec{a}$ is the acceleration of the object, in m s^{-2}

If there is little air resistance, gravity is essentially the only force acting on the object. Therefore, $F_{\text{net}} = mg = ma$ where a is the acceleration of the object. Hence the acceleration of an object falling near the Earth's surface is constant and can be calculated using the relationship:

FIGURE 2.3 Gravitational field close to the surface of the Earth



$$\vec{g} = G \frac{M}{r^2}$$

where: $\vec{g}$ is the gravitational field strength, in N kg^{-1}
 G is the gravitational constant $6.67 \times 10^{-11} \text{N m}^2 \text{kg}^{-2}$
 M is the mass of the Earth, in kg
 r is the radius of the Earth, in m

Using this, the gravitational field strength is calculated to be a constant 9.8 N kg^{-1} near the Earth's surface. This means that the speed of the object towards the centre of the Earth increases by the same amount, 9.8 m s^{-1} , every second, until it strikes the surface of the Earth.

Because the acceleration is constant, an estimate can be made of how high a ball will go when launched with a particular velocity, or how long it will take for an object dropped from a height to hit the ground using the familiar kinematic formulae for motion under constant acceleration.

SAMPLE PROBLEM 1

A ball is thrown vertically into the air with a speed of 20.0 m s^{-1} . How high does it go? (Ignore air resistance.)

 **Teacher-led video:** SP1 (tlvd-0120)

THINK

After leaving the hand of the person throwing the ball, the only force on the ball is the gravitational attraction of the ball to the Earth:

$$F_g = mg$$

This means that the net force, $F_{\text{net}} = ma = mg$ and the acceleration of the ball is simply $g = 9.8 \text{ m s}^{-2}$ downwards. This is motion under constant acceleration in a straight line, so the equation $v^2 = u^2 + 2as$ can be used to determine the maximum height reached by the ball.

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

WRITE

Take upwards as the positive direction.

$$a = g = -9.8, u = 20.0 \text{ m s}^{-1}, v = 0 \text{ m s}^{-1}$$

$$v^2 = u^2 + 2as$$

$$0^2 = 20^2 + (2 \times -9.8 \times s)$$

$$0^2 - 20^2 = 2 \times -9.8 \times s$$

$$s = \frac{0^2 - 20^2}{2 \times -9.8}$$

$$= 20 \text{ m}$$

The maximum height reached by the ball is
 20 m

PRACTICE PROBLEM 1

A ball is dropped from a bridge. The initial speed of the ball is 0 m s^{-1} . How fast is the ball travelling after falling 20 metres?

Resources

 **Digital document** Investigation 2.1 Using a pendulum to determine g (doc-31589)

 **Teacher-led video** Investigation 2.1 Using a pendulum to determine g (tlvd-0226)

2.2.2 Motion of satellites

Now consider an object considerably further from the surface of the Earth, such as a **satellite**. Any effect of the gravitational field of the satellite can be ignored because the mass of the satellite is so much smaller than that of the Earth.

There are many possibilities for the kind of motion that the satellite might experience in response to the gravitational field of the Earth but, for now, only consider the scenario where the satellite orbits the Earth at a constant height above the centre of the Earth with a constant speed. How might this be possible?

Figure 2.4 shows how the constantly changing direction of the velocity of an object moving in a circle results in an acceleration towards the centre of the circle. This kind of acceleration is called **centripetal acceleration**. When an object moves along a circular path with a constant speed, the direction of the change in the velocity always points along a line towards the centre of the circle, causing the acceleration to point in the same direction.

In figure 2.4, it can be deduced from the similar triangles that

$$\begin{aligned}\frac{\Delta v}{v} &= \frac{v\Delta t}{r} \\ \Rightarrow \Delta v &= \frac{v^2\Delta t}{r}\end{aligned}$$

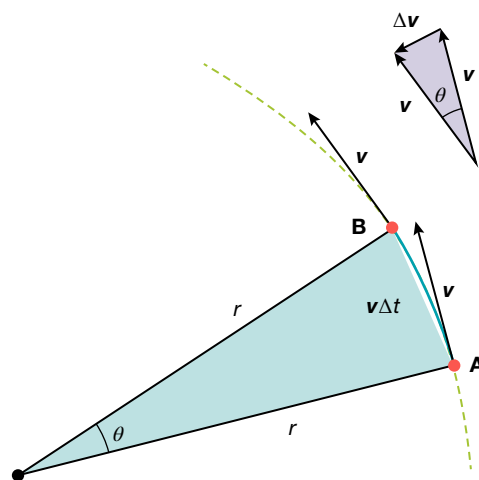
The acceleration of the object towards the centre of the circle (centripetal acceleration) is:

$$a = \frac{\Delta v}{\Delta t} = \frac{v^2\Delta t}{r\Delta t} = \frac{v^2}{r}$$

The speed of the satellite, v , is constant and can be expressed in terms of the radius, r , and period, T of the orbit:

$$v = \frac{\text{distance travelled}}{\text{time taken}} = \frac{2\pi r}{T}.$$

FIGURE 2.4 The acceleration of an object moving in a circle at a constant speed always points inwards towards the centre of the circle.



Hence, the magnitude of the centripetal acceleration of a satellite is given by:

$$\vec{a} = \frac{\vec{v}^2}{r} = \frac{4\pi^2 r}{T^2}$$

where: $\vec{v}$ is the speed of the satellite, in m s^{-1}
 r is the radius of the circular orbit, in m
 T is the period of orbit, in s

As it is known that the direction will always face inwards, the magnitude of the speed can be used rather than velocity (which is a vector quantity). The magnitude of the net (centripetal) force on the satellite then becomes:

$$\vec{F}_{\text{net}}(\text{or } \Sigma \vec{F}) = m\vec{a} = \frac{m\vec{v}^2}{r}$$

where: m is the mass of the satellite, in kg
 $\vec{v}$ is the speed of the satellite, in m s^{-1}
 r is the radius of the circular orbit, in m

Newton had already shown that objects moving in a circle with a constant speed experience a net force pointing radially inwards towards the centre of the circle. His great achievement with the Law of Universal Gravitation was to realise that the gravitational field from a large mass, such as that of the Earth, could be the source of the radially inwards net force on a satellite, such as the Moon.

By equating the gravitational force on a satellite with the net force experienced by an object undergoing circular motion, Newton obtained an expression for the gravitational force on a satellite of mass M_2 orbiting a central mass M_1 .

$$\vec{F}_g = G \frac{M_1 M_2}{r^2} = \frac{m\vec{v}^2}{r}$$

where: r is the distance between the centres of the central mass and the satellite's mass
 M_1 is the central mass, in kg
 M_2 (and m) is the mass of the satellite, in kg
 G is the gravitational constant, $6.67 \times 10^{-11} \text{ N m}^2 \text{ kg}^{-2}$
 $\vec{v}$ is the speed of the satellite, in m s^{-1}

Substituting $v = \frac{2\pi r}{T}$ into this equation, the following is obtained:

$$G \frac{M_1 M_2}{r^2} = \frac{4m\pi^2 r}{T^2}$$

To simplify this, M_1 or the central mass can be shown as M , and the mass of the satellite M_2 as m . This allows us to more easily rearrange the equation and show the relationship:

$$G \frac{M}{4\pi^2} = \frac{r^3}{T^2}$$

where: r is the distance between the centres of the two bodies (orbital radius), in m

M is the central mass, in kg

G is the gravitational constant, $6.67 \times 10^{-11} \text{ N m}^2 \text{ kg}^{-2}$

T is the orbital period, in s

This expression reveals the profound insight that the ratio of the cube of the radius of orbit of a satellite to the square of the period of the orbit has a constant value. This had already been discovered by the exceptional astronomer Johannes Kepler in his work on explaining the motion of the planets around the Sun and is known as Kepler's Third Law.

SAMPLE PROBLEM 2

The Moon orbits the Earth with a period of 2.36×10^6 s. The distance from the centre of the Earth to the centre of the Moon is 3.84×10^8 m.

- Calculate the speed of the Moon as it orbits the Earth.
- Calculate the acceleration experienced by the Moon.
- Use the provided data to calculate the mass of the Earth.

 **Teacher-led video:** SP2 (tlvd-0121)

THINK

- Recall that, for an object moving in a circle at a constant speed, $v = \frac{2\pi r}{T}$.

- Recall that, for an object moving in a circle at a constant speed,

$$a = \frac{v^2}{r} = \frac{4\pi^2 r}{T^2}$$

Ensure you use the non-rounded value if using the velocity from part a.

- Use the relationship $G \frac{M}{4\pi^2} = \frac{r^3}{T^2}$ to determine the mass of the Earth.

WRITE

$$\begin{aligned} \text{a. } v &= \frac{2\pi \times 3.84 \times 10^8}{2.36 \times 10^6} \\ &= 1020 \text{ m s}^{-1} \text{ (to 3 significant figures)} \end{aligned}$$

$$\begin{aligned} \text{b. } a &= \frac{4\pi^2 \times 3.84 \times 10^8}{(2.36 \times 10^6)^2} \\ &= 0.00272 \text{ m s}^{-2} \end{aligned}$$

or

$$\begin{aligned} a &= \frac{1020^2}{3.84 \times 10^8} \\ &= 0.00272 \text{ m s}^{-2} \end{aligned}$$

$$\begin{aligned} \text{c. } G \frac{M}{4\pi^2} &= \frac{r^3}{T^2} \\ \frac{6.67 \times 10^{-11} M_{\text{Earth}}}{4\pi^2} &= \frac{(3.84 \times 10^8)^3}{(2.36 \times 10^6)^2} \\ \Rightarrow M_{\text{Earth}} &= \frac{4\pi^2 \times (3.84 \times 10^8)^3}{(6.67 \times 10^{-11}) \times (2.36 \times 10^6)^2} \\ &= 6.02 \times 10^{24} \text{ kg} \end{aligned}$$

PRACTICE PROBLEM 2

Mars's moon, Phobos, orbits Mars with a period of 2.76×10^4 s. The distance from the centre of Mars to the centre of Phobos is 9.38×10^6 m.

- What is the speed of Phobos as it orbits Mars?
- What is the acceleration experienced by Phobos?
- Use the provided data to calculate the mass of Mars.

KEPLER'S LAWS

Isaac Newton (1642–1726) published his Law of Universal Gravitation in 1687. This law provided a mathematical and physical explanation for several important observations about the movement of planets in the solar system that had been made over the previous two centuries.

In 1542, Nicolaus Copernicus (1473–1543) published 'On the Revolution of the Heavenly Orbs', outlining an explanation for the observations of planetary motion with the Sun at the centre. In his explanation, the planets moved in circular orbits about the Sun. Copernicus's model became increasingly preferred over the geocentric model of Ptolemy because it made astronomical and astrological calculations easier. The publication had a significant scientific, social and political impact during the latter part of the sixteenth century.

Galileo Galilei (1564–1642) was a strong advocate for the view that the Copernican model was more than 'a set of mathematical contrivances, merely to provide a correct basis for calculation' and instead represented physical reality. (This had also been Copernicus's view, but he could not express this in print.) Galileo thought that astronomy could now ask questions about the structure, fabric and operation of the heavens but, as with so many of his scientific interests, Galileo did not pursue these questions further.

Johannes Kepler (1571–1630) decided his purpose in life was to reveal the fundamental coherence of a planetary system with the Sun at its centre. In 1600–1601, he was working as an assistant to Tycho Brahe (1546–1601), a Danish astronomer who had been compiling very precise measurements of the planets' positions for over twenty years. Brahe's data was so accurate that it is still valid today. Without the aid of a telescope, he was able to measure angles to an accuracy of half a minute of arc (for example $23^\circ 34' \pm 0.5'$).

Kepler was seeking to find patterns and relationships between the motions of the various planets. He used the data to calculate the positions of the planets as they would be observed by someone outside the solar system, rather than from the revolving platform of the Earth. Initially he was looking for circular orbits, but Brahe's precise data did not fit such orbits. Eventually he tried other shapes, until in 1604 he formulated what is known as Kepler's First Law:

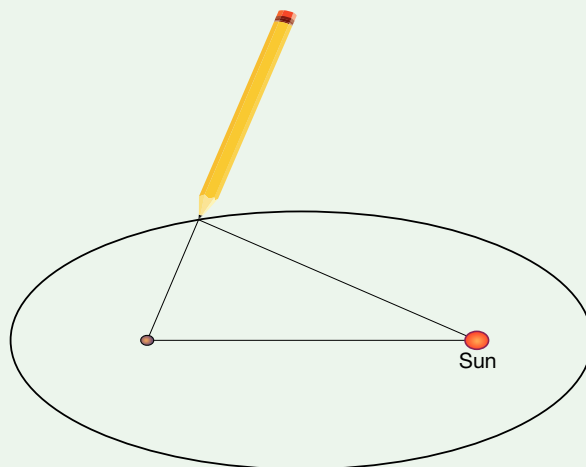
Each planet moves, not in a circle, but in an ellipse, with the sun, off centre, at a focus.

An ellipse is like a stretched circle. The shape can be drawn by placing two pins on the page several centimetres apart, with a loose piece of string tied between the pins. If a pencil is placed against the string to keep it tight and then the pencil is moved around the page, the drawn shape is an ellipse with a focus at each of the pins. The closer the two foci, the more like a circle the ellipse becomes.

The equinoxes are the two days in the year when the Sun is directly above the equator and the durations of night and day are equal. They occur when the line drawn from the Sun to the Earth is at right angles to the Earth's orbit. Because the Earth's orbit is an ellipse, when the Sun is off centre at one of the two foci, these two points are not directly opposite each other. This means the time for the Earth to go from the March equinox to the September equinox is longer by a few days than the time to go from the September equinox to the March equinox.

Look up the dates of the March and September equinoxes and determine the two times between them.

FIGURE 2.5 Drawing an ellipse



There was much speculation in Newton's time that gravitational attraction might vary inversely with the square of the distance, but it was Newton who was able to show mathematically, using a geometric proof, that the Earth's elliptical orbit means that the inverse square law applies to the attraction between the Sun and the Earth.

Kepler's First Law:

The planets move in elliptical orbits with the Sun at one focus.

Kepler also looked at the speeds of the planets in their orbits. His analysis of the data showed that the speeds of the planets were not constant. The planets were slower when they were further away from the Sun and faster when closer. He also found that their angular speed (the number of degrees a line from the Sun to a planet sweeps through every day) was not constant. Both results reinforced his first law. However, he did find in 1609 that the planets sweep out equal areas with time.

Kepler's Second Law:

The linear speed and angular speed of a planet are not constant, but the areal speed of each planet is constant. That is, a line joining the Sun to a planet sweeps out equal areas in equal times.

Newton was able to show mathematically that a constant areal velocity meant that the force acting on a planet must always act along the line joining the planet to the Sun.

Kepler was keen to find a mathematical relationship between the period of a planet's orbit around the Sun and its average radius that would give the same result for each planet. He tried numerous possibilities and eventually, in 1619, he found a relationship that fitted the data.

Kepler's Third Law:

For all planets, the cube of the average radius of orbit is proportional to the square of the orbital period; that is, $\frac{r^3}{T^2}$ is a constant for all planets going around the sun.

Kepler was also able to show that the relationship held for the orbits of the moons of Jupiter.

Kepler had constructed as detailed a description of the solar system as was possible without a mechanism to explain the motion of the planets, although he did understand gravity as a reciprocal attraction. Kepler wrote, 'Gravity is the mutual tendency between bodies towards unity or contact (of which the magnetic force also is), so that the Earth draws a stone much more than the stone draws the Earth...'

FIGURE 2.6 Location of the two equinoxes in the Earth's orbit

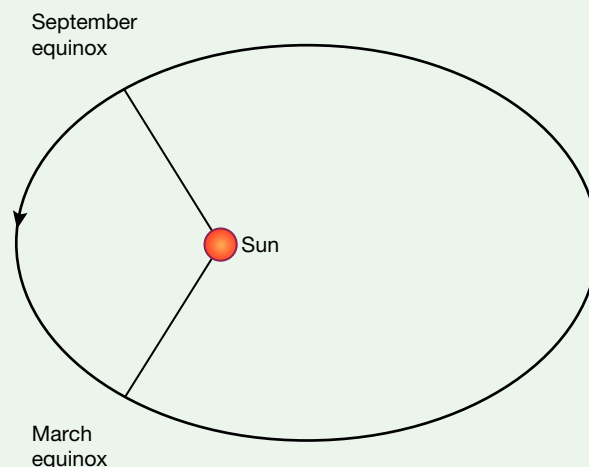
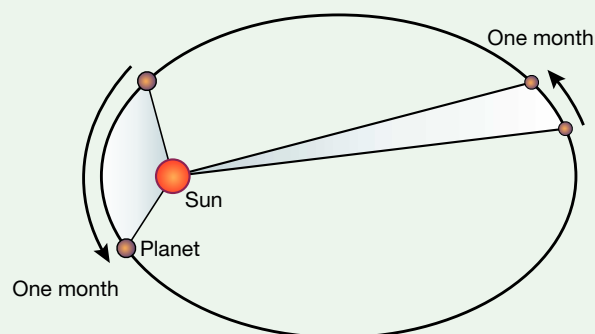


FIGURE 2.7 Kepler's Second Law



The formula found in Kepler's Third Law, $\frac{r^3}{T^2}$, shows a very important relationship between the orbital radius and the orbital period of planets orbiting a common mass.

TABLE 2.1 The solar system: some useful data

	Mean radius of orbit		Orbital period		Equatorial radius (m)	Mass (kg)
	(au)	(m)	(years)	(seconds)		
Sun					6.96×10^8	1.99×10^{30}
Mercury	0.387	5.79×10^{10}	0.241	7.60×10^6	2.44×10^6	3.30×10^{23}
Venus	0.723	1.08×10^{11}	0.615	1.94×10^7	6.05×10^6	4.87×10^{24}
Earth	1.00	1.50×10^{11}	1.00	3.16×10^7	6.37×10^6	5.98×10^{24}
Moon	2.57×10^{-3}	3.84×10^8	27.3 days*	2.36×10^6 *	1.74×10^6	7.35×10^{22}
Mars	1.52	2.28×10^{11}	1.88	5.94×10^7	3.39×10^6	6.42×10^{23}
Jupiter	5.20	7.78×10^{11}	11.9	3.74×10^8	6.99×10^7	1.90×10^{27}
Saturn	9.58	1.43×10^{12}	29.5	9.30×10^8	5.82×10^7	5.68×10^{26}
Titan	8.20×10^{-3}	1.22×10^9	15.9 days*	1.37×10^6 *	2.57×10^6	1.35×10^{23}
Uranus	19.2	2.87×10^{12}	84.0	2.65×10^9	2.54×10^7	8.68×10^{25}
Neptune	30.1	4.50×10^{12}	165	5.21×10^9	2.46×10^7	1.02×10^{26}
Pluto	39.48	5.91×10^{12}	248	7.82×10^9	1.15×10^6	1.31×10^{22}

*The orbital period for the Moon and Titan is the time it takes to complete one orbit around Earth and Saturn respectively. All other listed measurements is the time to orbit the Sun.

SAMPLE PROBLEM 3

Use the data in table 2.1 to calculate the value of $\frac{r^3}{T^2}$ for Mercury, Venus and Mars, and therefore confirm Kepler's Third Law.

 **Teacher-led video:** SP3 (tlvd-0122)

THINK

- 1 For Mercury, substitute the values $r = 5.79 \times 10^{10}$ m and $T = 7.60 \times 10^6$ s into the expression $\frac{r^3}{T^2}$.

- 2 For Venus, substitute the values $r = 1.08 \times 10^{11}$ m and $T = 1.94 \times 10^7$ s into the expression $\frac{r^3}{T^2}$.

- 3 For Mars, substitute the values $r = 2.28 \times 10^{11}$ m and $T = 5.94 \times 10^7$ s into the expression $\frac{r^3}{T^2}$.

- 4 Compare the values of $\frac{r^3}{T^2}$ for the three planets.

WRITE

$$\frac{r^3}{T^2} = \frac{(5.79 \times 10^{10})^3}{(7.60 \times 10^6)^2}$$

$$= 3.36 \times 10^{18}$$

$$\frac{r^3}{T^2} = \frac{(1.08 \times 10^{11})^3}{(1.94 \times 10^7)^2}$$

$$= 3.35 \times 10^{18}$$

$$\frac{r^3}{T^2} = \frac{(2.28 \times 10^{11})^3}{(5.94 \times 10^7)^2}$$

$$= 3.36 \times 10^{18}$$

The values of $\frac{r^3}{T^2}$ for the three planets are approximately the same, confirming Kepler's Third Law.

PRACTICE PROBLEM 3

Use the data in table 2.1 to calculate the value of $\frac{r^3}{T^2}$ for Saturn, Uranus and Neptune, and therefore confirm Kepler's Third Law.

Newton used his Law of Universal Gravitation to show that Kepler's Third Law applies to all satellites going around the same central mass.

In the context of the Earth, this means that the ratio $\frac{r^3}{T^2}$ is the same for every single artificial satellite, regardless of the orientation of its orbit, as well as for the Moon itself. If the period and the radius of one satellite's orbit is known, the method of ratios can be used to calculate the characteristics of any other satellite:

$$\frac{r_1^3}{T_1^2} = \frac{r_2^3}{T_2^2}$$
$$\left(\frac{r_1}{r_2}\right)^3 = \left(\frac{T_1}{T_2}\right)^2$$

where: r_1 is the distance between the central mass and satellite 1
 r_2 is the distance between the central mass and satellite 2
 T_1 is the period of orbit of satellite 1
 T_2 is the period of orbit of satellite 2

The benefit of this method is that, because you are working with ratios, you don't need to use metres and seconds for your data. However, it is important that you are consistent. (If you are using metres for the distance for one satellite, you must use metres for the other satellite.) Earth radii (1 Earth radius = 6.37×10^6 m) and days can be used, making for simpler calculations.

SAMPLE PROBLEM 4

The communications satellite Intelsat has an orbital period of 24.54 hours and an orbital radius of 4.25×10^6 m. The International Space Station (ISS) has an orbital period of 92.75 minutes. Use the method of ratios to find the orbital radius of the ISS.

 Teacher-led video: SP4 (tlvd-0123)

THINK

- 1 Convert all time periods to the same unit.

- 2 Apply Kepler's Third Law: $\frac{r_{\text{ISS}}^3}{T_{\text{ISS}}^2} = \frac{r_{\text{Intelsat}}^3}{T_{\text{Intelsat}}^2}$

WRITE

$$T_{\text{ISS}} = 92.75 \text{ minutes} = 5565 \text{ seconds}$$

$$T_{\text{Intelsat}} = 24.54 \text{ hours} = 88\,344 \text{ seconds}$$

$$\frac{r_{\text{ISS}}^3}{T_{\text{ISS}}^2} = \frac{r_{\text{Intelsat}}^3}{T_{\text{Intelsat}}^2}$$
$$\frac{r_{\text{ISS}}^3}{5565^2} = \frac{(4.25 \times 10^6)^3}{88\,344^2}$$
$$\Rightarrow r_{\text{ISS}}^3 = \frac{5565^2 \times (4.25 \times 10^6)^3}{88\,344^2}$$
$$= 3.046 \times 10^{17}$$
$$r_{\text{ISS}} = \sqrt[3]{3.046 \times 10^{17}}$$
$$= 6.73 \times 10^5 \text{ m}$$

PRACTICE PROBLEM 4

Mars has two moons, Phobos and Deimos. The orbital period of Phobos is 7.66 hours, whereas the orbital period of Deimos is 36.75 hours. If the orbital radius of Phobos is 9.38×10^6 m, calculate the orbital radius of Deimos using the method of ratios.

PERIOD OF THE MOON

The orbit of the Moon is slightly elliptical, but the average radius of the Moon's orbit is about 384 000 km or about 60 Earth radii.

The period of the Moon in relation to the stars is called the sidereal or **orbital period** and has been measured at 27.321 582 days (or approximately 2.36×10^6 seconds). As a close approximation, 27.3 days can be used. The period of the Moon in relation to the Sun, that is the time between full moons, is 29.5 days; this is longer than the sidereal period because during this time the Earth has moved further around the Sun.

Geostationary orbits

Artificial satellites are used for communication and exploration. Some transmit telephone and television signals around the world, some photograph cloud patterns to help weather forecasters, some are fitted with scientific equipment that enables them to collect data about X-ray sources in outer space, whereas others spy on neighbours! The motion of an artificial satellite depends on what it is designed to do. Those satellites that are required to stay constantly above one place on the Earth's surface are called **geostationary** satellites and they are said to be in geostationary orbit. In order to stay in position, a geostationary satellite must have an orbital period that is the same as the time for the central mass to complete one rotation about its axis. Therefore, geostationary satellites have a period of 24 hours, or 1 day, with the movement of the geostationary satellite corresponding to the rotation of the Earth about its axis.

SAMPLE PROBLEM 5

A geostationary satellite has a period of 24 hours. The mass of the Earth is 5.98×10^{24} kg. The radius of the Earth is 6.37×10^6 m. Find the altitude at which the geostationary satellite orbits the Earth.

 **Teacher-led video:** SP5 (tlvd-0124)

THINK

- 1 Convert the orbital period of the satellite to seconds.
- 2 Apply Kepler's Third Law:

$$G \frac{M}{4\pi^2} = \frac{r^3}{T^2}$$

WRITE

$$T = 24 \text{ hours} = 86\,400 \text{ seconds}$$

$$\begin{aligned} G \frac{M_{\text{Earth}}}{4\pi^2} &= \frac{r^3}{T^2} \\ \frac{6.67 \times 10^{-11} \times 5.98 \times 10^{24}}{4\pi^2} &= \frac{r^3}{86\,400^2} \\ \Rightarrow r^3 &= \frac{6.67 \times 10^{-11} \times 5.98 \times 10^{24} \times 86\,400^2}{4\pi^2} \\ \Rightarrow r &= \sqrt[3]{\frac{6.67 \times 10^{-11} \times 5.98 \times 10^{24} \times 86\,400^2}{4\pi^2}} \\ &= 4.23 \times 10^7 \text{ m} \end{aligned}$$

- 3 The question asks for the altitude of the satellite, which is the height **above** the surface of the Earth. Subtract the radius of the Earth from the radius of the satellite's orbit to determine the altitude.

$$\begin{aligned}\text{altitude} &= \text{radius of orbit} - \text{radius of Earth} \\ &= 4.23 \times 10^7 - 6.37 \times 10^6 \\ &= 3.59 \times 10^7 \text{ m}\end{aligned}$$

PRACTICE PROBLEM 5

A satellite is placed into a geostationary orbit above Mars. A day on Mars lasts for 24 hours and 37 minutes. The mass of Mars is 6.42×10^{23} kg and the radius is 3.39×10^6 m. Calculate the altitude of the satellite.

'Floating' in a spacecraft

The appearance of an astronaut floating around inside a spacecraft suggests that there is no force acting on them, leading some people to mistakenly think that there is no gravity in space. In fact, both the astronaut and the spacecraft are in a circular orbit about the Earth.

However, you also know that if an object is moving in a curved path, therefore changing its direction, there must be acceleration. If the path is circular, the acceleration is directed towards the centre of that path. The astronaut and the spacecraft are in the same gravitational field. They are at the same distance from the centre of the Earth. They are travelling at the same speed, taking the same time to orbit the Earth. Therefore, their centripetal accelerations provided by the gravitational field are the same.

FIGURE 2.8 An astronaut inside the International Space Station. Both the astronaut and the station are in orbit around the Earth.



TABLE 2.2 Comparing the gravitational fields of an astronaut and spacecraft

For the spacecraft:	For the astronaut:
$G \frac{M_{\text{Earth}} M_{\text{spacecraft}}}{r^2} = M_{\text{spacecraft}} \times \frac{4\pi^2 r}{T^2}$	$G \frac{M_{\text{Earth}} m_{\text{astronaut}}}{r^2} = m_{\text{astronaut}} \times \frac{4\pi^2 r}{T^2}$
$G \frac{M_{\text{Earth}}}{r^2} = \frac{4\pi^2 r}{T^2}$	$G \frac{M_{\text{Earth}}}{r^2} = \frac{4\pi^2 r}{T^2}$

There is no need for a normal force by the spacecraft on the astronaut to explain the astronaut's motion. The astronaut inside the spacecraft circles the Earth as if the spacecraft was not there. Indeed, if the astronaut is outside the spacecraft doing a spacewalk, the astronaut's speed and acceleration around the Earth will be unchanged as they 'float' beside the spacecraft. Once back inside, their speed and acceleration are still unchanged, and this time they are 'floating' inside the spacecraft.

If the astronaut steps onto a set of bathroom scales, they will give a reading of zero. As shown in figure 2.9, an astronaut running on a treadmill needs stretched springs attached to his waist to pull him down to the treadmill.

FIGURE 2.9 The cloth-covered stretched springs are pulling the astronaut down so he can exercise on the treadmill.



Source: © NASA

SAMPLE PROBLEM 6

An astronaut on the International Space Station stands on a set of bathroom scales. Explain what the expected reading would be.

 **Teacher-led video:** SP6 (tlvd-0125)

THINK

The only force acting on the astronaut is the gravitational force from the Earth.

The only force acting on the bathroom scales is the gravitational force from the Earth.

WRITE

The net force on the astronaut is equal to the force due to gravity on the astronaut, because the astronaut is in circular motion around the Earth with acceleration g . The bathroom scales are also in circular motion around the Earth with acceleration g . This means that the normal force experienced by the astronaut from the bathroom scales is 0 N.

PRACTICE PROBLEM 6

In an attempt to increase the reading on the bathroom scales, the astronaut on the International Space Station holds a 10 kg mass. What difference will this make to the reading on the bathroom scales?

Resources



Interactivity How the speed and period changes with the radius of a satellite's orbit (int-0062)

2.2 EXERCISE

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

- (a) Calculate the gravitational field strength on a 1.5 kg ball held at a height of 2.0 metres above the surface of the Earth.
(b) The ball is dropped. Calculate the net force on the 1.5 kg ball as it falls to the surface of the Earth.
- A gravitational field strength detector is released into the atmosphere and reports back a reading of 9.70 N kg^{-1} .
(a) If the detector has a mass of 10 kg, what is the force of gravity acting on it?
(b) If the detector is to remain stationary at this height, what upward force must be exerted on the detector?
(c) How far is the detector from the centre of the Earth?
- The Moon orbits the Earth with a period of 27.32 days. The orbital radius is $3.84 \times 10^8 \text{ m}$. Calculate the orbital speed of the Moon.
- A space station orbits at a height of 355 km above the Earth and completes one orbit every 92 min.
(a) What is the orbital speed of the space station?
(b) What is the centripetal acceleration of the space station?
(c) What gravitational field strength does the space station experience?
(d) Your answers to (b) and (c) should be the same. (i) Explain why. (ii) Explain any discrepancy in your answers.
(e) If the mass of the space station is 1200 tonnes, what is the centripetal force on the space station?
(f) The mass of an astronaut and the special spacesuit he wears when outside the space station is 270 kg. If he is a distance of 10 m from the centre of mass of the space station, what is the force exerted on the astronaut by the floor of the space station?
- In the future, it is predicted that space stations may rotate to simulate the gravitational field of Earth and therefore make life more normal for the occupants. Draw a diagram of such a space station. Include on your diagram:
 - the axis of rotation
 - the distance of the occupants from the axis
 - arrows indicating the direction the occupants would consider as 'down'.(Remember to consider the frame of reference of the occupants!) Make an estimate of the period of rotation your space station would need to simulate Earth's gravitational field.
- The asteroid 243 Ida was discovered in 1884. The Galileo spacecraft, on its way to Jupiter, visited the asteroid in 1993. Search online for images of the flyby. The asteroid was the first to be found to have a natural satellite, that is, its own moon, now called Dactyl. Dactyl orbits Ida at a radius of 100 km and with a period of 27.0 hours. What is the mass of the asteroid?
- Venus and Saturn both orbit the Sun. Using only information about the Sun and the periods of the two planets from table 2.1, calculate the value of the ratio:

$$\frac{\text{distance of Saturn from the Sun}}{\text{distance of Venus from the Sun}}$$

- A satellite is in a circular orbit around the Earth with a radius equal to half the radius of the Moon's orbit. What is the satellite's period expressed as a fraction of the Moon's period about the Earth?
- A new geostationary satellite is to be launched. At what distance from the centre of the Earth must the satellite orbit?
- A spacecraft leaves Earth to travel to the Moon. How far from the centre of the Earth is the spacecraft when it experiences a net force of zero? Use the following data to determine where that point is, and draw a scale diagram to show its location.

$$\begin{aligned}M_{\text{Moon}} &= 7.35 \times 10^{22} \text{ kg} \\M_{\text{Earth}} &= 5.98 \times 10^{24} \text{ kg} \\Distance_{\text{Earth-moon}} &= 3.84 \times 10^8 \text{ m}\end{aligned}$$

2.3 Energy changes in gravitational fields

KEY CONCEPTS

- Analyse the use of gravitational fields to accelerate mass, including:
 - potential energy changes in a uniform gravitational field: $E_g = mg\Delta h$
 - the change in gravitational potential energy from area under a force–distance graph and area under a field–distance graph multiplied by mass.

Consider the following scenarios:

1. On 15 February 2013, an asteroid approached the Earth, gaining speed in the Earth's gravitational field. By the time it reached the atmosphere and vaporised into a meteor, it was travelling at a speed of 19 km s^{-1} . With a mass of approximately $1.2 \times 10^7 \text{ kg}$, its **kinetic energy** was approximately $2.2 \times 10^{15} \text{ J}$. It exploded about 30 km above Chelyabinsk, in Russia. This caused a large shock wave that damaged buildings and injured over 1000 individuals. Smaller meteorite fragments fell to the ground after this explosion (with one fragment being found to be over 600 kg).
2. Edmund Halley used Newton's law of gravitation to calculate the effect of Jupiter and Saturn on the orbits of comets. He concluded that comet sightings in 1531 and 1607 were sightings of the same comet and that it should appear again in 1758. This comet is now called Halley's Comet.

Halley's Comet orbits the Sun every 75.3 years in a very stretched path. The closest it gets to the Sun is about 0.6 times the radius of the Earth's orbit, while its furthest distance is 35 times the radius. At its closest approach, its kinetic energy is $1.6 \times 10^{23} \text{ J}$ with a speed of 38 km s^{-1} but, at its furthest, it has only $4.5 \times 10^{19} \text{ J}$, travelling at 0.64 km s^{-1} .

3. Ignoring the initial air resistance, a rock thrown at 11 km s^{-1} would eventually escape the effect of the Earth's gravitational pull, slowing down to zero only at an infinite distance away.

In each of these scenarios, there are changes in speed and height, and thus in kinetic energy and **gravitational potential energy**. How are these changes described using Newton's law of gravitation?

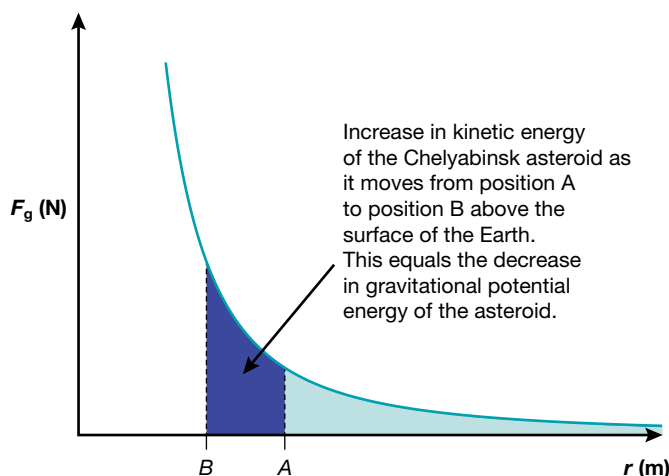
2.3.1 Force—distance graphs

The change in gravitational potential energy can be obtained from the area under a force–distance graph.

The gravitational force experienced by the Chelyabinsk asteroid, Halley's comet and a rock thrown at 11 km s^{-1} away from the Earth's surface changes as the distance between them and the central larger mass changes. The gravitational force on the Chelyabinsk asteroid increased as it approached the Earth. As a result, the gravitational field did work on the asteroid, increasing its kinetic energy. The increase in the kinetic energy can be found from the area under the graph of gravitational force versus distance experienced by the asteroid. The total energy of the asteroid/Earth system remained constant, so as the kinetic energy of the asteroid increased, the gravitational potential energy of the asteroid in the Earth's gravitational field decreased.

As Halley's comet moves to a position of decreased gravitational force, it does work against the gravitational field, which decreases the kinetic energy of the comet. Because the total energy of the system is constant, the gravitational potential energy of the comet must simultaneously increase. As the comet orbits, it will move again into a region of increasing gravitational force, increasing the comet's kinetic energy and decreasing its gravitational potential. A rock launched with a speed of 11 km s^{-1} from the surface of the Earth has sufficient kinetic energy to be able to move to a position where the gravitational field of the Earth is too weak to hold the rock in an orbit around it. It will 'escape' the Earth's gravity. Space probes need to be launched with sufficient kinetic energy to allow them to escape Earth's gravity and explore the wider solar system and beyond, often carrying booster rockets to enable this.

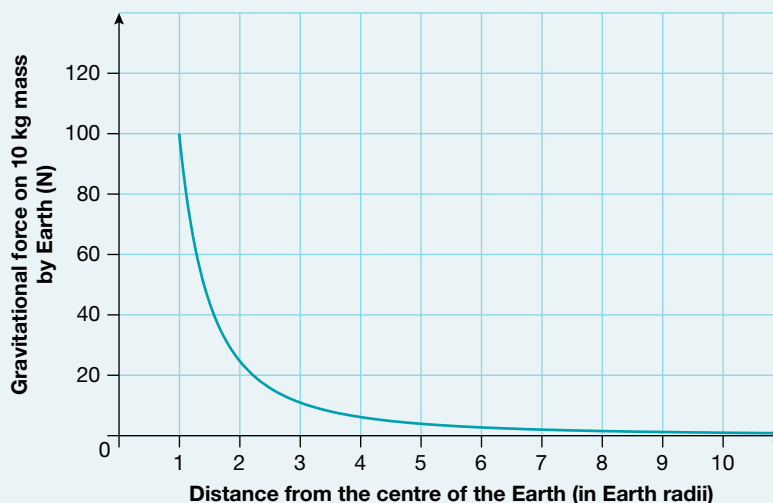
FIGURE 2.10 The total energy of the asteroid at B equals the total energy of the asteroid at A.



Note: Sometimes you may be given a negative value for the gravitational force rather than a positive value, and so the graph will be inverted vertically. It is important that you are calculating the area between the graph and the horizontal axis in this case when calculating the change in kinetic energy.

SAMPLE PROBLEM 7

A mass of 10 kg falls to the surface of the Earth from an altitude equal to two Earth radii (or $1.27 \times 10^7 \text{ m}$). What is the gain in kinetic energy?



 **Teacher-led video:** SP7 (tlvd-0126)

THINK

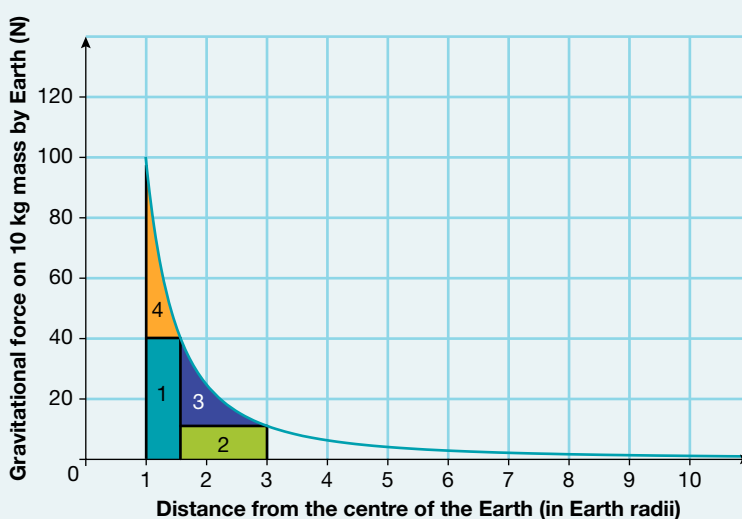
- 1 The gravitational field does the work on the mass, so the change in kinetic energy can be found from the area under the force–displacement graph. (Remember that the surface of the Earth is 1 Earth radius away from the centre of the Earth. So an altitude of 2 radii from the surface is in fact 3 Earth radii from the centre, as given in the graph.)

There are two methods you can use to determine the area. For these questions, VCAA will accept a range of answers, so either technique may be used, depending on the grid you are given. How to find the area under a curved graph:

Method 1:

1. Divide the area under the graph into simple shapes and estimate the area in terms of the sum of the areas of the shapes.
2. If the graph is drawn on a fine grid, count the grid squares under the graph.
3. Convert the grid areas to the correct units.

WRITE



$$\begin{aligned}\text{Area 1 (blue)} &= 40 \times 0.5 \\ &= 20 \text{ energy units}\end{aligned}$$

$$\begin{aligned}\text{Area 2 (green)} &= 10 \times 1.5 \\ &= 15 \text{ energy units}\end{aligned}$$

$$\begin{aligned}\text{Area 3 (purple)} &= \frac{1}{2} \times 24 \times 1.5 \\ &= 18 \text{ energy units}\end{aligned}$$

(Note: The triangle with area $\frac{1}{2} \times 30 \times 1.5$ would be larger than the purple area, so the height of 30 was reduced to a level where the areas matched.)

$$\begin{aligned}\text{Area 4 (orange)} &= \frac{1}{2} \times 53 \times 0.5 \\ &= 13.25 \text{ energy units}\end{aligned}$$

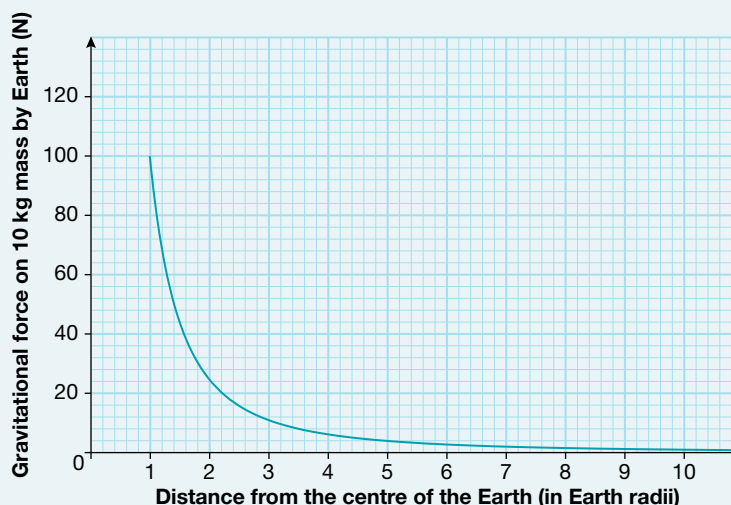
$$\begin{aligned}\text{Total area} &= 20 + 15 + 18 + 13.25 \\ &= 66.25 \text{ energy units}\end{aligned}$$

$$\begin{aligned}1 \text{ energy unit} &= 1\text{N} \times 1 \text{ Earth radius} \\ &= 1\text{N} \times 6.37 \times 10^6 \text{ m} \\ &= 6.37 \times 10^6 \text{ J}\end{aligned}$$

$$\begin{aligned}\text{Therefore, the kinetic energy gained} &= 66.25 \times 6.37 \times 10^6 \\ &= 4.22 \times 10^8 \text{ J}\end{aligned}$$

Method 2: Use this method when the graph has a relatively fine grid.

1. Count the number of small squares between the graph and the zero-value line or horizontal axis. Tick each one as you count it to avoid counting squares twice. For partial squares, find two that add together to make one square and tick both.
2. Calculate the area of one small square.
3. Multiply the area of one small square by the number of small squares.



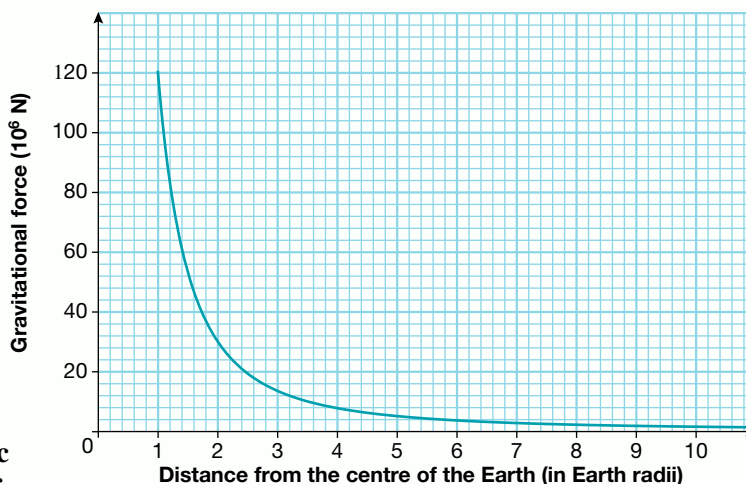
Number of small squares = 80.5

$$\begin{aligned}\text{Area of one small square} &= 4 \text{ N} \times 0.2 \times 1 \text{ Earth radius} \\ &= 4 \text{ N} \times 0.2 \times 6.38 \times 10^6 \text{ m} \\ &= 5.1 \times 10^6 \text{ J}\end{aligned}$$

Therefore, the gain in kinetic energy = $80.5 \times 5.1 \times 10^6 \text{ J}$
 $= 4.11 \times 10^8 \text{ J}$

PRACTICE PROBLEM 7

- Use the following graph of the gravitational force on the Chelyabinsk asteroid to show that, in moving from an altitude of two Earth radii to an altitude of one Earth radius, the asteroid gained 1.25×10^{14} joules of kinetic energy.
- Use the graph to find, to the nearest whole number, approximately how much kinetic energy was gained from falling from an altitude of one Earth radius to the Earth's surface. Compare this value with your answer to part a.



Note: Sometimes you may be given a negative value for the gravitational force rather than a positive value, and so the graph will be inverted vertically. It is important that you are calculating the area between the graph and the horizontal axis in this case when calculating the change in kinetic energy.

2.3.2 Field–distance graphs

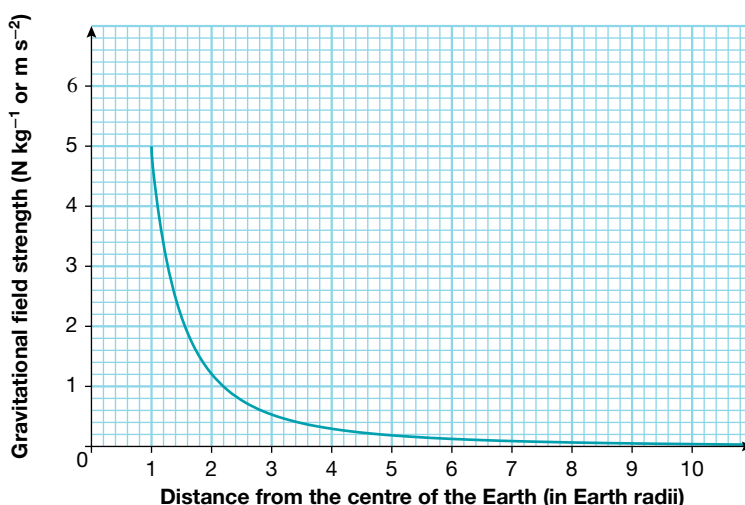
The graphs for the 10 kg mass and the Chelyabinsk asteroid have different values on the force axis. To find the changes in energy of a rock escaping the Earth, a different graph would be needed, because the mass of the rock is different and thus the gravitational force on it is different. It would be simpler if the same graph could be used for different objects regardless of their mass.

The graph that can be used for this purpose is a graph of the gravitational field against distance. The gravitational force on a mass at a point in space is just the value of the gravitational field at the point multiplied by its mass.

The change in energy for an object that moves from one point to another can be obtained by multiplying the area under the graph of the gravitational field against distance by its mass.

The unit for gravitational field is newtons per kilogram. The unit for the area under a graph of gravitational field against distance is (newtons per kilogram) $\times$ metre, hence newton metre per kilogram or simply joule per kilogram. The change in energy can be obtained from this area by multiplying by the mass of the object. Sometimes, instead of being given the distance in metres, you may be given the distance in Earth radii (as seen in figure 2.11). In this case, you need to ensure you convert into metres before multiplying by newtons per kilogram.

FIGURE 2.11 Graph of the the Earth's gravitational field strength



SAMPLE PROBLEM 8

Find the increase in kinetic energy for a 100 kg mass that falls from a distance of 4 Earth radii from the centre of the Earth to 2 Earth radii using figure 2.11.

 **Teacher-led video:** SP8 (tlvd-0127)

THINK

- 1 Determine the area between the curve and the axis between the distance of 2 and 4 Earth radii and convert the units to SI units. (Remember, there are two methods you can use for these questions. You may count the squares or split them into smaller areas. Due to the provision of small squares, the method of counting squares has been used.)

WRITE

The area under the curve between 2 Earth radii and 4 Earth radii is 29 squares, with each square having an area of $0.2 \text{ N kg}^{-1} \times 0.2 \text{ Earth radii}$.

One Earth radius = $6.37 \times 10^6 \text{ m}$

$$\begin{aligned}\text{Area under curve} &= 0.2 \times 0.2 \times 6.37 \times 10^6 \\ &= 2.55 \times 10^6 \text{ N m kg}^{-1}\end{aligned}$$

- 2 Remember that $F_g = mg$.
Multiply the area by the mass to obtain the change in energy.

$$\begin{aligned}\text{Change in energy} &= 100 \text{ kg} \times 2.55 \times 10^6 \text{ N m kg}^{-1} \\ &= 2.55 \times 10^8 \text{ N m} \\ &= 2.55 \times 10^8 \text{ J}\end{aligned}$$

PRACTICE PROBLEM 8

Find the increase in kinetic energy for a 20 kg mass that falls from a distance of 3 Earth radii from the centre of the Earth to 2 Earth radii from the centre of the Earth.

2.3.3 Energy changes close to the Earth's surface

You have learned that the gravitational field of the Earth decreases as the square of the distance from the centre of the Earth. However, the Earth is huge compared to the scale of ordinary human actions. For a distance of 1000 m from the surface of the Earth, the gravitational field has decreased by a mere 0.03%, from 9.805 N kg^{-1} to 9.802 N kg^{-1} . The gravitational field strength experienced by a ball dropped from an initial height of a couple of metres above the surface of the Earth is effectively constant.

What about the energy transformations experienced by the ball? As the ball falls, work is done on the ball by the gravitational field, and the ball speeds up. Energy is transferred from the gravitational field into the kinetic energy of the ball. The formulae for gravitational potential energy and kinetic energy are as follows:

$$\Delta E_g = m\vec{g} \times \text{distance travelled} = m\vec{g} \Delta h$$

where: ΔE_g 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, in N kg^{-1}
 Δh is the change in height, in m

$$E_k = \frac{1}{2}m\vec{v}^2$$

where: E_k is the kinetic energy of the object, in J
 m is the mass of the object, in kg
 $\vec{v}$ is the speed of the object, in m s^{-1}

When work is done on an object by the force of gravity causing it to move a distance in the gravitational field, the result is a conversion of gravitational potential energy and kinetic energy.

$$\Delta E = W = \vec{F} \vec{s}$$

where: ΔE is the change in gravitational potential energy and kinetic energy, in J
 W is the work done, in J
 $\vec{F}$ is the force of gravity, in N
 $\vec{s}$ is the distance moved in the gravitational field, in m

If you think back to what you already know in this topic, the force close to the Earth's surface is equal to $m \times g$ and the distance is the change in height, Δh . Therefore it can also be stated that $\Delta E = Fs = mg\Delta h$, which is the same as the first formula shown.

SAMPLE PROBLEM 9

- Find the work done by the gravitational field on a 30 kg ball that is dropped from the top of a 150 m building.
- Calculate the change in kinetic energy of a 30 kg ball that is dropped from the top of 150 m building.

 Teacher-led video: SP9 (tlvd-0128)

THINK

- Determine the magnitude of the force due to gravity acting on the ball.
 - The work done can be calculated using $W = Fs$.
- b. The change in kinetic energy is equal to the work done by the field.

WRITE

a. $F = mg$
 $= 30 \times 9.8$
 $= 294 \text{ N}$

$W = Fs$
 $= 294 \times 150$
 $= 44\,100 \text{ J}$

b. $\Delta E_k = \text{work done by field}$
 $= 44\,100 \text{ J}$
 $= 4.4 \times 10^4 \text{ J}$

PRACTICE PROBLEM 9

A 2.0 kg ball is thrown vertically upwards from a height of 1.0 m, with an initial speed of 5.0 m s^{-1} . What is the change in kinetic energy of the ball just before it hits the ground?



Resources

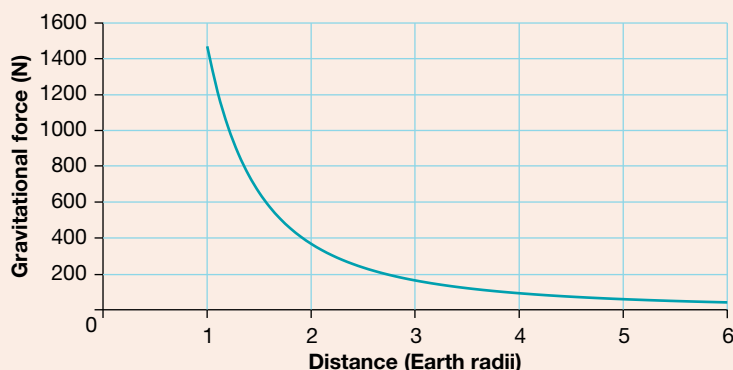


Digital document Investigation 2.2 Exploring the relationship between gravitational and kinetic energy (doc-31590)

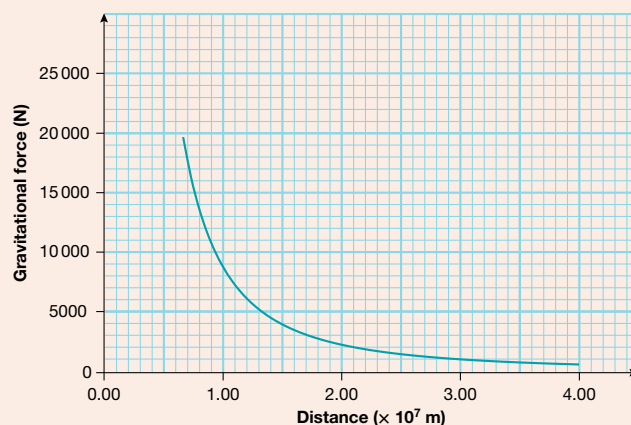
2.3 EXERCISE

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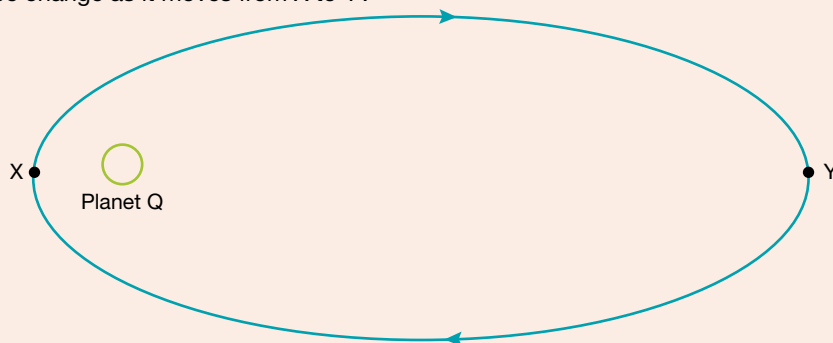
- Calculate the work done moving a 150 kg mass from a distance of 1 Earth radius to 3 Earth radii from the centre of the Earth.



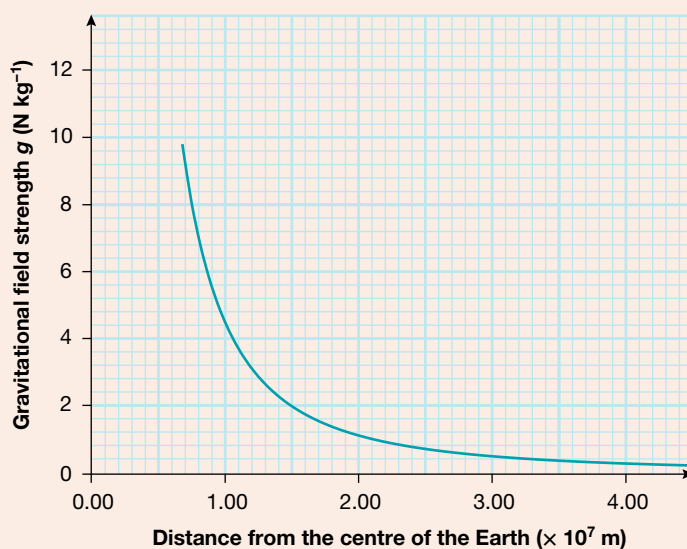
2. A 2000 kg satellite falls from a distance of 3.5×10^7 m to 1.0×10^7 m. What is the gain in kinetic energy of the satellite?



3. Explain why the area under a gravitational force–distance graph gives the energy needed to launch a satellite, but the area under a gravitational field strength–distance graph gives the energy *per kilogram* needed to launch a satellite.
4. A space probe traverses an elliptical orbit as it passes around a distant unknown planet, Planet Q. How does the kinetic energy of the space probe change as it moves from X to Y? How does the total energy of the space probe change as it moves from X to Y?

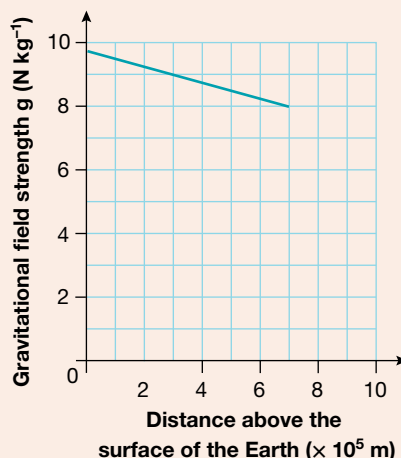


5. Calculate the change in gravitational potential energy of a 300 kg satellite carried from the surface of the Earth to an orbit at an altitude of 1.4×10^7 m (or 14 000 km).



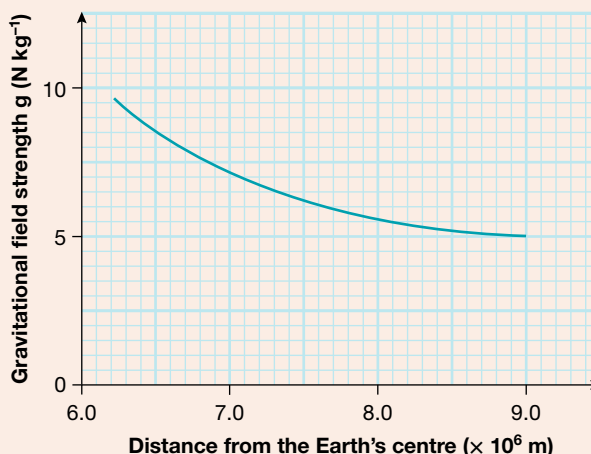
6. A space shuttle, orbiting Earth once every 93 min at a height of 400 km above the surface, deploys a new 800 kg satellite that is to orbit a further 200 km away from Earth.

- Use the following graph to estimate the work needed to deploy the satellite from the shuttle.
- Use the mass and radius of the Earth to assist you in determining the period of the new satellite.
- Show how the period of the new satellite can be determined without knowledge of the mass of the Earth.
- If the new satellite was redesigned so that its mass was halved, how would your answers to (a) and (b) change?



7. A disabled satellite of mass 2400 kg is in orbit around the Earth at a height of 2000 km above sea level. It falls to a height of 800 km before its built-in rocket system can be activated to stop the fall.

- Calculate the gravitational force on the satellite while it is in its initial orbit.
- Calculate the loss of gravitational potential energy of the satellite during its fall.
- If the speed of the satellite during its initial orbit is 6900 m s^{-1} , what is its velocity when the rocket system is activated?



- Close to the surface of the Earth, the gravitational field can be approximated as a constant. Calculate the change in kinetic energy of an 85 g apple as it falls from a branch at a height of 3.0 m above the ground.
- A 500 g cannonball is launched from the deck of a ship with an initial velocity of 100 m s^{-1} . It misses its target and splashes into the sea, 30 metres below the deck of the ship. What is the speed of the cannonball just before it hits the sea?

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2.4 Review

2.4.1 Summary

- A mass, m , in a gravitational field, g , experiences a force, $F_g = mg$, which, if there are no other forces acting on the mass, causes the mass to accelerate, with $a = g$.
- Close to the surface of the Earth, the gravitational field can be approximated by a constant value, 9.8 m s^{-2} . Objects close to the surface of the Earth that experience negligible air resistance fall towards the Earth's surface with an acceleration of 9.8 m s^{-2} .
- Newton showed that objects moving in a circular orbit at a constant speed experience an acceleration towards the centre of the circle. This means that the net force acting on the object is pointing towards the centre of the circle at all times.
- Newton's Law of Universal Gravitation explains how it is possible for natural and artificial satellites in a circular orbit around the Earth to experience a net force towards the centre of the Earth.
- If a natural or artificial satellite orbits the Earth at a distance from the centre of the Earth, r , then the acceleration experienced by the satellite is equal to the gravitational field of the Earth at the distance r from the surface.
- For a given planetary or satellite system, $\frac{r^3}{T^2} = G \frac{M}{4\pi^2}$, where G is the gravitational constant, $6.67 \times 10^{-11} \text{ N kg}^{-2} \text{ m}^2$, and M is the mass of the central body.
- Satellites in orbit and their occupants (who are also in orbit) experience no reaction force.
- The gravitational potential energy of a mass depends on its position in a gravitational field.
- The gravitational field can do work on a mass and move it to a position of lower gravitational potential, causing the kinetic energy of the mass to increase. The change in kinetic energy is given by the product of the mass times the area under a field versus displacement graph.
- A rocket or space probe can do work against the gravitational field and move to a position of higher gravitational potential energy and/or increase its kinetic energy.
- For objects close to the surface of the Earth, where the gravitational field is approximately uniform, the change in gravitational potential energy of an object falling through a height, h , causes a change in kinetic energy, $\Delta E_k = \Delta E_g = mg\Delta h$.



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2.4.2 Key terms

Centripetal acceleration is the acceleration towards the centre of a circle experienced by an object moving in a circular motion.

A satellite in **geostationary** orbit is stationary relative to a point directly below it on the Earth's surface.

A geostationary orbit has the same period as the rotation of Earth.

A **gravitational field** is a vector field describing the property of space around an object with mass that causes a second object with mass to experience a gravitational force towards the object.

Gravitational potential energy is the energy stored in an object as a result of its position relative to another object to which it is attracted by the force of gravity.

Kinetic energy is the energy associated with the movement of an object. Like all forms of energy, it is a scalar quantity.

The **orbital period**, or sidereal period, is the time it takes for a satellite to complete one orbit around a central object.

A **satellite** is an object that is orbiting a larger central mass. Satellites can be natural (such as the Moon) or man-made (such as the International Space Station).

on Resources

 **Digital document** Key terms glossary (doc-32248)

2.4.3 Practical work and investigations

Investigation 2.1

Using a pendulum to determine g

Aim: To determine the rate of acceleration due to gravity using the motion of a pendulum

Digital document: doc-31589

Teacher-led video: tlvd-0226



Investigation 2.2

Exploring the relationship between gravitational and kinetic energy

Aim: To calculate the gravitational energy and kinetic energy of a falling ball and determine if the change in gravitational energy is equal to the kinetic energy

Digital document: doc-31590

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 **Digital document** Practical investigation logbook (doc-32249)

2.4 Exercises

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2.4 Exercise 1: Multiple choice questions

- Mass A and Mass B are placed in a gravitational field, at the exact same distance from a central body. Mass A is 1000 times larger than Mass B. There are no other forces acting on the masses. Which of the following is correct?
 - The force on mass A is the same as the force on mass B.
 - The acceleration of mass A is 1000 times larger than the acceleration of mass B.
 - The gravitational field experienced by mass A is 1000 times larger than the gravitational field strength experienced by mass B.
 - The acceleration of mass A is the same as the acceleration of mass B.
- When a satellite orbits the Earth with uniform circular motion, which of the following is incorrect?
 - The magnitude of the velocity is constant.
 - The magnitude of the acceleration is constant.
 - The period of the orbit is constant.
 - The direction of the velocity is constant.

3. When a satellite orbits the Earth with uniform circular motion, which of the following is true?
 - A. The speed of the satellite is constant, so the satellite is not accelerating.
 - B. Engines on the satellite cause the direction of the velocity of the satellite to change constantly, so that it goes in a circle.
 - C. The gravitational field of the Earth constantly changes the direction of the velocity of the satellite.
 - D. Energy is used to keep the satellite moving in a circle.
4. Which of the following does **not** affect the orbital period of a satellite orbiting the Earth?
 - A. The orbital radius of the satellite.
 - B. The mass of the satellite.
 - C. The mass of the Earth.
 - D. The altitude of the satellite.
5. Satellites A and B orbit the Earth. The orbital radius of A is four times as large as the orbital radius of B. Which of the following is correct?
 - A. The period of orbit of A is four times as large as the period of orbit of B.
 - B. The period of orbit of A is one-quarter of the period of orbit of B.
 - C. The period of orbit of A is eight times as large as the period of orbit of B.
 - D. The period of orbit of A is one-eighth of the period of orbit of B.
6. Two moons, Castor and Pollox, orbit a recently discovered planet. The orbital period of Castor is three times larger than the orbital period of Pollox. Which of the following is correct?
 - A. The orbital radius of Castor is equal to the orbital radius of Pollox.
 - B. The orbital radius of Castor is three times larger than the orbital radius of Pollox.
 - C. The square of the orbital radius of Pollox is nine times larger than the square of the orbital radius of Pollox.
 - D. The cube of the orbital radius of Castor is nine times larger than the cube of the orbital radius of Pollox.
7. Which of the following statements regarding geostationary orbits is correct?
 - A. A geostationary orbit is an orbit in which the satellite has zero velocity.
 - B. A geostationary orbit is an orbit in which the velocity relative to a point on the Earth's equator is zero.
 - C. A geostationary orbit is an orbit that has a period of approximately 365 days.
 - D. A geostationary orbit is an orbit that has an altitude close to the Earth's surface.
8. Astronauts on space stations orbiting the Earth do not experience a normal force when they stand on bathroom scales. This is because:
 - A. they are too far from the Earth's surface to experience gravity.
 - B. the net force on the astronaut is equal to the force due to gravity on the astronaut, so there is no reaction force from the scales.
 - C. they don't have any weight.
 - D. bathroom scales don't work properly away from the Earth's surface.
9. The change in kinetic energy of a space probe in a gravitational field as it moves further away from a planet can be calculated from:
 - A. the area under a gravitational force versus distance graph.
 - B. the area under a gravitational field strength versus distance graph.
 - C. the area under a gravitational force versus distance graph multiplied by the mass of the space probe.
 - D. the area under a gravitational field strength versus distance graph divided by the mass of the space probe.

10. A space probe can use the gravitational fields of planets that it is passing to change its speed. Which of the following is **not** possible?
- Gravitational potential energy can be converted into kinetic energy.
 - Work can be done on the space probe by the gravitational field, increasing its kinetic energy.
 - Kinetic energy can be converted into gravitational potential energy.
 - The gravitational field can do work on the space probe, increasing its gravitational potential and kinetic energy.

2.4 Exercise 2: Short answer questions

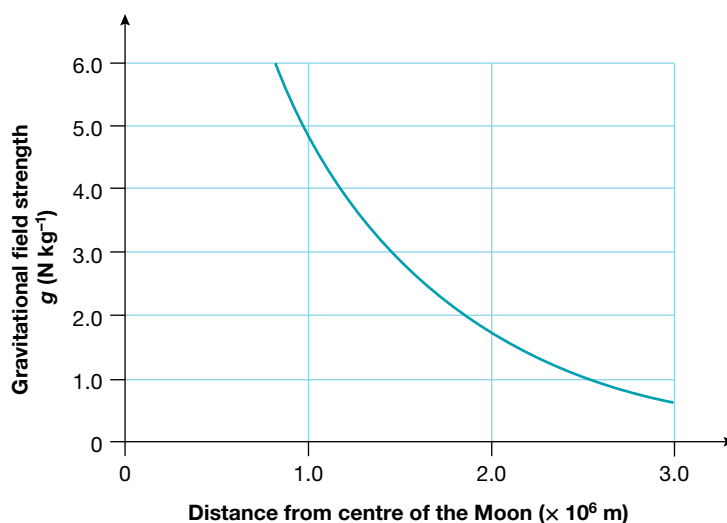
1. Jupiter has many moons, two of which are Io and Ganymede. The following table shows some data for each:

Moon	Mass	Period of orbit	Radius of orbit
Io	8.932×10^{22} kg	1.7691 days	4.217×10^8 m
Ganymede	1.482×10^{23} kg		1.0704×10^9 m

- What is the orbital speed of Io's orbit?
 - Calculate the centripetal acceleration experienced by Io.
 - What is the period of Ganymede's orbit?
 - Use the data provided to calculate the mass of Jupiter.
- What is the centripetal acceleration of a person standing on Earth's equator due to Earth's rotation about its axis? (Radius of Earth = 6.37×10^6 m.) Would the centripetal acceleration be greater or less for a person standing in Victoria? Justify your answer.
 - A spacecraft of mass 470 kg is orbiting the Earth with a period of 2.5 hours. Calculate its altitude. (Mass of Earth = 5.98×10^{24} kg; radius of Earth = 6.37×10^6 m)
 - Neutron stars are thought to rotate on their axis approximately 1 revolution every second. What is the minimum mass for a neutron star (with a radius of 10 km) so that a mass on the star's surface is in the same situation as a satellite in orbit, that is, the strength of the gravitational field equals the centripetal acceleration at the surface? (For this question, assume hypothetically that the net force is solely due to the gravitational force. Do not factor in the normal force in your calculations.)
 - A spacecraft orbits the Earth with an orbital radius of 20 000 km. If the orbital radius were doubled, calculate the expected change in the period of orbit.
 - A geostationary satellite remains above the same position on Earth's surface. Once in orbit, the only force acting on the satellite is that of gravity towards the centre of the Earth. Why doesn't the satellite fall straight back down to Earth?
 - In a space shuttle that is in orbit around Earth at an altitude of 360 km, what is the magnitude of:
 - the gravitational field strength
 - the normal force by the shuttle on a 70.0 kg astronaut
 - the gravitational force by the Earth on this astronaut?
 - An astronaut is living on the International Space Station. When the astronaut sits down, he needs to strap himself in so that he does not float away. Why does he need to do this?

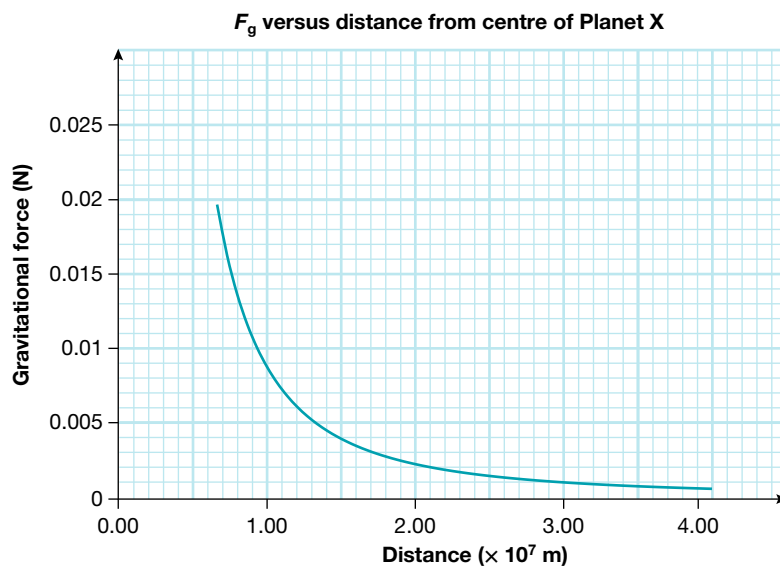


9. The following graph shows how the gravitational field strength, g , varies with distance from the centre of the Moon. An artificial satellite of mass 150 kg orbits the Moon at a distance of 2.0×10^6 m.



What is the change in the satellite's potential energy if it is moved to a new orbit with a radius of 3.0×10^6 m?

10. A particular space probe is in orbit at a distance of 10 000 km from Planet X.



The orbit is increased to 20 000 km from Planet X.

- How much kinetic energy does the space probe have in its new orbit?
 - How much energy is needed to move the probe from its original orbit at 10 000 km to its new orbit at 20 000 km?
11. Calculate the change in kinetic energy of a 25 kg object dropped from 10 metres above the surface of the Moon. (mass of the Moon = 7.35×10^{22} kg; radius of the Moon = 1.74×10^6 m)

2.4 Exercise 3: Exam practice questions

Question 1 (3 marks)

A 300 kg terrestrial satellite has a circular orbit 10 000 km above the surface of the Earth.

- a. Calculate the gravitational force experienced by the satellite. **1 mark**
- b. A second satellite is launched, and it takes twice as long to orbit the Earth. How much larger is the orbital radius of the second satellite? **2 marks**

Question 2 (4 marks)

Miranda, a moon of Uranus, has a circular orbit. The following table shows some data for Miranda and Uranus:

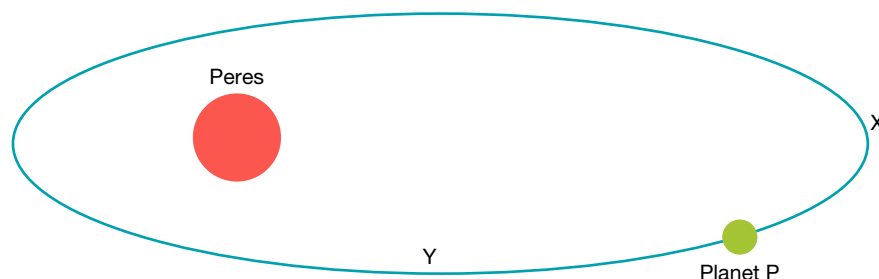
Object	Mass (kg)	Radius (km)	Orbital radius (km)
Uranus	8.68×10^{25}	25 362	
Miranda	66.0×10^{18}		129 390

Assume that Uranus is spherical.

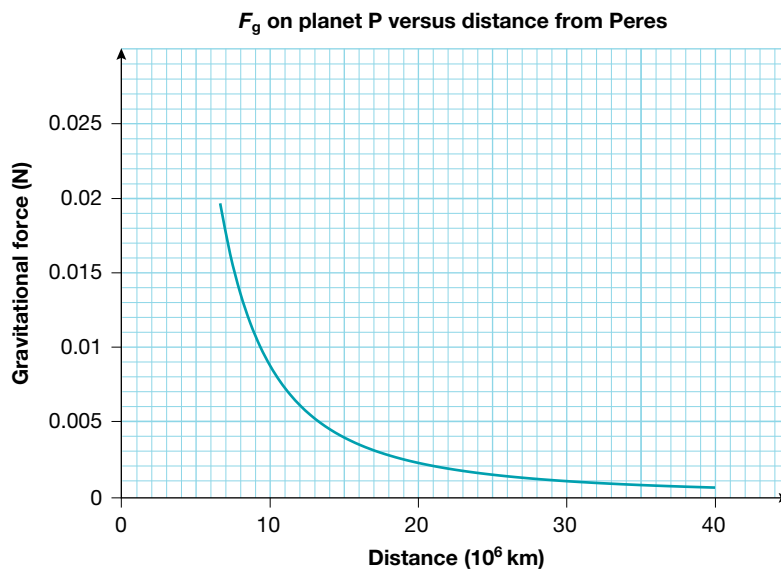
- a. Calculate the gravitational field strength at the surface of Uranus. **1 mark**
- b. Calculate the orbital period of Miranda. **3 marks**

Question 3 (3 marks)

Planet P in a distant solar system is observed moving in an elliptical orbit around the central star, Peres.

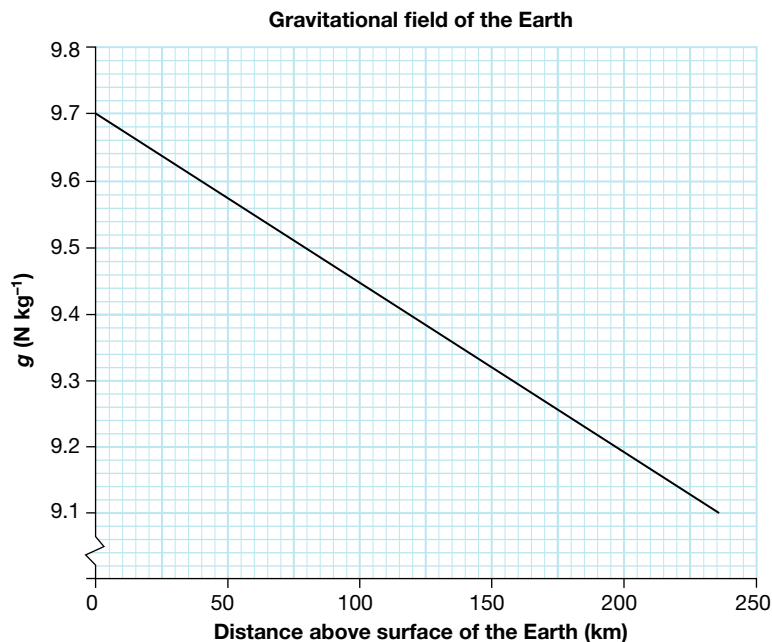


The gravitational force experienced by the planet is shown in the following graph. Calculate the change in kinetic energy as the planet moves from the point X, 30×10^6 km from the Peres, to point Y, 10×10^6 km from Peres.



Question 4 (3 marks)

A 1.5 kg weather balloon is placed 50 km above the surface of the Earth. Use the following graph to calculate the energy required to move the balloon from the Earth's surface to its new position.



Question 5 (5 marks)

An astronaut is aboard a mission that is currently in a circular orbit around Jupiter with a radius of 100 000 km and a period of 4.9 hours.

- a. Calculate the orbital speed of the astronaut. **1 mark**
- b. Use the provided data to estimate the mass of Jupiter. **2 marks**
- c. The astronaut sits down to eat dinner. Explain the value of the normal force experienced by the seated astronaut. **2 marks**

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3 Electric and magnetic fields (effects and applications)

3.1 Overview

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3.1.1 Introduction

Different types of electric fields, magnetic fields and forces were studied in topic 1. Knowledge of the forces acting on charged and magnetic objects allows us to determine how the objects will move and what energy transfers will occur. The operation of the DC motor relies upon the force exerted on a current-carrying wire in a magnetic field. The electron gun, a key component in the production of X-rays, accelerates electrons by employing an electric field between two oppositely charged plates. The mass spectrometer, an important tool in chemical analysis, uses both electric and magnetic fields to make a device that can determine the isotopic composition of a sample.

FIGURE 3.1 Cloud chambers reveal the paths of charged particles produced in radioactive decay. A combination of magnetic and electric fields allows the tracks to be linked to particles with particular charge, mass and velocity, giving clues to the identity of the products.



Source: physicsopenlab.org

3.1.2 What you will learn

KEY KNOWLEDGE

After completing this topic, you will be able to:

- analyse the use of an electric field to accelerate a charge, including:
 - potential energy changes in a uniform electric field: $W = qV$, $E = \frac{V}{d}$
 - the magnitude of the force on a charged particle due to a uniform electric field: $F = qE$.
 - investigate theoretically and practically electric fields about a point charge (positive or negative) with reference to:
 - potential energy changes (qualitative) associated with a point charge moving in the field
- analyse the use of a magnetic field to change the path of a charged particle, including:
 - the magnitude and direction of the force applied to an electron beam by a magnetic field: $F = qvB$, in cases where the directions of v and B are perpendicular or parallel
 - the radius of the path followed by a low-velocity electron in a uniform magnetic field: $qvB = \frac{mv^2}{r}$.
- describe the interaction of two fields, allowing that electric charges, magnetic poles and current-carrying conductors can either attract or repel, whereas masses only attract each other
- investigate and analyse theoretically the force on a current-carrying conductor due to an external magnetic field, $F = nI\ell B$, where the directions of I and B are either perpendicular or parallel to each other
- investigate and analyse theoretically and practically the operation of simple DC motors consisting of one coil, containing a number of loops of wire, which is free to rotate about an axis in a uniform magnetic field and including the use of a split ring commutator
- model the acceleration of particles in a particle accelerator (limited to linear acceleration by a uniform electric field and direction change by a uniform magnetic field).

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PRACTICAL WORK AND INVESTIGATIONS

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

on Resources

 **Digital documents** Key science skills — VCE Physics Units 1–4 (doc-32112)

Key terms glossary (doc-32250)

Practical investigation logbook (doc-32251)

studyon

To access key concept summaries and past VCAA exam questions download and print the **studyON: Revision and past VCAA exam question booklet** (sonr-0052).

3.2 Motion of a charged particle in a uniform electric field

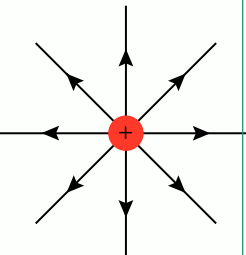
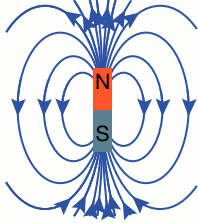
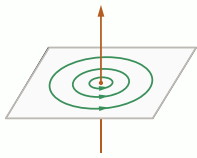
KEY CONCEPTS

- Analyse the use of an electric field to accelerate a charge, including:
 - potential energy changes in a uniform electric field: $W = qV$, $E = \frac{V}{d}$
 - the magnitude of the force on a charged particle due to a uniform electric field: $F = qE$.
 - investigate theoretically and practically electric fields about a point charge (positive or negative) with reference to:
 - potential energy changes (qualitative) associated with a point charge moving in the field
- Model the acceleration of particles in a particle accelerator (limited to linear acceleration by a uniform electric field and direction change by a uniform magnetic field).

A REVIEW OF VECTOR FIELDS

This topic is about electric and magnetic fields, but these fields have similarities to gravitational fields (with which you are quite familiar) and so these will be used for comparison. Each of these vector fields can exert a force within a certain space and each has a field vector that indicates the strength and direction of the field at given points. Recall that vector fields can be drawn using lines of force and vectors can be represented using either a bold typeface or a right-facing arrow (when bold is not appropriate to distinguish the vector). The direction of a line of force indicates the direction of the field, and the spacing of the lines indicates the strength of the field. The following table briefly compares these three vector fields.

TABLE 3.1 Summary of gravitational, electric and magnetic fields

	Gravitational field	Electric field	Magnetic field	
Surrounds	a mass	a charge	(i) a magnet	(ii) a moving charge
Diagram				
Affects	other masses	other charges	other magnetic materials and/or moving charges	
Field strength symbol and units	g N kg^{-1} (or m s^{-2})	E N C^{-1} (or V m^{-1})	B T (or N mA^{-1})	
Magnitude of field from a point source	$g = G \frac{M}{r^2}$	$E = \frac{kq}{r^2}$	A magnetic north or south pole cannot be isolated to make a point source (monopole). Calculating the magnetic field strength due to a bar magnet or current-carrying wire is beyond the scope of this course.	

(continued)

TABLE 3.1 Summary of gravitational, electric and magnetic fields (*continued*)

	Gravitational field	Electric field	Magnetic field	
Direction of the field is defined by	the direction of the force on a test mass placed in the field.	the direction of the force on a positive test charge placed in the field.	the direction of the orientation of the north pole of a compass placed in the field.	
Force in the field	A mass m placed in the field experiences a force $m\mathbf{g}$ in the direction of $\mathbf{g}$.	A charge q placed in the field experiences a force $q\mathbf{E}$ in the direction of $\mathbf{E}$.	The quantitative force on a magnet by a magnetic field $\mathbf{B}$ is beyond the scope of this course.	The force on a moving charge in the presence of a magnetic field $\mathbf{B}$ is $q\mathbf{v}\mathbf{B}$ and the force on a current-carrying wire in the presence of a magnetic field $\mathbf{B}$ is $n\mathbf{l}\mathbf{B}$.
Polarity of the field	Unipolar	Positive or negative monopoles. A dipole field is the field from a separated positive and negative charge.	The north or south pole cannot be isolated to create a magnetic monopole.	
A uniform field exists	on the Earth's surface.	between two oppositely charged parallel conducting plates.	between the poles of a large horseshoe magnet.	inside a current carrying coil.
A static field exists	around a mass.	around charges that are not moving.	around magnetised materials.	around a wire carrying a constant current.

In section 1.3.3, it was shown that a pair of oppositely charged conducting plates has a uniform **electric field** between the plates. That is, if positive and negative charges were lined up in two rows facing each other, the lines of electric field in the space between the rows would be evenly spaced; the value of the strength of the field would be constant. See figures 3.2 and 3.3.

FIGURE 3.2 A uniform electric field

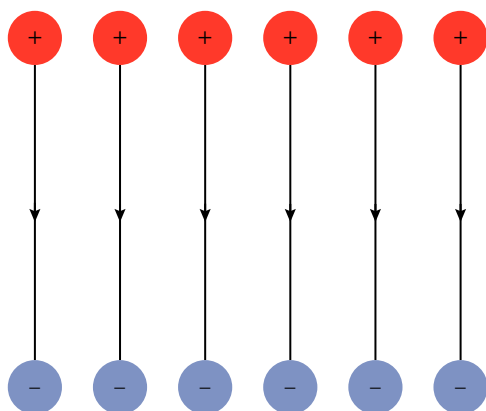
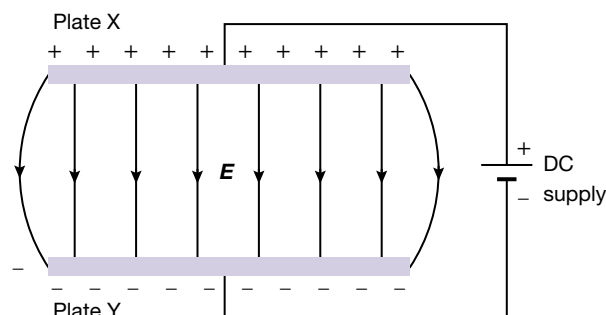


FIGURE 3.3 An electric field between two plates



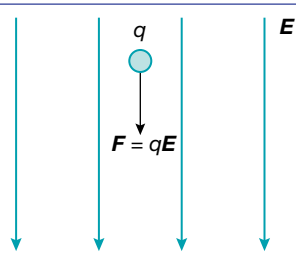
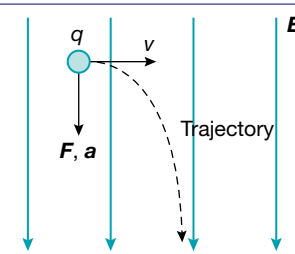
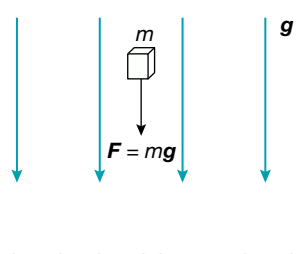
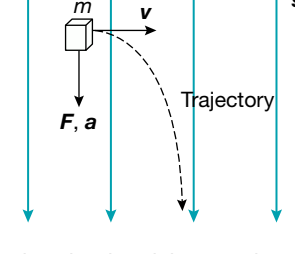
The force F on a charged particle with charge q placed between the plates is given by:

$$\vec{F} = q\vec{E}$$

where: $\vec{F}$ is the force on the charged particle, in N
 q is the charge of the charged particle, in C
 $\vec{E}$ is the strength of the electric field, in N C^{-1}

This relationship holds no matter where the charge is placed between the plates. If there is no other force acting on the charged particle, then the force due to the interaction with the electric field is the net force, and, applying Newton's second law, the particle experiences an acceleration parallel to the field, a , where $a = \frac{F}{m} = \frac{qE}{m}$. This can be observed in table 3.2. It is clear that this motion is very similar to that experienced in gravitational fields.

TABLE 3.2 Comparing trajectories in electric fields to those in gravitational fields

Electric fields	
Charge placed at a point	Charge with velocity
 When a charge q is placed in a uniform electric field, it will experience a force $F = qE$. Therefore, the charge will accelerate uniformly along the field (in the direction that the field lines are facing).	 When a charge q travelling with a velocity v across the field is placed in an electric field, it will have a trajectory motion. This is because its motion has two components: Uniform velocity perpendicular to the field Uniform acceleration parallel to the field (along the field lines).
Gravitational fields	
Mass placed at a point	Mass with velocity
 Similar to the situation involving an electric field, when a mass m is placed in a gravitational field, it will experience a force $F = mg$. Therefore, the mass will accelerate uniformly along the field (in the direction that the field lines are facing).	 Similar to the situation involving an electric field, when a mass m is placed in a gravitational field, it will have a trajectory motion. This is because its motion has two components: Uniform velocity perpendicular to the field Uniform acceleration parallel to the field (along the field lines).

Hence, the motion of a charged particle has two components:

1. uniform velocity perpendicular to the field
2. uniform acceleration parallel to the field.

The combination of these two components produces a parabolic trajectory very similar to that of projectile motion (which is covered in subtopic 6.4).

3.2.1 Energy changes for a charged particle in a uniform electric field

In the situation of an electric field between two plates, it is not easy to apply Coulomb's Law, as there are many charges on each plate interacting with one another. An alternative approach is needed — one that uses the concept of energy.

The EMF of a battery, or its voltage, is the amount of energy that the battery gives to each coulomb of charge. A battery of V volts would use up J joules of energy by transferring one coulomb of electrons from the top plate through the wires to the bottom plate. Once on the negative plate, this coulomb of electrons would have J joules of electrical potential energy.

If this coulomb of electrons could be released from the negative plate, it would be accelerated by the constant force of the electric field between the plates, gaining kinetic energy like a stone falling in a gravitational field. And as in a gravitational field, the gain in kinetic energy ($E_k = \frac{1}{2}mv^2$) equals the loss in electrical potential energy.

- The gain in kinetic energy of one coulomb of charge = J joules.
- The gain in kinetic energy for q coulombs of charge = qJ joules.

Hence the work done on q coulombs of charge is:

$$\Delta E_k = W = qV$$

where: ΔE_k is the change in kinetic energy, in J

W is the work done on q coulombs of charge, in J

q is the quantity of charge, in C

V is the potential difference of the voltage drop, in V

However, the work is done by the electric force on the charge, which can be expressed as:

$$\text{Work done } (W) = \text{force } (F) \times \text{displacement } (s)$$

$$W = Fs$$

The electric force is given by $F = qE$, and the charge is displaced a distance equal to the separation of the plates (rather than displacement), d , so $W = qE \times d$.

Equating the two expressions for work done, $qE \times d = q \times V$.

Cancelling the charge, q , gives:

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

where: E is the electric field strength, in V m^{-1}

V is the electric potential difference, in V

d is the distance between two points in the electric field, in m

This provides an alternative unit for electric field of volts per metre or V m^{-1} . So, like gravitational field strength, electric field strength has two equivalent units: either newtons per coulomb (N C^{-1}) or volts per metre. Using volts per metre makes it very easy to determine the strength of a uniform electric field.

SAMPLE PROBLEM 1

What is the strength of the electric field between two plates 5.0 cm apart connected to a 100 V DC supply?

THINK

Recall the formula for the electric field between two parallel plates with a potential difference V across the plates:

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

where $V = 100 \text{ V}$ and $d = 5.0 \text{ cm} = 0.05 \text{ m}$.

 **Teacher-led video:** SP1 (tlvd-0129)

WRITE

$$\begin{aligned} E &= \frac{V}{d} \\ &= \frac{100}{0.05} \\ &= 2000 \text{ V m}^{-1} \end{aligned}$$

PRACTICE PROBLEM 1

Calculate the strength of the electric field between a storm cloud 1.5 km above ground and the ground itself if the electric potential difference is 30 000 000 V. Assume a uniform field.

3.2.2 The linear accelerator

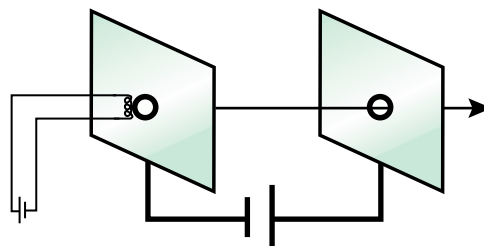
An electric field can be used to increase the speed and kinetic energy of charged particles. This principle is the basis of a **linear particle accelerator**. This occurs in devices such as mass spectrometers, synchrotrons, electron microscopes and Hadron colliders. These devices use both electric and magnetic fields, and are explored further in subtopic 3.5.

The first component of all these devices is an electron gun, a device that is designed to produce electrons and then give them an initial acceleration.

Figure 3.4 shows two metal plates with a small hole cut in the middle of each plate. The plates have been connected to a DC power supply. In the hole of the negative plate is a filament of wire, like the filament in an incandescent light globe, connected to a low voltage. When the current flows in this circuit, the filament glows red hot. The electrons are, in a sense, 'boiling at the surface' of the filament. The electric field can easily pull the electrons off the surface of the filament.

The hole in the positive plate is in a direct line with the filament, so as the electrons are accelerated across the space between the plates, they go straight through the hole to the next part of the machine. This design is called an electron gun. It produces the electrons required for many devices, such as for a synchrotron.

FIGURE 3.4 The electrons on the hot filament are attracted across to the positive plate and pass through the hole that is in line with the beam.



SAMPLE PROBLEM 2

An electron is accelerated from one plate to another. The electrical potential difference between the plates is 100 V.

- How much energy does the electron gain as it moves from the negative plate to the positive plate?
- How fast will the electron be travelling when it hits the positive plate, if it left the negative plate with a speed of 0 m s^{-1} ?

mass of electron = $9.1 \times 10^{-31} \text{ kg}$; charge on electron = $1.6 \times 10^{-19} \text{ C}$.

 **Teacher-led video:** SP2 (tlvd-0130)

THINK

- a. The change in kinetic energy can be found by the work done by the electric field:

$$\Delta E_k = W = qV$$

Where $q = 1.6 \times 10^{-19} \text{ C}$ and $V = 100 \text{ V}$.

- b. The electron began with a speed of 0 m s^{-1} , so the final speed can be found from the final kinetic energy, $E_k = \frac{1}{2}mv^2$.

WRITE

$$\begin{aligned} \text{a. } \Delta E_k &= qV \\ &= 1.6 \times 10^{-19} \times 100 \\ &= 1.6 \times 10^{-17} \text{ J} \end{aligned}$$

$$\begin{aligned} \text{b. } E_k &= \frac{1}{2}mv^2 \\ 1.6 \times 10^{-17} &= \frac{1}{2} \times 9.1 \times 10^{-31} \times v^2 \end{aligned}$$

$$\begin{aligned} v &= \sqrt{\frac{2 \times 1.6 \times 10^{-17}}{9.1 \times 10^{-31}}} \\ &= 5.9 \times 10^6 \text{ m s}^{-1} \end{aligned}$$

Note that the final speed of the electron is about 2% of the speed of light!

PRACTICE PROBLEM 2

Repeat the calculation in sample problem 2 for an electrical potential difference across the plates of 1000 V.

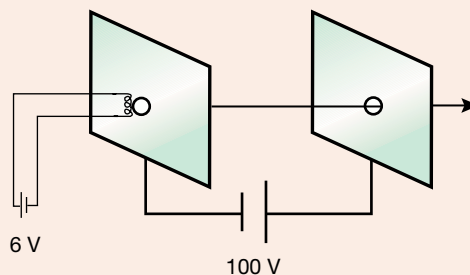
3.2 EXERCISE

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

- The electric field strength between two oppositely charged conducting plates is 15.0 N C^{-1} . If the electrical potential difference across the plates is 100 V, find the separation of the plates.
- Two metal plates, X and Y, are set up 20 cm apart. The X plate is connected to the positive terminal of a 120 V battery and the Y plate is connected to the negative terminal. A small positively charged sphere is midway between the plates and it experiences a force of $4.0 \times 10^{-3} \text{ N}$.
 - What would be the size of the force on the sphere if it was placed 7.5 cm from plate X?
 - The sphere is placed back in the middle and the plates are moved apart to a separation of 15 cm. What is the size of the force now?
 - The plates are returned to a separation of 20 cm but the battery is changed. The force is now $6.0 \times 10^{-3} \text{ N}$. What is the voltage of the new battery?
- The electric field strength between two oppositely charged conducting plates 15 mm apart is 200 N C^{-1} . Calculate the work done by the field on a $2.0 \times 10^{-9} \text{ C}$ charge as it moves from one plate to the other.
- A 10 nC charge travels 1.0 cm parallel to a 300 N C^{-1} electric field. Calculate the change in potential energy of the 10 nC charge.
- John finds that, in dry weather, the rubbing of his clothes when walking causes static electricity to build up. When he goes to touch a metal door handle, he observes a brief spark and feels a small, sharp shock. The discharging occurs when the electric field strength between himself and the door handle exceeds $3.0 \times 10^6 \text{ V m}^{-1}$. His finger is 5.0 mm from the door handle when the discharge occurs. Calculate the electrical potential difference between himself and the door handle.
- Two oppositely charged conducting plates have an electrical potential difference of 1000 V. An electron is accelerated from the negative plate to the positive plate.
 - Determine the electrical potential energy of the electron at the following points:
 - when the electron is at the negative plate
 - when the electron is halfway between the plates
 - when the electron arrives at the positive plate.
 - Determine the change in kinetic energy of the electron at the following points:
 - when the electron is halfway between the plates
 - when the electron is at the positive plate.

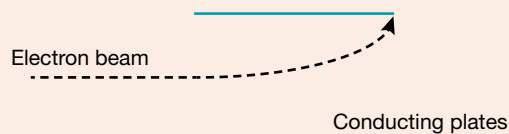
7. Jacinta applies a uniform electric field to slow down over-energetic electrons. She wants to reduce the kinetic energy of the electrons from 1000 eV to 100 eV as they pass between a pair of parallel plates. The spacing of the plates is 1.0 cm. How large is the electric field between the plates?

8. Electrons from a hot filament are emitted into the space between two parallel plates, as shown in the following diagram, and are accelerated across the space between them.



- Which battery supplies the field to accelerate the electrons?
- How much energy would be gained by an electron in crossing the space between the plates?
- How would your answer to (b) change if the plate separation was halved?
- How would your answer to (b) change if the terminals of the 6 V battery were reversed?
- How would your answer to (b) change if the terminals of the 100 V battery were reversed?
- How would the size of the electric field between the plates, and thus the electric force on the electron, change if the plate separation was halved?
- Explain how your answers to (c) and (f) are connected.

9. In a cathode ray oscilloscope, an electron beam passes between a pair of conducting plates that can deflect the beam in a vertical direction, as shown in the following diagram.



The beam is observed to be deflected vertically upwards by 5.0 mm during the 2.0 μs that it takes an electron to traverse the length of the plates.

- Calculate the magnitude of the average vertical acceleration of the beam.
- Calculate the magnitude and direction of the electric field between the plates.
- Calculate the potential difference between the plates.
- Is the upper or lower plate at a higher electrical potential?

studyon

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Fully worked solutions and sample responses are available in your digital formats.

3.3 Motion of a charged particle in a magnetic field

KEY CONCEPTS

- Analyse the use of a magnetic field to change the path of a charged particle, including:
 - the magnitude and direction of the force applied to an electron beam by a magnetic field: $F = qvB$, in cases where the directions of $\mathbf{v}$ and $\mathbf{B}$ are perpendicular or parallel
 - the radius of the path followed by a low-velocity electron in a uniform magnetic field: $qvB = \frac{mv^2}{r}$.

Topic 1 showed that moving charges produce magnetic fields. So, can moving charges be affected by other **magnetic fields**? The answer is yes!

Velocity perpendicular to the field

The motion of a charged particle in a magnetic field is particularly interesting. It turns out that the magnetic field applies a force to the charged particle that is *both* at right angles to the motion of the charge and the direction of the magnetic field. This behaviour was initially identified by J.J. Thomson in the late 1800s; however, it was Hendrik Lorentz in 1895 who published a paper identifying the correct form of the force.

The magnitude of the magnetic force of a moving particle for a charge, q , moving with a velocity, v , perpendicular to a magnetic field, B , is:

$$F = qvB$$

where: F is the magnitude of the force on the particle, in N

q is the charge of the particle, in C

v is the component of the velocity of the particle that is perpendicular to the magnetic field, in m s^{-1}

B is the strength of the magnetic field, in T

The direction of the force on the charged particle, which is perpendicular to both the particle velocity and the magnetic field, can be determined using a helpful hand rule. There are two alternative hand rules commonly used. The rule applies both to moving single positive charges and to currents. Both of these rules will give you the same result for the direction of the force, so you can choose the one which works best for you. It is important to note that both the right and left-hand rules apply to a positive charge and positive current. If the particle has a negative charge, or the direction of the current is reversed, then the direction of the force on the particle or current is reversed.

Left-hand rule

The **left-hand rule** applies as follows:

- the index finger, pointing straight ahead, represents the magnetic field (B)
- the middle finger, at right angles to the index finger, represents the current (I) or particle velocity (v)
- the thumb, upright at right angles to both fingers, represents the force (F).

Lock the three fingers in place so they are at right angles to one another. Now rotate your hand so that the field and current (or particle velocity) line up with the directions in your problem. The thumb will now point in the direction of the force.

FIGURE 3.5 Left-hand rule for determining the direction of the magnetic force of a magnetic field on a current or moving positive charge

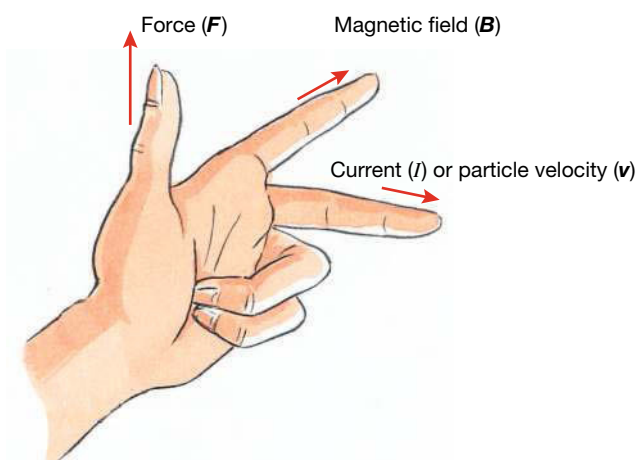
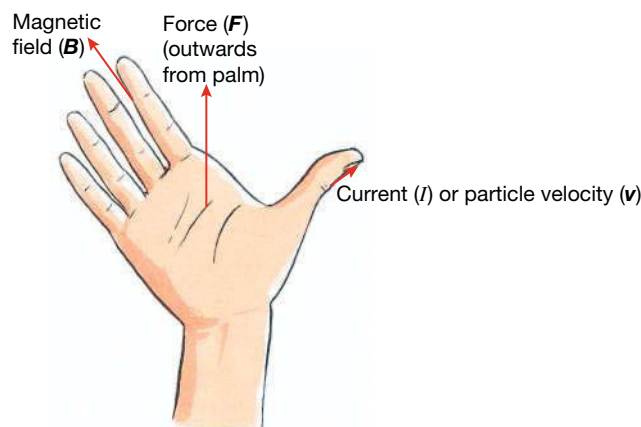


FIGURE 3.6 Right-hand-slap rule for determining the direction of the magnetic force of a magnetic field on a current or moving positive charge



Right-hand-slap rule

The **right-hand-slap rule** applies as follows:

- the fingers (out straight) represent the magnetic field (B)
- the thumb (out to the side of the hand) represents the current (I) or particle velocity (v)
- the palm of the hand represents the force (F).

Hold your hand flat with the fingers outstretched and the thumb out to the side, at right angles to your fingers. Now rotate your hand so that the field and current or particle velocity line up with the direction in your problem. The palm of your hand now gives the direction of the force, hence the name.

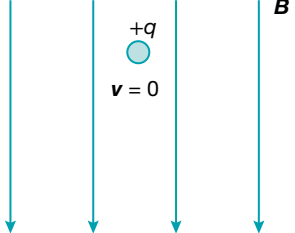
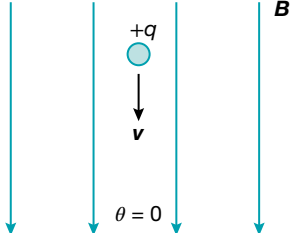
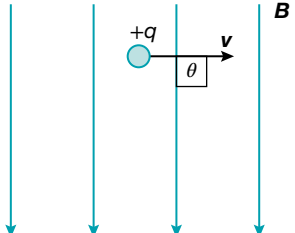
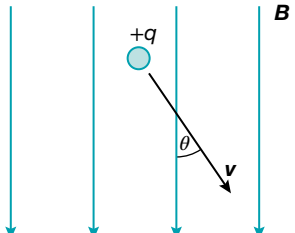
Velocity parallel to the field

What about when the velocity is moving parallel to a magnetic field? When the particle's velocity is parallel to the magnetic field, the magnetic force (F) is zero. Therefore, as there is no net force, the particle continues to move in a straight line and the velocity will remain constant.

We can consider a magnetic field that is moving out of the page. If we had an electron moving either out of or into the the page, this velocity would be parallel to the field. Therefore there is no force on the electron and it will not change its motion.

These different forces can be summarised in table 3.3:

TABLE 3.3 Summarising the effect of different velocities

	If velocity is equal to 0, $F = q\mathbf{v}\mathbf{B}$ is equal to 0. Therefore the motionless charged particles in a magnetic field experience no force.
	If the velocity is parallel to the field lines, charged particles in a magnetic field experience no force and will continue moving at the same velocity.
	If velocity is perpendicular to the field lines (90°), then there will be a force, the direction of which can be determined by the left-hand or right-hand-slap rule. This allows for the magnetic force to be at its maximal value.
	If velocity is at an angle between 0 and 90°, there will be a force that will be greater than 0 N, but less than the force if the velocity was perpendicular to the magnetic field.

SAMPLE PROBLEM 3

An electron moving towards the right of the page at $1.5 \times 10^5 \text{ m s}^{-1}$ enters a uniform 0.060 T magnetic field that is coming out of the page.

- Calculate the magnitude of the magnetic force on the electron.
- Determine the direction of the force on the electron.

 **Teacher-led video:** SP3 (tlvd-0131)

THINK

- Recall the formula $F = qvB$, where $q = -1.6 \times 10^{-19} \text{ C}$, $v = 1.5 \times 10^5 \text{ m s}^{-1}$ and $B = 0.060 \text{ T}$ (as we are being asked only for magnitude of force here, vector notation is not required for F).
- Apply the right-hand-slap rule and reverse the direction of the current, as the electron has a negative charge. The electron moves to the right of the page, so the conventional current flows to the left of the page.

WRITE

- $F = qvB$
 $= -1.6 \times 10^{-19} \times 1.5 \times 10^5 \times 0.060$
 $= 1.4 \times 10^{-15} \text{ N}$
- v is to the left and will be along the thumb.
 - B is out of the page and follows the direction of the fingers.
 - The force on the electron is in the direction of the palm, namely pointing up the page.

PRACTICE PROBLEM 3

An alpha particle (charge $+2e$) moving towards the right of the page at $1.0 \times 10^7 \text{ m s}^{-1}$ enters a uniform 0.060 T magnetic field pointing down the page.

- Calculate the magnitude of the magnetic force on the alpha particle.
- Determine the direction of the force.
- Calculate the magnitude of the magnetic field on a positron (charge $+e$) moving up the page at $3.0 \times 10^7 \text{ m s}^{-1}$ in the same magnetic field.



Resources



Digital document Hand-rules (doc-18541)

3.3.1 Circular motion of charged particles in magnetic fields

Previously shown was the situation where the net force on a particle is perpendicular to the velocity of the particle. This is the case when a satellite orbits a large body, such as the Earth. Topic 2 showed that the effect of the net force constantly pointing towards the centre of the orbit causes the satellite to follow a circular path around the Earth. For charged particles moving in a magnetic field, the force on the particle due to the magnetic field causes it to change the direction of its motion so that it moves in a circular path perpendicular to the direction of the field.

The magnitude of the force on the moving charged particle due to the magnetic field is $F = qvB$. The magnetic force is always at right angles to the direction of the charge's motion; therefore, the magnetic force cannot increase the speed on the charge — it can only change its direction at a constant rate.

The mass spectrometer, the electron microscope and the synchrotron are instruments that use a magnetic force in this manner.

So what is the radius of the circle? How does it depend on the strength of the magnetic field, the speed of the charge and size of the charge?

TABLE 3.4 Observations concerning the strength of magnetic fields, and speed and size of the charge

What is observed?	What does the formula predict?	Do the observations match the formula's prediction?
If the charge is stationary, the current is zero, so there is no force.	If $v = 0$, then $F = 0$.	Yes
A stronger magnetic field will produce a larger force and deflect the charge more.	Force is proportional to the field.	Yes

The net force on the charged particle as it moves in the magnetic field is $F_{\text{net}} = ma$. In this case the only significant force is the magnetic force:

$$F = qvB$$

$$\Rightarrow qvB = ma$$

Because the acceleration is centripetal and constant in magnitude, its magnitude can be expressed as $a = \frac{v^2}{r}$, where r is the radius of the circular motion.

$$qvB = \frac{mv^2}{r}$$

where: q is the charge on the particle, in C

v is the speed of the particle, in m s^{-1}

B is the strength of the magnetic field, in T

m is the mass of the particle, in kg

r is the radius of the path followed by the particle, in m

The expression for the radius is therefore:

$$r = \frac{mv}{Bq}$$

Does this relationship make sense?

TABLE 3.5 Observations concerning the radius of circular motion

What is observed?	What does the formula predict?	Do the observations match the formula's prediction?
Hard to turn heavy objects	The heavier the mass, the larger the radius	Yes
Hard to turn fast objects	The faster the object, the larger the radius	Yes
The larger the force, the smaller the radius	The stronger the field, the smaller the radius; the larger the charge, the smaller the radius	Yes

Note that because the direction of the magnetic field is always at right angles to the direction in which the charged particles are moving, the magnetic field cannot make the particles go faster — it can only change their direction.

SAMPLE PROBLEM 4

An electron travelling at $5.9 \times 10^6 \text{ m s}^{-1}$ enters a magnetic field in a direction perpendicular to its motion with a magnitude of 6.0 mT . What is the radius of its path in the magnetic field?

 Teacher-led videos: SP4 (tlvd-0132)

THINK

Recall the expression for the radius that comes from equating the net force on objects moving in a circle with the magnetic force.

Recall the mass of an electron is $9.1 \times 10^{-31} \text{ kg}$ and the charge of an electron is $1.6 \times 10^{-19} \text{ C}$.

WRITE

$$\begin{aligned} r &= \frac{mv}{qB} \\ &= \frac{9.1 \times 10^{-31} \times 5.9 \times 10^6}{1.6 \times 10^{-19} \times 6.0 \times 10^{-3}} \\ &= 5.6 \times 10^{-3} \text{ m} \end{aligned}$$

PRACTICE PROBLEM 4

Calculate the speed of an electron moving in a 3.0 mT magnetic field in a circle with radius 1.0 mm .

AURORAE

The aurorae at the North Pole and South Pole are glorious displays of waves of coloured light, high in the atmosphere. They are produced when charged particles ejected by the Sun enter Earth's magnetic field.

The particles spiral down to the poles, producing an amazing display of light as they move in smaller and smaller circles from the increasing magnetic field.

FIGURE 3.7 Charged particles entering Earth's magnetic field

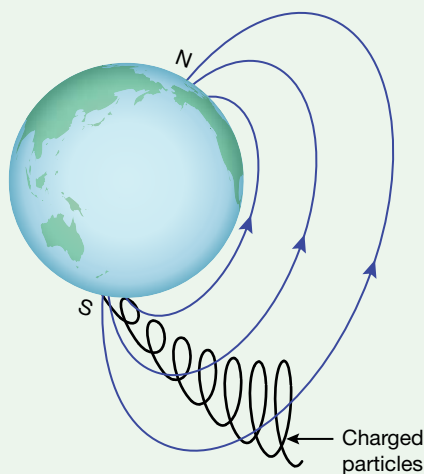


FIGURE 3.8 Aurora Australis, seen from the International Space Station



on Resources

 **Digital document** Investigation 3.1 Electrons in a magnetic field (doc-31591)

 **Interactivity** Electrons in a magnetic field (int-0124)

3.3.2 Controlling charged particle motion with magnetic fields

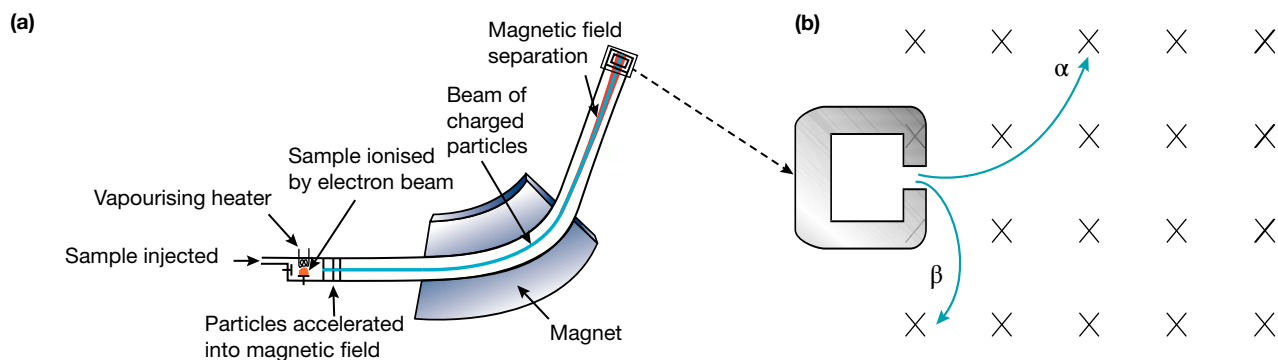
Section 3.2.2 discusses how electric fields are used as linear accelerators in a variety of devices. Magnetic fields can be used to control charged particles in a number of important applications.

The mass spectrometer is able to separate ions with different ratios of mass to charge because, as shown previously, the radius of the trajectory of the ion depends on the ratio of mass to charge. The sample is initially vapourised and ionised, then passed through an accelerating electric field, followed by a magnetic field. The ions are then deflected. The radius of this deflection depends on the mass to charge ratio of the particle being examined. The mass spectrometer is an essential analytical tool for determining the composition of a chemical sample and is often used to determine the mass of various atomic particles, by exploring the radius of their curvature.

FIGURE 3.9 A mass spectrometer

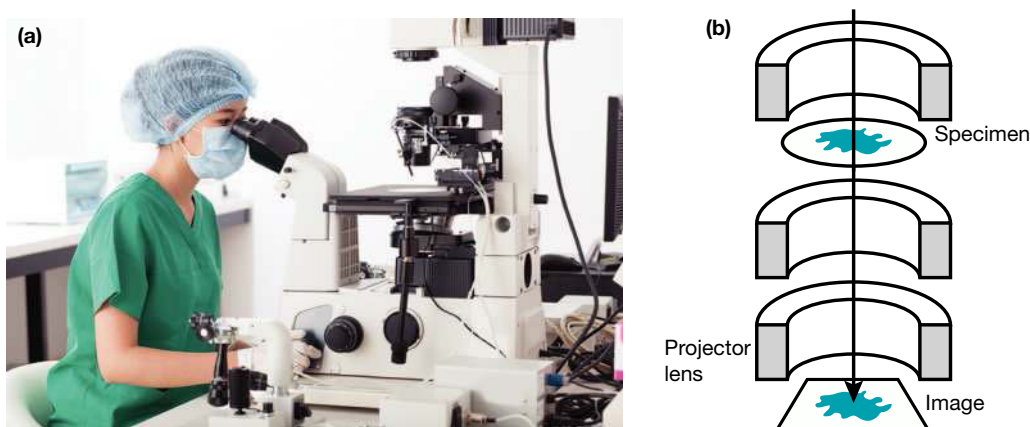


FIGURE 3.10 Mass spectrometers deflect particles based on their mass to charge ratios. When the magnetic field is pointing into the page, positive alpha particles are deflected up and beta particles are deflected down. The section of the magnetic field separation is shown in (a) and zoomed in at (b) to show this deflection.



In the electron microscope, magnetic fields focus the electron beam after it is scattered from a sample, in the same way that optical lenses focus the light scattered from a sample under an ordinary microscope.

FIGURE 3.11 Electron microscopes use magnetic fields to focus the electron beam, allowing an image to be observed.



3.3 EXERCISE

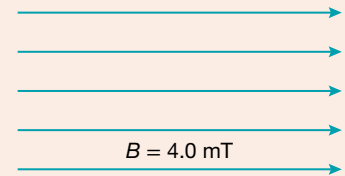
To answer questions online and to receive **immediate feedback** and **sample responses** for every question go to your learnON title at www.jacplus.com.au.

1. A proton travelling vertically at $3.0 \times 10^5 \text{ m s}^{-1}$ enters a uniform horizontal magnetic field with a field strength of 4.0 mT. Calculate the magnitude of the force experienced by the proton.

2. An alpha particle enters a uniform magnetic field of 4.0 mT with a speed of $1.5 \times 10^7 \text{ m s}^{-1}$ as shown in the diagram at right:

$$v = 1.5 \times 10^7 \text{ m s}^{-1}$$

(+2e)



- (a) Calculate the force on the alpha particle.
 (b) Describe the trajectory of the alpha particle as it passes through the magnetic field.
3. An electron travelling east at $1.2 \times 10^5 \text{ m s}^{-1}$ enters a region of uniform magnetic field of strength 2.4 T pointing north.
- (a) Calculate the magnitude of the magnetic force acting on the electron.
 (b) Describe the path taken by the electron, giving a reason for your answer.
 (c) Calculate the magnitude of the acceleration of the electron.

4. In the diagram at right, a tauon enters the magnetic field from the left and executes the trajectory shown.

- (a) Does the tauon carry a positive or negative charge? Give your reasons for your choice.
 (b) The tauon exits the magnetic field at the point shown. Describe its trajectory after it leaves the field.

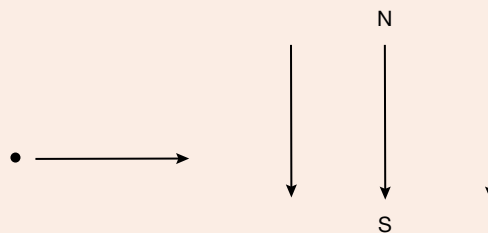


5. Determine the direction of the magnetic force in the following situations, using your preferred hand rule. Use the following terminology in your answers: up the page, down the page, left, right, into the page, out of the page.

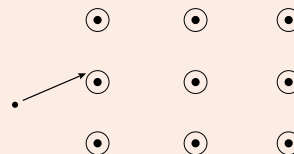
- (a) Magnetic field into the page, electron entering from left



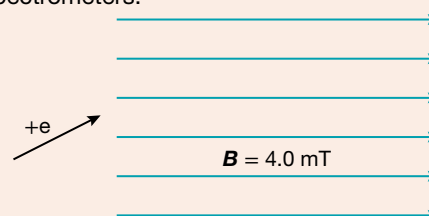
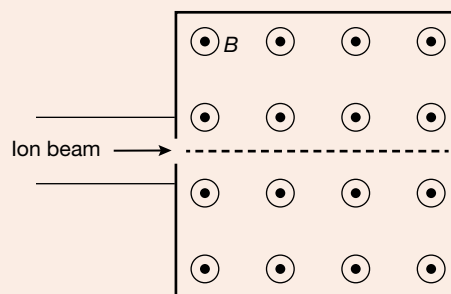
- (b) Magnetic field down the page, electron entering from left



- (c) Magnetic field out of the page, proton entering obliquely from left



6. How could a moving electron remain undeflected in a magnetic field?
7. An ion beam consisting of three different types of charged particles is directed eastwards into a region having a uniform magnetic field, B , directed out of the page. The particles making up the beam are (i) an electron, (ii) a proton and (iii) a helium nucleus or alpha particle. Copy the diagram at right and draw the paths that the electron, proton and helium nucleus could take.
8. Calculate the radius of curvature of the following particles travelling at 10% of the speed of light in a magnetic field of 4.0 T.
 - (a) an electron
 - (b) a proton
 - (c) a helium nucleus.
9. Explain how magnetic fields are used in the functioning of mass spectrometers.
10. A positron enters the magnetic field shown at right, with a velocity in the direction indicated. Describe the trajectory of the positron as it traverses the magnetic field.



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3.4 Forces on current-carrying wires in a magnetic field

KEY CONCEPTS

- Investigate and analyse theoretically the force on a current-carrying conductor due to an external magnetic field, $F = nI\ell B$, where the directions of I and B are either perpendicular or parallel to each other
- Investigate and analyse theoretically and practically the operation of simple DC motors consisting of one coil, containing a number of loops of wire, which is free to rotate about an axis in a uniform magnetic field and including the use of a split ring commutator.

Once the technology of electromagnets (which are introduced in topic 1) was developed, very strong magnetic fields could be achieved. This enabled the reverse of Oersted's discovery to be investigated: what is the effect of a magnetic field on a current in a wire?

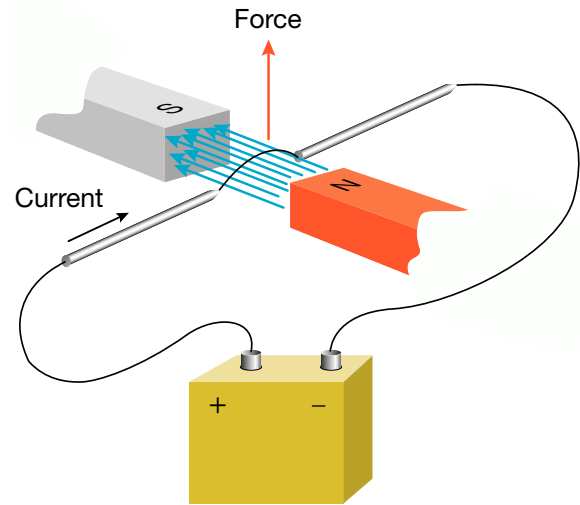
In Oersted's experiment, the magnetic field due to the current exerts a force on the magnetic field of the compass. So, according to Newton's Third Law of Motion, the compass exerts an equal and opposite force on the current. What is the size of this force and in what direction does it act?

Observations of the magnetic force applied to the current-carrying wire or conductor show that:

- if the strength of the magnetic field increases, there is a larger force on the wire
- if the magnetic field acts on a larger current in the wire, there is a larger force
- if the magnetic field acts on a longer wire, there is a larger force
- it is only the component of the magnetic field that is perpendicular to the current that causes the force
- if there are more wires in the magnetic field, there is a larger force.

Combined, these findings can be expressed as:

FIGURE 3.12 The magnetic field exerts a magnetic force on a current-carrying wire.



$$\vec{F} = nI\vec{B}$$

where: $\vec{F}$ is the force on the conductor perpendicular to the magnetic field, in N

n is the number conductors (or loops)

I is the current in the conductor, in A

l is the length of the conductor, in m

$\vec{B}$ is the component of the magnetic field that is perpendicular to the current, in T

When the magnetic field is perpendicular to the direction of the current in a single wire, the magnitude of the force is given by:

$$F = IlB$$

When the magnetic field is not perpendicular to the direction of the current, it is important to remember that the force on the wire is less. In fact, if the magnetic field is parallel to the direction of the current, the force on the wire is zero. That is because the component of magnetic field perpendicular to the current is zero.

The same result can also be obtained starting from Lorentz's expression for the magnetic force on a charged particle.

The current, I , is the motion of charges along a length of wire, l . If a charge q travels a distance l in a time Δt , then the velocity of the charge is $v = \frac{l}{\Delta t}$. Rewriting the force in terms of the current and length of wire, the following is obtained:

$$F = qvB = q \frac{l}{\Delta t} B = \frac{q}{\Delta t} l B = IlB$$

SAMPLE PROBLEM 5

If a straight wire of length 8.0 cm carries a current of 300 mA, calculate the magnitude of the force acting on it when it is in a magnetic field of strength 0.25 T if:

- a. the wire is at right angles to the field
- b. the wire is parallel with the field.

 Teacher-led video: SP5 (tlvd-0133)

THINK

- a. Recall that $F = nIlB$ and that B is the component of the field that is perpendicular to the length of the wire, l . Ensure your units are correct. In this case, you need to convert mA to A and cm to m.
- b. The wire is parallel to the field so there is no component of the field perpendicular to the wire.

WRITE

- a. $F = nIlB$
 $= 1 \times 300 \times 10^{-3} \times 0.080 \times 0.25$
 $= 6.0 \times 10^{-3} \text{ N}$
- b. The force on the wire is 0 N.

PRACTICE PROBLEM 5

- a. Calculate the force on a 100 m length of wire carrying a current of 250 A when the strength of Earth's magnetic field at right angles to the wire is $5.00 \times 10^{-5} \text{ T}$.
- b. The force on a 10 cm wire carrying a current of 15 A when placed in a magnetic field perpendicular to B has a maximum value of 3.5 N. What is the strength of the magnetic field?

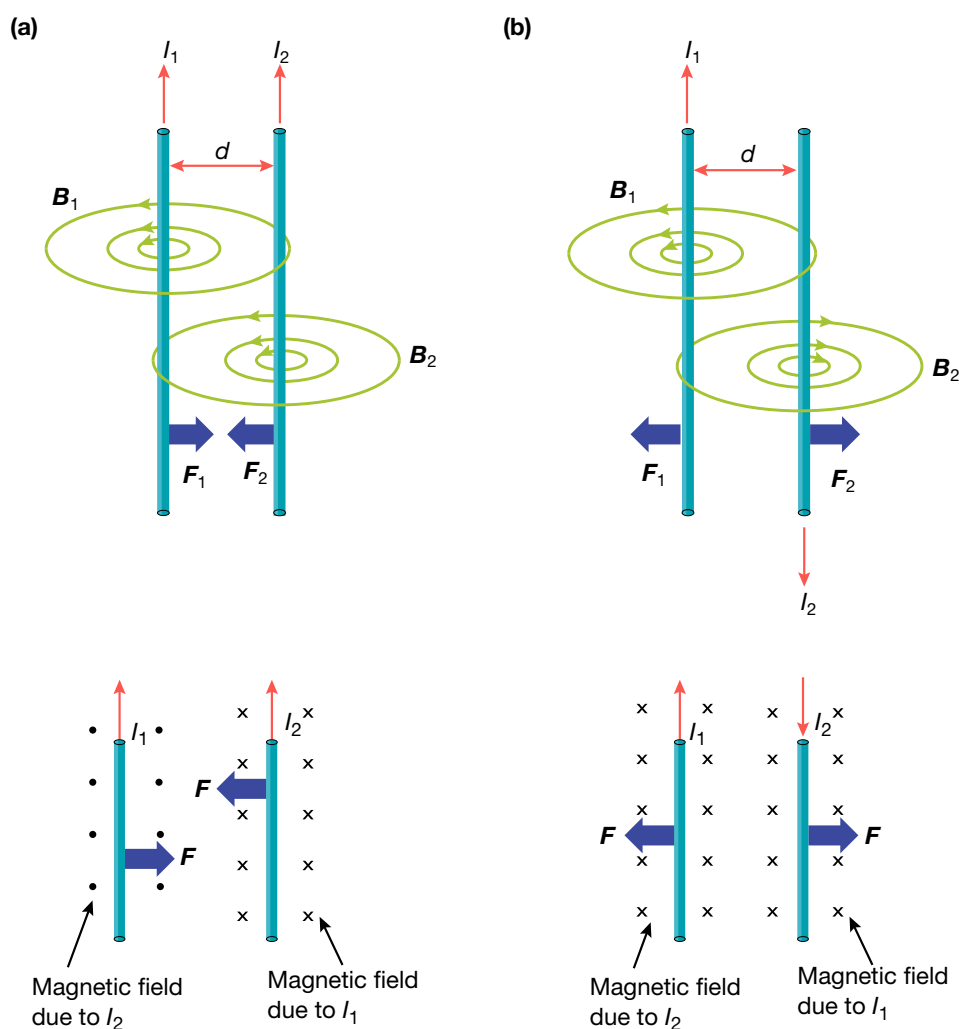
Magnetic fields between parallel wires

Two current-carrying wires each have their own magnetic field, the direction of which is determined using the right-hand grip rule. When these wires are brought together in close proximity and placed parallel to each other, the wires are observed to either repel each other or to be attracted to each other, depending on the direction of current flow in the wire. This can be explained by understanding that each wire experiences a force on the current that it is carrying due to the magnetic field that is being produced by the other wire. If the current in the left-hand wire is up the page, the magnetic field experienced by the right-hand wire is into the page. If the current in the right-hand wire is also up the page, then applying either the left-hand rule or right-hand-slap rule shows that the magnetic force on the right-hand wire is towards the left-hand wire.

Similarly, the magnetic force on the left-hand wire due to the magnetic field from the right-hand wire acting on the current in the left-hand wire is towards the right-hand wire. The two wires attract one another!

If, however, the current in the right-hand wire is down the page, then the right-hand wire experiences a magnetic force away from the left-hand wire and the left-hand wire experiences a magnetic force away from the right-hand wire. Hence, parallel wires carrying currents in opposite directions repel each other. The effects can be observed in figure 3.13.

FIGURE 3.13 Magnetic fields interact between parallel wires, leading to either (a) attraction when the current runs in the same direction or (b) repulsion when the current runs in opposite directions.



on Resources

-  **Digital document** Investigation 3.2 Measuring the force on a current-carrying wire in a magnetic field (doc-31605)
Investigation 3.3 The motor effect (doc-31606)
-  **Teacher-led video** Investigation 3.2 Measuring the force on a current-carrying wire in a magnetic field (tlvd-0242)
-  **Interactivity** Changing magnetic force (int-0115)
-  **Weblink** Lorentz force applet

3.4.1 The DC Motor

An electric motor is a device that transforms electrical potential energy into rotational kinetic energy. A DC motor (a simplified example of which is shown in figure 3.14) uses the current from a battery flowing through a coil in a magnetic field to produce continuous rotation of a shaft. The coil carries a direct current — in figure 3.14, only one loop of wire is shown with straight sides to make it easier to visualise how forces on the sides come about. The coil is usually wound around a frame known as an **armature**, which is made of ferromagnetic material and can rotate on an axle. The armature and coil together are known as the rotor. How do forces allow the coil to rotate?

1. In figure 3.15 when the coil is in position 1 with the coil parallel to the magnetic field and the current flowing $A \rightarrow B \rightarrow C \rightarrow D$, there will be a downward force on side AB and an upward force on side CD, causing the coil to rotate.
2. As the coil rotates, as shown in position 2, the forces remain unchanged in size and direction. This is because the magnetic field and the current in the wire are still the same size and in the same direction. However, their lines of action are closer to the axle, so they have less turning effect.
3. When the coil reaches position 3, at right angles to the magnetic field, the forces are still unchanged in size and direction but, in this case, the lines of action of the forces pass through the axle and have no turning effect.
4. Since the coil was already moving before it arrived at position 3, the momentum of its rotation will carry it beyond position 3 to position 4(a). In this position, the current is still travelling in the same direction $A \rightarrow B \rightarrow C \rightarrow D$, so, in this position, there is still a downward force on side AB and an upward force on side CD acting to rotate the coil in the opposite direction, that is, back to position 3.

FIGURE 3.14 A simplified DC motor

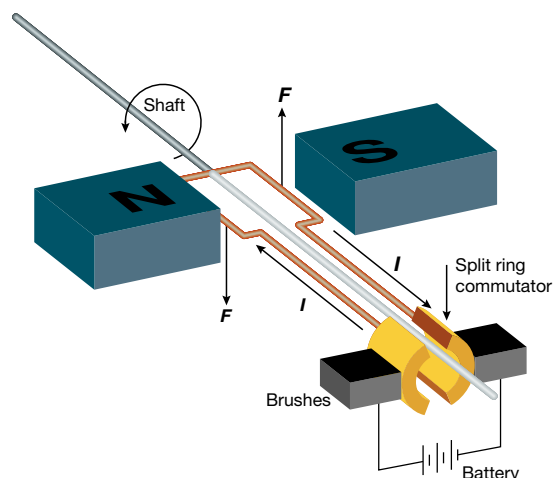
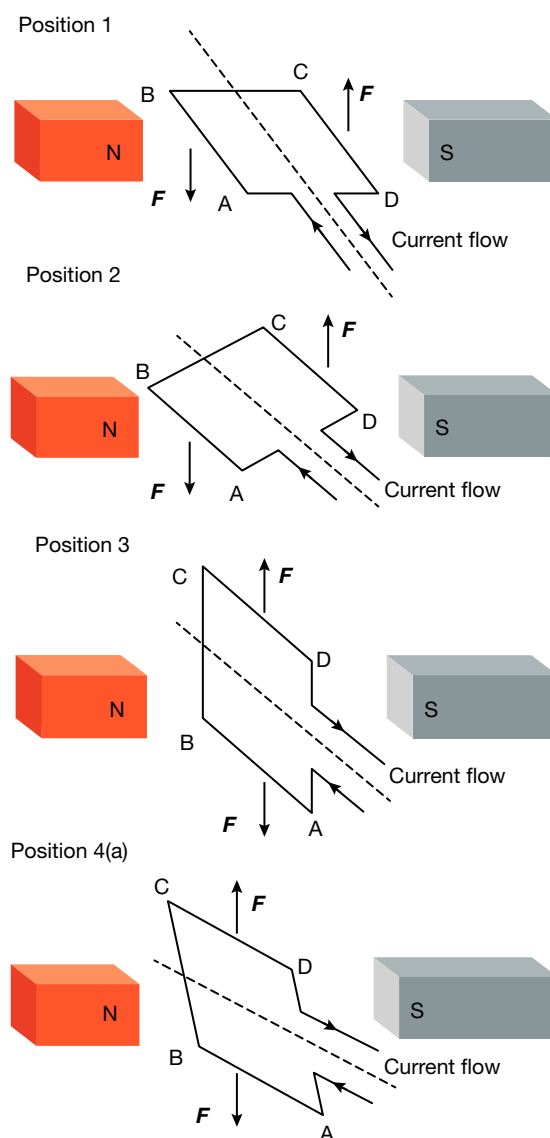


FIGURE 3.15 Force on a coil in a DC motor



If this was the design of a DC motor, the coil would turn 90° and then stop! If the coil was in position 3 when the battery was first connected, the coil would not even move. The starting position of the motor affects how far it will turn before it stops and reaches a position of zero torque (torque will be further discussed in section 3.4.2).

5. So, if the motor is to continue to turn, it needs to be modified when the coil reaches position 3. If the direction of the forces can be reversed at this point, as shown in position 4(b), the forces will make the coil continue to turn for another 180° . The forces need to be reversed again at this point to complete the rotation, and reversed every half turn when the coil is perpendicular to the field. In order to reverse the direction of the forces acting on the coil, the direction of the current through the coil needs to be reversed.

So, to keep the coil continuously rotating in the same direction, the current needs to be reversed twice every rotation when the coil is at right angles to the magnetic field.

This reversal is done with a **split ring commutator**. The commutator consists of two semicircular pieces of metal attached to the axle, with a small insulating space between their ends. The ends of the coil are soldered to these metal pieces.

Wires from the battery are attached to conducting **brushes** that rest against the commutator pieces. As the axle turns, these commutator pieces turn so that they are no longer in contact with the brushes, stopping the flow of electrical current through the coil. As they continue to rotate, they again make contact with the brushes, but are now in contact with the opposite brush, causing current to flow through the coil in the opposite direction. This enables the current through the coil to change direction every time the insulating spaces pass the brushes.

Brushes are often small carbon blocks that allow charge to flow and the axle to turn smoothly. The brushes are often made of graphite, which conducts electricity and acts as a lubricant.

A DC motor is a device used to turn electrical energy into kinetic energy, usually rotational kinetic energy, with the aid of a magnetic field (usually either an electromagnet or a permanent magnet). As an energy transfer device of some industrial significance, there are some important questions to be asked about the design for a DC motor. Are there some starting positions of the coil that won't produce rotation? How can this be overcome? Can it run backwards and forwards? Can it run at different speeds?

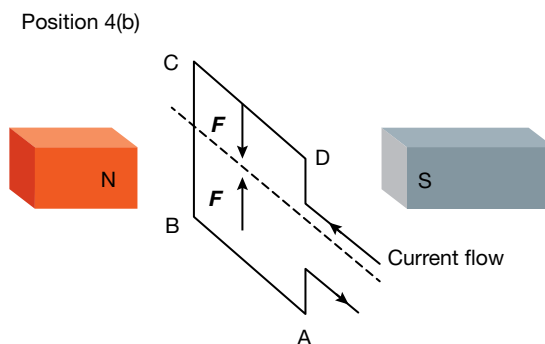


FIGURE 3.16 Commutator and coil from a hair dryer



AS A MATTER OF FACT

The principle of the electric motor was proposed by Michael Faraday in 1821, but a useful commercial motor was not designed until 1873. Direct current (DC) motors were installed in trains in Europe in the 1880s.



Resources



Digital document Investigation 3.4 Designing an electric DC motor (doc-31607)



Teacher-led video Investigation 3.4 Designing an electric DC motor (tlvd-0244)



Weblink DC motor applet

3.4.2 Torque

The turning effect of the forces on the coil in an electric motor is called a **torque**. The magnitude of the torque on a coil is the product of the component of the force perpendicular to the plane of the coil and the perpendicular distance between the point of application of the force and the shaft or axle (the axis of rotation).

$$\vec{\tau} = r_{\perp} \vec{F}$$

where: $\vec{\tau}$ is the torque, in N m (or newton metre)

$r_{\perp}$ is the perpendicular distance between the point of application of the force and the axis of rotation, in m

$\vec{F}$ is the component of the force perpendicular to the axis of rotation, in N

Consider the case of the coil in figure 3.15. The sides of the coil perpendicular to the magnetic field, sides AB and CD, experience a force that is constant in size and magnitude no matter which position they are in; however, only the component of this force that is perpendicular to the plane of the coil contributes to the torque. When the coil is in the vertical position with its plane perpendicular to the field, the force on AB and CD is parallel to the plane of the coil, so the component of the force perpendicular to the plane is zero and hence the torque on the coil is zero. When the coil is parallel to the field, the force acting on AB and CD is perpendicular to the plane of the coil, so the coil experiences maximum torque in this position.

Each of the two sides that are perpendicular to the magnetic field, sides AB and CD, experience a force that contributes to the overall torque on the coil, so the total torque is equal to twice the torque acting on one of these sides.

To summarise this, increasing the maximum torque will increase the speed of a DC motor. This can be achieved by:

- Increasing the force acting on the side (by either increasing the current in the coil, increasing the number of loops in the coil, producing a stronger magnetic field or adding an iron core in the centre of the loop as part of the armature)
- Increasing the width of the coil
- Using multiple coils mounted on the armature.

SAMPLE PROBLEM 6

A student constructs a simple DC motor, exactly like the motor in figure 3.14, with a square loop having side lengths 2.0 cm and a uniform 0.0050 T magnetic field. A current of 1.5 A passes through the coil.

- Calculate the magnitude and direction of the force on the wire in the following sections, referring to figure 3.15 for the positions of these sections:
 - AB
 - BC
 - CD
- Explain why the motor is most easily started when the coil is parallel to the magnetic field.
- Explain why the commutator is essential if the coil is to rotate continuously in one direction.

 Teacher-led video: SP6 (tlvd-0134)

THINK

- a. Recall that the force on a current-carrying wire in a magnetic field is $\mathbf{F} = nI\mathbf{B}$ when the current and magnetic field are perpendicular to each other.
Use the right-hand-slap rule or left-hand rule to find the direction of the force on each side of the wire loop.
- b. Recall that the turning force, or torque, is given by $\tau = r_{\perp}F$.
- c. Review the operation of the commutator.

WRITE

- a. $F = nIB$
- $F = 1 \times 1.5 \times 0.020 \times 0.0050$
 $= 1.5 \times 10^4 \text{ N, down}$
 - $F = 0 \text{ N}$, because I and B are parallel to each other
 - $F = 1 \times 1.5 \times 0.020 \times 0.0050$
 $= 1.5 \times 10^4 \text{ N, up}$
- b. Torque is a maximum when the axis of rotation and the line of action of the force are perpendicular to each other, and the distance between them is at a maximum. This occurs when the coil is parallel to the field.
- c. Without the commutator, after the loop passes through the vertical position, the direction of the forces on the coil would reverse, causing the loop to slow down and then reverse the direction of rotation. Every time the loop passes through the vertical position, the direction of the forces reverse again, causing the loop to slow and reverse the direction of rotation. The loop would just oscillate around the vertical position. The commutator enables the direction of current through the loop to be reversed every time the loop passes through the vertical position, reversing the direction of the forces so that the loop can rotate continuously in the one direction.

PRACTICE PROBLEM 6

The terminals of the battery supplying the motor in sample problem 6 are reversed.

- a. Calculate the magnitude and direction of the force on the wire in the following sections:
- AB
 - BC
 - CD
- b. Explain the differences, if any, between the two motors.

**Resources**

eLessons How maglev trains work (eles-2556)
Torque (eles-0025)



Interactivity Torque (int-0049)

3.4.3 The analogue meter

Electrical meters such as ammeters, voltmeters and galvanometers use the magnetic force exerted by a current-carrying wire to control the deflection of a pointer, where the amount of deflection is calibrated to enable a reading of current or voltage.

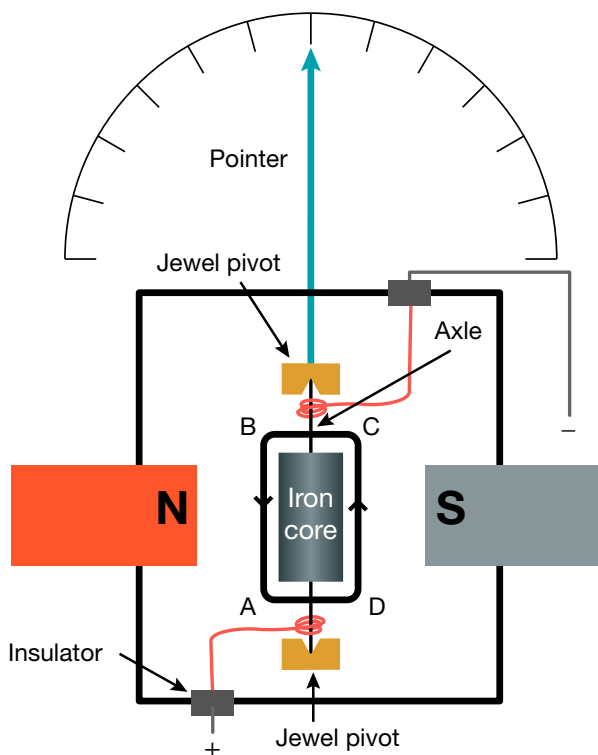
In the electrical meter illustrated in figure 3.17, the force on the wire BA is out of the page. The current travels around to D and then to C, so the force on wire DC is into the page. The two forces are the same size because:

- the strength of the magnetic field is the same on both sides of the coil
- the current through the coil is the same at all points
- the lengths BA and DC are the same.

However, the forces are in opposite directions. The net force is therefore zero. However, the forces do not act through the centre of the coil, so the combined forces have a turning effect, creating torque.

If a spring is attached to the axle, the turning effect of the forces unwinds the spring until the spring pushes with an equal torque. A pointer attached to the axle measures the size of the torque, which depends on the size of the current. The larger the current through the meter, the larger the magnetic force, and hence torque, on the coil and the further the spring and the pointer are pushed back to achieve balance. Spiral springs have the fortunate property that the deflection of the pointer is proportional to the torque. This means that the scale on the meter can be linear, or evenly spaced.

FIGURE 3.17 An electrical meter



on Resources

 **Digital document** Investigation 3.5 Meters (doc-31608)

3.4.4 Magnetic propulsion

The magnetic force on a current-carrying wire is the basis for magnetic propulsion.

Consider a conductor rod rolling along two rails in a magnetic field, as shown in figure 3.18. When a current flows along the closest rail (the lower of the two rails in the figure), through the conductor rod and back to the power supply, the conductor will experience a force to the right due to the magnetic field. This force will make the conductor rod accelerate. If there is little friction, it can move at high speeds.

This is the principle underlying the rail gun, which is currently being studied for potential military application and magneto-hydrodynamic propulsion.

FIGURE 3.18 A metal conductor rod rolling along two rails

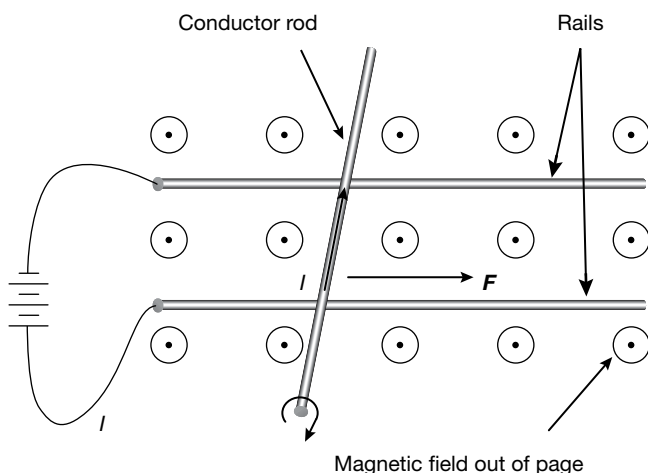


FIGURE 3.19 The world's first superconducting, magneto-hydrodynamically propelled vessel, the Yamato 1, launched in 1991

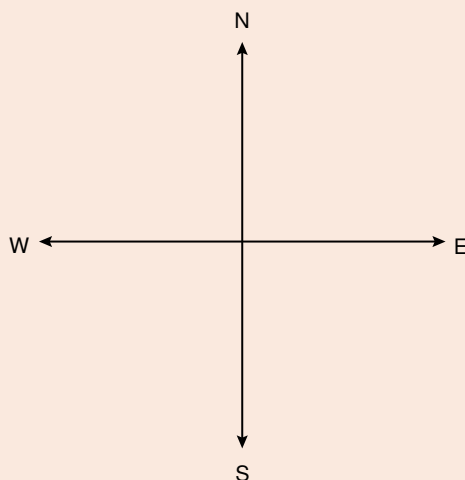


Source: Mugu-shisai

3.4 EXERCISE

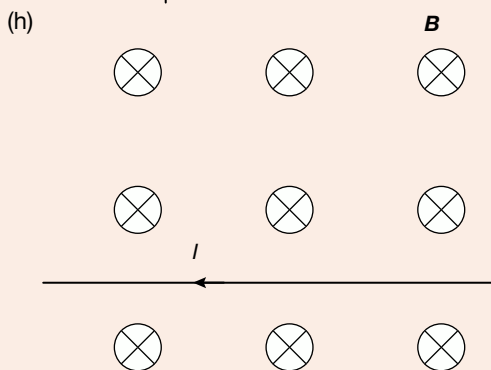
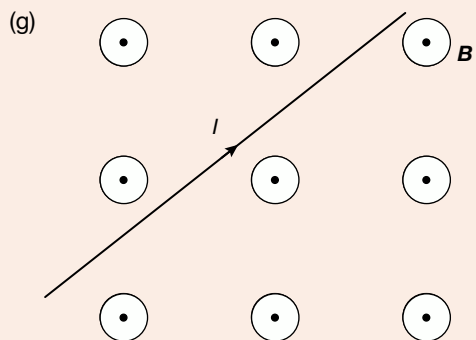
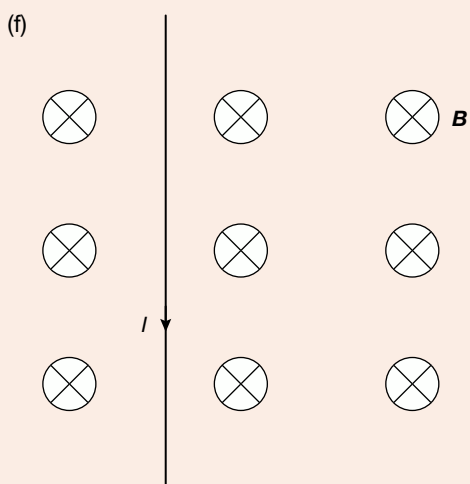
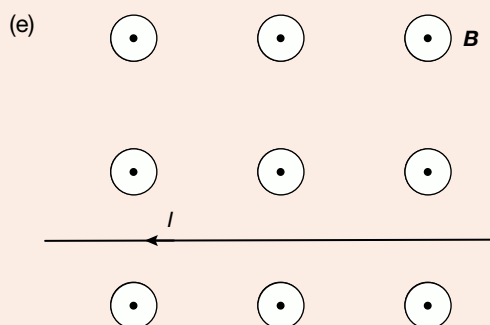
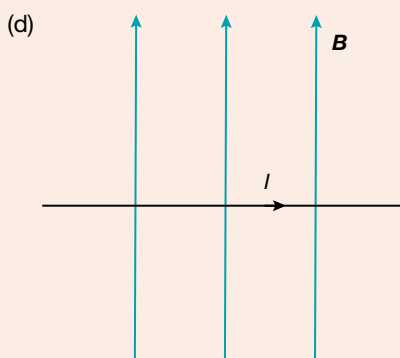
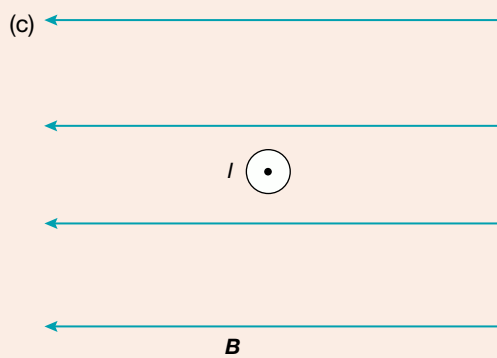
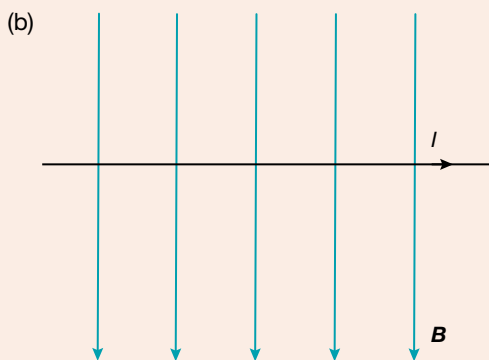
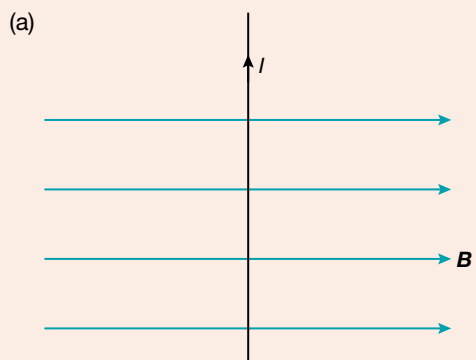
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1. Calculate the size of the force on a wire of length 0.05 m in a magnetic field of strength 0.30 T if the wire is at right angles to the field and it carries a current of 4.5 A.
2. Calculate the size of the force on an 8.0 cm wire carrying a current of 1.8 A at an angle parallel to a magnetic field with strength 40 mT.
3. Calculate the size of the force exerted on a loudspeaker coil of radius 1.5 cm and 500 turns that carries a current of 15 mA in a radial magnetic field of 2.0 T. (*Hint: Consider what aspect of the circle takes the place of l in this question.*)
4. Use the answer key provided to indicate the direction of the force of the magnetic field on the current-carrying wire in the following diagrams (a) to (h).



Answer key





5. Wires A and B are parallel to each other and carry current in the same direction.
 - (a) Draw a diagram to represent this situation, and determine the direction of the magnetic field at B due to wire A.
 - (b) This magnetic force will act on the current in wire B. What is the direction of the force by wire A on wire B?
 - (c) Now draw a diagram and determine the direction of the magnetic field at A due to wire B and the direction of the force by wire B on wire A.
 - (d) Is the answer to (c) what you expected? Why? (*Hint: Consider Newton's laws of motion.*)
6. What is the purpose of each of the following in a DC motor?
 - (a) The magnet
 - (b) The brushes
 - (c) The commutator (mention three aspects)
 - (d) The large number of turns in the wire
7. Look at the simplified DC motor in figure 3.15.
 - (a) Are there some starting positions of the coil that won't produce rotation? How can this be overcome?
 - (b) Can the DC motor run backwards and forwards?
 - (c) Can it run at different speeds? If so, how?
8. Would a DC motor work if it was connected to an alternating current (AC) power source?
9. An example of a DC motor without a commutator is the homopolar motor shown in the following image. The upper section of the copper loop is in continuous contact with the positive terminal of the battery, and the lower section of the loop is in continuous contact with the negative terminal of the battery via the surface of the magnet. Explain how this arrangement results in a continuously rotating loop.
10. Stronger magnetic fields can be obtained with an electromagnet.

The same DC power source can supply current to the electromagnet as well as to the rotating coil. The two components of the circuit, the electromagnet and the rotating coil, can be connected to the power source in two different ways.

 - (a) What are these ways?
 - (b) How do you think the starting and operating characteristics of these two types will differ?



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3.5 Combining electric and magnetic fields

KEY CONCEPT

- Describe the interaction of two fields, allowing that electric charges, magnetic poles and current-carrying conductors can either attract or repel, magnetic and electric forces are balanced, then whereas masses only attract each other.

The functioning of many devices relies on combining magnetic and electric fields to achieve their function. A summary of this is outlined in Table 3.6.

For mass spectrometers and electron microscopes to work, the charged particles all need to be travelling at the same speed. This is because the radius of the path in a magnetic field for a particle with a given charge and mass depends on the particle's speed.

TABLE 3.6 Devices that use electric fields and magnetic fields

Device	Operation	Purpose
Mass spectrometer	Accelerates positive ions of different mass, which then enter a uniform magnetic field and curve around to hit a screen in different spots	To measure the abundance of different elements and isotopes in a sample
Electron microscope	Accelerates electrons, which then pass through electric and magnetic lenses to produce an image where magnetic fields guide their motion	To use an electron beam to examine very small objects
Synchrotron	Accelerates electrons close to the speed of light, then feeds them into a storage ring. A magnetic field bends this beam around the circular path.	To produce intense and very narrow beams of mainly X-rays to examine the fine structure of substances such as proteins
Large Hadron Collider	Accelerates protons or lead ions close to the speed of light, then lets them collide, using electromagnets	To test the predictions of theories of particle physics, for example, the existence of the Higgs boson

In 1898, Wilhelm Wien (after whom Wien's Law in thermodynamics is named) was investigating the charged particles that are produced when electricity is passed through gases. To investigate their speed and their charge, he set up a magnetic field to deflect the beam of charged particles in one direction, and an electric field to deflect the beam in the opposite direction. For the charged particles that were undeflected, the magnetic force must have been balanced by the electric force. This configuration is now called a **Wien filter**.

The electric force on a charge in an electric field is $F = qE$, and the magnetic force on a moving charge is $F = qvB$. If the magnetic and electric forces are balanced, then:

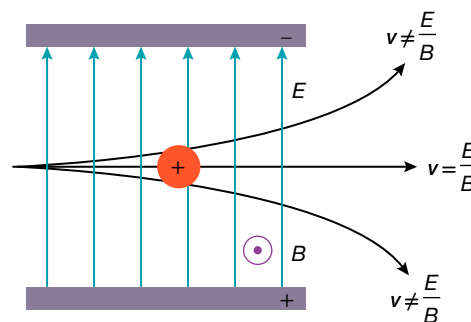
$$qE = qvB$$

and cancelling q gives:

$$\vec{v} = \frac{\vec{E}}{\vec{B}}$$

where: $\vec{v}$ is the velocity of an undeflected particle, in m s^{-1}
 $\vec{E}$ is the strength of the electric field, in N C^{-1}
 $\vec{B}$ is the strength of the magnetic field, in T

This formula implies that by controlling the strength of the magnetic and electric fields, one can determine the velocity of the undeflected particles. Particles travelling faster or slower than the undeflected particles will be deflected out of the beam. This means that a Wien filter can essentially be used to filter out particles that are travelling faster or slower than a desired velocity and select only those particles travelling at the desired velocity. For this reason, a Wien filter is often referred to as a **velocity selector**.

FIGURE 3.20 A Wien filter (also known as a velocity selector)

SAMPLE PROBLEM 7

An electron travels undeflected through a Wien filter, where the magnetic field is 0.0030 T . The electric field strength is 500 N C^{-1} . Calculate the velocity of the electron.

 Teacher-led video: SP7 (tlvd-0135)

THINK

For the undeflected electron, the magnetic and electric forces are balanced. Use the formula

$$v = \frac{E}{B} \text{ to calculate the velocity of an electron.}$$

WRITE

$$\begin{aligned} v &= \frac{500}{0.0030} \\ &= 1.67 \times 10^5 \text{ m s}^{-1} \end{aligned}$$

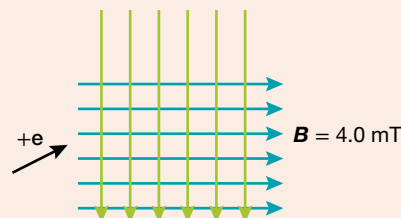
PRACTICE PROBLEM 7

An electron beam requires electrons moving at $6 \times 10^6 \text{ m s}^{-1}$. A Wien filter, or velocity selector, is set up with a magnetic field of 0.02 T . How large must the electric field be to select electrons travelling at $6 \times 10^6 \text{ m s}^{-1}$?

3.5 EXERCISE

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1. An electron travels undeflected through a Wien filter, where the magnetic field is 0.0060 T . The electric field strength is 200 N C^{-1} . Calculate the velocity of the electron.
2. An electron beam requires electrons moving at $8.0 \times 10^6 \text{ m s}^{-1}$. A velocity selector is set up with an electric field of 5000 V m^{-1} . How large must the magnetic field be in order to select electrons travelling at $8.0 \times 10^6 \text{ m s}^{-1}$ perpendicular to the field?
3. Consider a Wien filter with the magnetic field coming out of the page and the electric field pointing up the page. Electrons arrive at the Wien filter from the left. In which direction are electrons with a velocity less than $\frac{E}{B}$ deflected?
4. In a mass spectrometer, the sample is vapourised and ionised, resulting in ions with a random distribution of velocities that are accelerated by a uniform electric field. The ions are then passed through a velocity selector with a magnetic field strength of 500 mT and an electric field provided by an electrical potential difference of 1000 V across conducting plates separated by 1.5 mm . Calculate the velocity of ions that pass through undeflected.
5. Describe the features of a velocity selector with a magnetic field down the page, assuming the charged particles are coming from the left.
6. (a) Calculate the speed acquired by an electron accelerated by an electrical potential difference of 100 V .
(b) The electron from part (a) enters a velocity selector with a magnetic field of strength 6.00 mT . For what electric field strength would the electron be undeflected?
(c) If the plate separation for the electric field was 5.00 cm , what is the voltage across the plates?
7. A positron enters the following crossed electric and magnetic field, with a velocity in the direction indicated. The magnetic field is to the right and the electric field points down the page. Suggest what might happen to the trajectory of the positron as it traverses the magnetic field.



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3.6 Review

3.6.1 Summary

- A uniform electric field exists between two metal plates connected to a DC supply. The strength of the electric field, E , is given by the voltage drop or potential difference across the plates, V , over the plate separation, d : $E = \frac{V}{d}$. This uniform field produces a constant force on a charge and thus a constant acceleration.
- The work done by the field in moving a charge from one plate to the other is given by $W = qV$.
- This is the basis of the operation of a linear particle accelerator.
- A magnetic field exerts a force on a moving charged particle, $F = qvB$, where v and B are perpendicular to each other. The direction of the force for a positive moving charge can be determined by the right-hand-slap rule. The direction of the force is reversed for a negative moving charge.
- A magnetic field exerts a force on a wire carrying an electric current. When the magnetic field and electric current are perpendicular to each other, the magnitude of the force can be calculated using the formula $F = I\ell B$.
- The direction of the force can be determined by the left-hand rule or the right-hand-slap rule.
- In a DC motor, a magnetic field is used to rotate a coil of current-carrying wire around a shaft. The magnetic force produces a torque that turns the coil.
- A commutator is used in a DC motor to reverse the current passing through the coil twice during each rotation. This ensures that the coil keeps rotating in one direction.
- The force by a magnetic field on a moving charged particle is always at right angles to the direction the particle is heading. The force constantly changes the direction of travel, producing a circular path.
- The size of the magnetic force on a moving charged particle is equal to qvB , where q and v are the charge and speed of the particle respectively, and B is the strength of the magnetic field.
- The radius, r , of the curved path of a charged particle in a magnetic field is given by $r = \frac{mv}{Bq}$.
- Perpendicular electric and magnetic fields can be used to construct a Wien filter (or velocity selector).

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3.6.2 Key terms

An **armature** is a frame around which a coil of wire is wound, which rotates in a motor's magnetic field.

Brushes are conductors that make electrical contact with the moving split ring commutator in a DC motor.

An **electric field** is a vector field describing the property of the space around a charge that causes a second charge in that space to experience a force due only to the presence of the first charge.

The **left-hand rule** and **right-hand-slap rule** are used to determine the direction of the magnetic force of a magnetic field on a current or moving positive charge.

A **linear particle accelerator** is a type of particle accelerator based on the work done by the field in moving a charge from one plate to the other.

A **magnetic field** is a vector field describing the property of the space around a magnet that causes an object in that space to experience a force due only to the presence of the magnet.

A **split ring commutator** is a device that reverses the direction of the current flowing through an electric circuit.

The **torque** is the turning effect of the forces on the coil in an electric motor.

A **Wien filter** (or **velocity selector**) is a device that can be used as a velocity filter using a magnetic field to deflect the beam of charged particles in one direction, and an electric field to deflect the beam in the opposite direction.



Resources



Digital document Key terms glossary (doc-32250)

3.6.3 Practical work and investigations

Investigation 3.1

Electrons in a magnetic field

Aim: To use a cathode ray oscilloscope (CRO) to display variations in voltage applied to the input terminals

Digital document: doc-31591

Investigation 3.2

Measuring the force on a current-carrying wire in a magnetic field

Aim: To investigate the relationship $F = IIB$ and determine strength of the magnetic field experienced by the wire loop

Digital document: doc-31605

Teacher-led video: tlvd-0242

Investigation 3.3

The motor effect

Aim: To observe the direction of the force on a current-carrying conductor in an external magnetic field

Digital document: doc-31606

Investigation 3.4

Designing an electric DC motor

Aim: To construct a working electric motor and analyse and explain the physics principles behind its operation

Digital document: doc-31607

Teacher-led video: tlvd-0244



Investigation 3.5

Meters

Aim: To examine a meter and use it to show the direction of a magnetic field

Digital document: doc-31608

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 **Digital document** Practical investigation logbook (doc-32251)

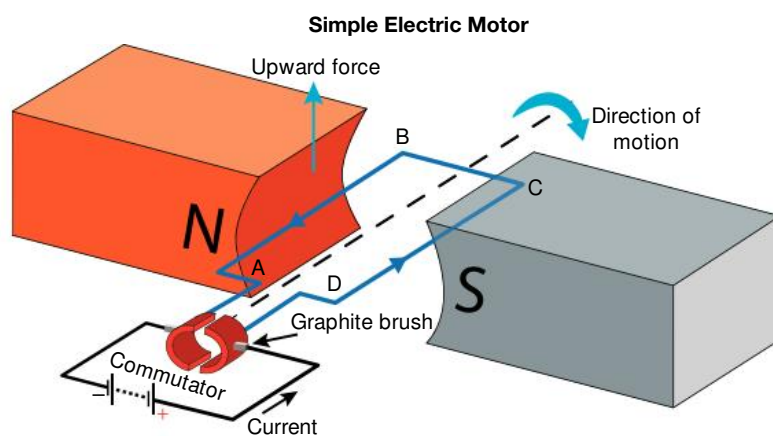
3.6 Exercises

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3.6 Exercise 1: Multiple choice questions

1. A proton is placed between two conducting plates separated by 1.0 cm, with a potential difference of 500 V across the plates. Which of the following statements is correct?
 - A. The strength of the electric field varies from $50\,000\text{ V m}^{-1}$ to 0 V m^{-1} between the plates.
 - B. The potential difference halfway between the plates is 250 V.
 - C. The proton is accelerated towards the plate at the lowest potential difference.
 - D. The field between the plates is uniform, so the particle moves with a constant speed.
2. In a linear accelerator, a potential difference of 1000 V is used to accelerate electrons to the right over a 10.0 cm length. Which of the following is the acceleration to the right experienced by the electrons? ($m_e = 9.1 \times 10^{-31}\text{ kg}$; $q = 1.6 \times 10^{-19}\text{ C}$)
 - A. $1.8 \times 10^{-47}\text{ m s}^{-2}$
 - B. $1.8 \times 10^{-46}\text{ m s}^{-2}$
 - C. $1.8 \times 10^{14}\text{ m s}^{-2}$
 - D. $1.8 \times 10^{15}\text{ m s}^{-2}$
3. In an electron gun, electrons are emitted from a hot metal filament and then accelerated between two charged conducting plates. Which of the following is correct?
 - A. The kinetic energy of the electrons increases as they pass between the two plates because the electric field does work on the electrons.
 - B. The potential energy of the electrons increases as they pass between the two plates because the electric field does work on the electrons.
 - C. The force on the electrons changes as they move between the two plates.
 - D. The acceleration of the electrons changes as they move between the two plates.
4. An electron moves between two conducting plates separated by a distance d with a potential difference V . If the two plates are brought closer together so that the distance d is halved, how are the acceleration and change in kinetic energy of an electron that moves between the two plates affected?
 - A. The acceleration halves and the change in kinetic energy halves.
 - B. The acceleration halves and the change in kinetic energy stays the same.
 - C. The acceleration doubles and the change in kinetic energy doubles.
 - D. The acceleration doubles and the change in kinetic energy stays the same.
5. A proton and an electron have the same speed upon entering a magnetic field that is pointing out of the page from the left. Both particles follow circular trajectories in the magnetic field. Which of the following is the trajectory followed by the proton?
 - A. A clockwise circle with a larger radius than that of the electron.
 - B. A clockwise circle with a smaller radius than that of the electron.
 - C. An anti-clockwise circle with a larger radius than that of the electron.
 - D. An anti-clockwise circle with a smaller radius than that of the electron.

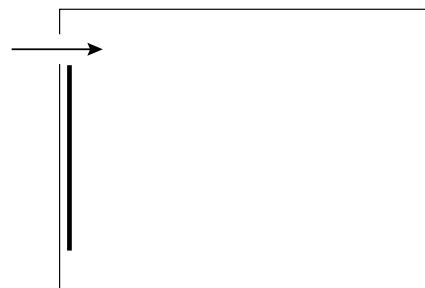
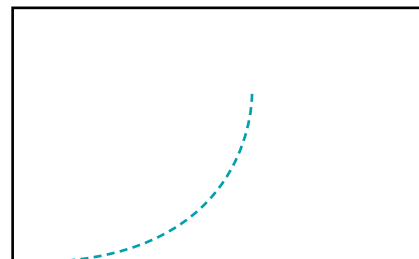
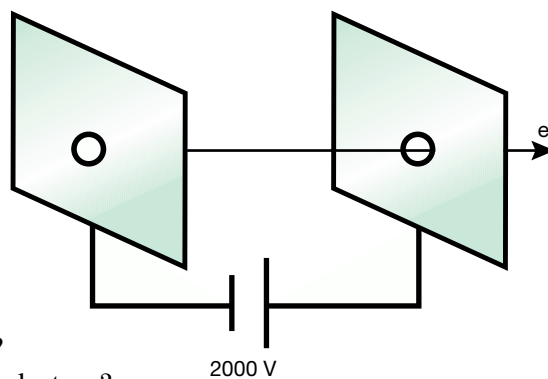
6. Two current-carrying wires A and B are placed parallel to each other. Both wires are conducting equal currents in the same direction. Which of the following is correct?
- Wire A produces a magnetic field, which causes the current in wire B to experience a repulsive force.
 - Wire B produces a magnetic field, which causes the current in wire A to experience a repulsive force.
 - Wire B produces a magnetic field, which causes the current in wire A to experience an attractive force.
 - If the current in one wire was reversed, the wires would attract each other.
7. A mass spectrometer is used to separate different isotopes of potassium, namely potassium-39 and potassium-41. The isotopes form positive ions. The ions enter a magnetic field that is pointing into the page from the left. Which of the following is correct?
- Potassium-39 will experience a larger radius of curvature than potassium-41 and will be deflected initially upwards.
 - Potassium-39 will experience a larger radius of curvature than potassium-41 and will be deflected initially downwards.
 - Potassium-39 will experience a smaller radius of curvature than potassium-41 and will be deflected initially upwards.
 - Potassium-39 will experience a smaller radius of curvature than potassium-41 and will be deflected initially downwards.
8. A Wien filter is being designed to filter electrons with a speed of $1.5 \times 10^6 \text{ m s}^{-1}$. The electrons are travelling horizontally and enter the filter from the left. If the electric field was 542 N C^{-1} , what would the magnetic field need to be in order for the filter to be successful?
- $2.8 \times 10^{-4} \text{ T}$
 - 2767.5 T
 - $0.36 \times 10^3 \text{ T}$
 - $3.6 \times 10^{-4} \text{ T}$
9. Consider the simple DC motor shown in the diagram at right. Which of the following actions would increase the average torque on the loop?
- Decreasing the side length BC
 - Halving the voltage supplied to the circuit
 - Decreasing the size of the magnetic field
 - Increasing the number of loop windings.
10. Which of the following changes would stop the motor in question 9 from rotating continuously?
- Reversing the direction of the magnetic field
 - Reversing the direction of the voltage
 - Rotating the direction of the magnetic field to be perpendicular to the direction shown in the diagram
 - Reversing the direction of the current in the circuit.



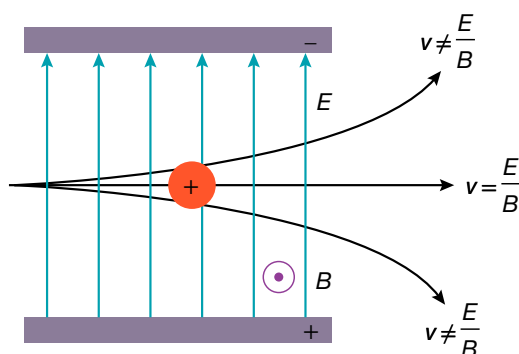
3.6 Exercise 2: Short answer questions

- An electron passes between two charged conducting plates separated by 3.0 cm, with a potential difference of 2000 V.
 - What is the magnitude and direction of the electric field between the plates?
 - How long does it take the electron to pass from the first to the second plate?
 - What is the work done by the electric field on the electron as it passes from the first to the second plate?
 - What is the kinetic energy change experienced by the electron?
 - What is the kinetic energy change experienced by the electron when it is halfway between the plates?
 - What would be the effect of reversing the applied potential difference?
- A student wants to increase the energy of particles emitted from an electron gun that has a design essentially the same as the diagram in question 1. He proposes to do this by doubling the strength of the electric field through halving the separation between the charged conducting plates. Explain whether or not this change will achieve the aim of increasing the energy of the emitted particles.
- What is the size of the magnetic force on an electron entering perpendicularly to a magnetic field of 250 mT at a speed of $5.0 \times 10^6 \text{ m s}^{-1}$?
 - Use the mass of the electron (mass = $9.1 \times 10^{-31} \text{ kg}$) to determine its centripetal acceleration.
 - If a proton entered the same field with the same speed, what would its centripetal acceleration be?
- After a radioactive decay, a beta particle is observed to execute the following trajectory in a cloud chamber:

What is the direction of the magnetic field experienced by the beta particle?
- What strength of magnetic field would be needed to obtain a radius of 1000 m if an electron has momentum of $1.0 \times 10^{-18} \text{ kg m s}^{-1}$? (Assume the direction of the momentum of the electrons is perpendicular to the direction of the magnetic field.)
- Calculate the magnitude of the force of a magnetic field of strength 0.25 T on a wire of length 0.30 m carrying a current of 2.4 A at right angles to the field.
- A horizontal beam of electrons is directed at right angles to a wire carrying a conventional current from left to right. What happens to the electrons?
 - A beam of electrons is directed parallel to the same wire with the conventional current travelling in the same direction. What happens to the electrons?
- In a mass spectrometer, positively charged ions are curved in a semicircle by a magnetic field in order for them to hit a detector at different points depending on the radius and mass. The ions enter the chamber at the top left corner and curve around to hit the detector (see the following diagram). What should be the direction of the magnetic field for the spectrometer to work properly?



9. Outline the operating principles of a DC motor.
10. Consider the velocity selector shown in the following diagram:

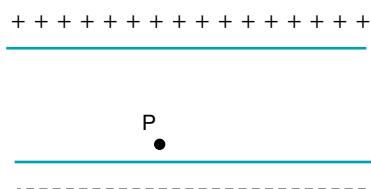


Would the same configuration of electric and magnetic fields work for negatively charged particles?

3.6 Exercise 3: Exam practice questions

Question 1 (6 marks)

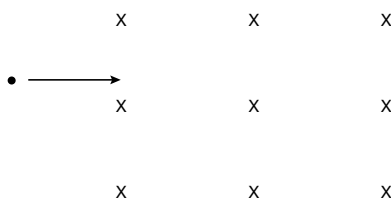
An electron is placed between two charged conducting plates separated by a distance of 10.0 cm as shown in the following diagram. The electric field strength between the plates is 100 N C^{-1} .



- Draw an arrow showing the direction of the force on an electron placed at point P, 2.5 cm above the bottom plate. **1 mark**
- Calculate the potential difference between the top and bottom plate. **2 marks**
- Calculate the change in kinetic energy of the electron as it moves from point P to the top plate. **3 marks**

Question 2 (7 marks)

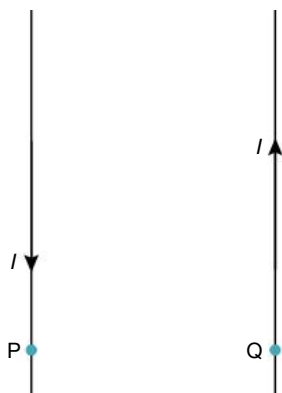
A mass spectrometer is designed to separate particles based on the ratio of their mass to charge. The spectrometer consists of three stages: a linear accelerator, a velocity selector and a uniform magnetic field. Ions with a mass of $1.2 \times 10^{-26} \text{ kg}$ and a charge of $+2e$ are passed through a linear accelerator with a potential difference of 2000 V.



- Assume that the ions are initially at rest. Show that, after passing through the linear accelerator, the velocity of the ions is $3.3 \times 10^5 \text{ m s}^{-1}$. **2 marks**
The ions pass through the velocity selector undeflected into a uniform 0.50 T magnetic field pointing into the page, as shown in the following diagram:
- Calculate the magnitude of the force experienced by the ions while they are in the magnetic field. **2 marks**
- Calculate the radius of curvature of the trajectory followed by the ions. **3 marks**

Question 3 (5 marks)

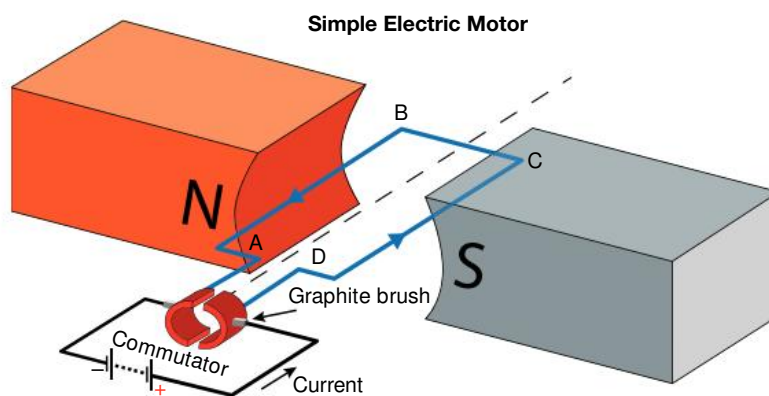
Two sturdy wire cables connect a power supply to a piece of heavy machinery as shown in the following diagram.



- a. Draw an arrow at P indicating the direction of the magnetic field from the right-hand wire. **1 mark**
- b. Draw an arrow at Q indicating the direction of the force on the right-hand wire. **1 mark**
- c. Do the two wires attract or repel each other? Explain your response. **3 marks**

Question 4 (8 marks)

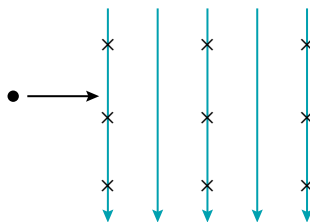
Consider the DC motor shown in the following diagram. The strength of the magnetic field is 0.030 T. The loop consists of 50 turns of wire. The loop is a rectangle with side lengths AB and CD of 15 cm and side lengths BC and DA of 10 cm. The current in the wire is 3.0 A.



- a. Calculate the magnitude of the force on the side length AB. **2 marks**
- b. Draw an arrow on side AB indicating the direction of the force on AB at that moment. **1 mark**
- c. The polarity of the DC supply is reversed. Explain how this will affect the operation of the motor. **2 marks**
- d. A student attempts to make their own motor but has difficulty attaching the commutator. The commutator is attached with the split in the ring at an angle of 45° from the vertical. Explain how this will affect the operation of the motor. **3 marks**

Question 5 (8 marks)

An alpha particle (charge = $+2e$; mass = 6.64×10^{-27} kg) enters a pair of crossed electric and magnetic fields. The magnetic field is going into the page and the electric field is pointing downwards. The magnitude of the electric field is 2000 N C^{-1} .



- a. Calculate the electric force on the alpha particle. **2 marks**
- b. Given that the initial velocity of the alpha particle is $2.5 \times 10^6 \text{ m s}^{-1}$, find the magnitude of the magnetic field strength required for the alpha particle to continue undeflected. **3 marks**
- c. A proton with the same initial kinetic energy as the alpha particle enters the crossed fields. Explain whether the proton will also continue undeflected. **3 marks**

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UNIT 3 | AREA OF STUDY 1 REVIEW

AREA OF STUDY 1 How do things move without contact?

OUTCOME 1

Analyse gravitational, electric and magnetic fields, and use these to explain the operation of motors and particle accelerators and the orbits of satellites.

PRACTICE EXAMINATION

STRUCTURE OF PRACTICE EXAMINATION		
Section	Number of questions	Number of marks
A	20	20
B	3	25
Total		45

Duration: 50 minutes

Information:

- This practice examination consists of two parts. You must answer all question sections.
- Pens, pencils, highlighters, erasers, rulers and a scientific calculator are permitted.
- You may use the VCAA Physics formula sheet for this task.



Resources



Weblink VCAA Physics formula sheet

SECTION A — Multiple choice questions

All correct answers are worth 1 mark each; an incorrect answer is worth 0.

1. The planet Jupiter has a mass of 1.9×10^{27} kg and a radius of 7.0×10^7 m. What is the gravitational potential on the surface of Jupiter?
 - A. 26 N kg^{-1}
 - B. 59 N kg^{-1}
 - C. 62 N kg^{-1}
 - D. 95 N kg^{-1}
2. The gravitational potential on the surface of the Moon, a distance of r_{Moon} from the centre of the Moon, is approximately 1.6 N kg^{-1} . Which of the following is the best estimate of the gravitational potential at an altitude of $2 \times r_{\text{Moon}}$ above the Moon?
 - A. 0.18 N kg^{-1}
 - B. 0.40 N kg^{-1}
 - C. 0.53 N kg^{-1}
 - D. 0.80 N kg^{-1}

3. Two spherical bodies, each with a mass of 4.5 kg and radius of 4.5 m, are touching each other in deep space. They exert an attractive force on each other. The magnitude of this attractive force would be closest to:
 - A. 1.5×10^{-11} N
 - B. 1.7×10^{-11} N
 - C. 6.7×10^{-11} N
 - D. 3.0×10^{-10} N
4. The gravitational field around Earth may be described as:
 - A. Uniform and constant
 - B. Non-uniform and changing in time
 - C. Uniform and changing in time
 - D. Non-uniform and constant

Use the following information to answer questions 5 and 6:

Two satellites, Rhodium-45 and Palladium-64, are orbiting the Earth at the same altitude. Palladium-64 is twice the mass of Rhodium-45.

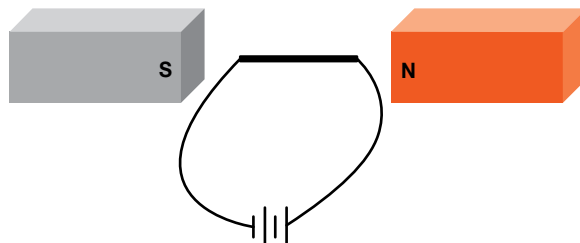
5. Which of the following statements best describes the orbital period of each satellite and the gravitational force of the Earth on each satellite?
 - A. The orbital period of each satellite is the same and the gravitational force acting on each satellite is the same.
 - B. The orbital period of each satellite is different and the gravitational force acting on each satellite is the same.
 - C. The orbital period of each satellite is the same and the gravitational force acting on each satellite is different.
 - D. The orbital period of each satellite is different and the gravitational force acting on each satellite is different.
6. Rhodium-45 is moved by a booster rocket to a higher orbit. Which of the following statements best describes the orbital period and orbital speed of Rhodium-45 in the new orbit?
 - A. The orbital period has increased and the orbital speed has increased.
 - B. The orbital period has increased and the orbital speed has decreased.
 - C. The orbital period has decreased and the orbital speed has increased.
 - D. The orbital period has decreased and the orbital speed has decreased.
7. The force acting on an electric charge of $+9.6 \times 10^{-19}$ C in a uniform electric field with a magnitude of 250 V m^{-1} is closest to:
 - A. 2.4×10^{-16} N
 - B. 2.6×10^{-16} N
 - C. 2.4×10^{-19} N
 - D. 2.6×10^{-19} N

Use the following information to answer questions 8 and 9:

A small sphere is fixed in place with a charge of $+4.5 \text{ } \mu\text{C}$. Another sphere, with a charge of $-3.2 \text{ } \mu\text{C}$ and suspended on a string, is brought close to the fixed sphere. The two spheres may be considered as point charges.

8. The distance between the centres of the two spheres is 7.5 cm. What is the magnitude of the electric force acting on the fixed sphere?
 - A. 2.3×10^{-4} N
 - B. 2.3×10^{-3} N
 - C. 23 N
 - D. 2.3×10^2 N
9. What is the size of the electric field strength due to the fixed sphere at the position of the suspended sphere?
 - A. $5.1 \times 10^6 \text{ NC}^{-1}$
 - B. $7.2 \times 10^6 \text{ NC}^{-1}$
 - C. $8.1 \times 10^6 \text{ NC}^{-1}$
 - D. $9.2 \times 10^6 \text{ NC}^{-1}$

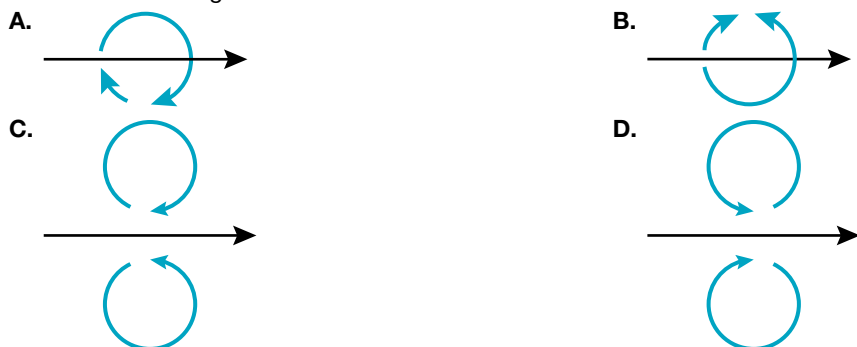
10. Two metal plates are placed parallel to each other and connected to a 120 V DC power supply. A uniform electric field is created between the two plates, which are separated by a distance of 32 mm. The strength of the uniform electric field between the two plates is approximately:
- 38 N C^{-1}
 - $3.8 \times 10^2 \text{ N C}^{-1}$
 - $3.8 \times 10^3 \text{ N C}^{-1}$
 - $3.8 \times 10^4 \text{ N C}^{-1}$
11. An electron is travelling in a straight line in a vacuum tube. Its path may be deflected by a force field. Which of the following fields could cause the deflection?
- An electric field only
 - Either an electric field or a magnetic field only
 - Either an electric field, a magnetic field, or a gravitational field
 - A gravitational field only
12. Two metal plates are used to create a uniform electric field between them with a field strength of 2300 N C^{-1} . The distance between the plates is 3.0 cm. An electron is held at rest on the positively charged plate. It is released and accelerated towards the negatively charged plate. What is the gain in kinetic energy by the electron when it just reaches the negatively charged plate?
- $1.1 \times 10^{-24} \text{ J}$
 - $1.1 \times 10^{-21} \text{ J}$
 - $1.1 \times 10^{-19} \text{ J}$
 - $1.1 \times 10^{-17} \text{ J}$
13. The electric potential between the anode and cathode in a cathode ray tube is 1800 V. An electron starts at rest on the cathode and accelerates towards the anode. What is the expected velocity of the electron as it arrives at the anode?
- $1.3 \times 10^7 \text{ m s}^{-1}$
 - $2.5 \times 10^7 \text{ m s}^{-1}$
 - $2.9 \times 10^7 \text{ m s}^{-1}$
 - $3.0 \times 10^7 \text{ m s}^{-1}$
14. A copper conductor with length 5.0 cm is placed entirely between the poles of two magnets as shown in the following diagram.



The magnetic field strength is 3.0 mT and the current in the conductor is 4.0 A. What is the magnitude of the magnetic force on the conductor?

- 0.0 N
 - $2.0 \times 10^{-4} \text{ N}$
 - $4.0 \times 10^{-4} \text{ N}$
 - $6.0 \times 10^{-4} \text{ N}$
15. The field lines of the Earth's magnetic field run from south to north on the surface of the Earth. A power line carrying a DC current runs from east to west. What is the direction of the magnetic force acting on the power line?
- Up
 - Down
 - North
 - South

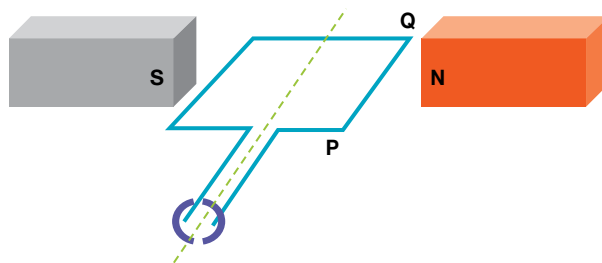
16. A straight conductor is carrying a current of 5.0 A. Which of the following diagrams best represents the direction of the magnetic field around the conductor?



17. A straight length of wire carries a current of 3.5 A and passes perpendicularly within a magnetic field of unknown field strength. A force meter measures the magnetic force on the wire to be 0.35 N. The length of the portion of wire within the magnetic field is 15 cm. The magnetic field strength is approximately:

- A. 6.7 T
- B. 0.67 T
- C. 0.067 T
- D. 0.0067 T

18. The following diagram shows a model DC motor with a split ring commutator that connects the rotating coil to the battery.



At one instance, the current is flowing around the coil in the direction of P to Q. As seen from the front of this motor, what is the direction of the rotation of the coil?

- A. Clockwise
 - B. Anticlockwise
 - C. The coil will not rotate as a slip ring commutator should be used.
 - D. There is insufficient information — for example, the size of the current.
19. A stream of electrons enters a region of magnetic field with a field strength of 8.0 mT that is oriented perpendicularly to the direction of electron motion. The electrons are travelling at a velocity of $8.0 \times 10^6 \text{ m s}^{-1}$. What is the radius of the electron path within the magnetic field?
- A. 5.7 μm
 - B. 5.7 mm
 - C. 5.7 cm
 - D. 5.7 m
20. A stream of electrons may be deflected by a magnetic field or by an electric field. Which of the following options best describes the path taken by the electrons after being deflected?

	Uniform magnetic field	Uniform electric field
A.	Circular path	Circular path
B.	Parabolic path	Parabolic path
C.	Circular path	Parabolic path
D.	Parabolic path	Circular path

SECTION B — Short answer questions

Question 1 (10 marks)

Saturn has at least 18 natural satellites, two of which are Titan and Tethys. Data for Titan and Tethys is shown below:

Mass of Titan	$1.35 \times 10^{23} \text{ kg}$
Radius of Titan	$2.57 \times 10^6 \text{ m}$
Period of Titan's orbit	$1.38 \times 10^6 \text{ s}$
Radius of Titan's orbit	$1.22 \times 10^9 \text{ m}$
Mass of Tethys	$6.18 \times 10^{20} \text{ kg}$
Radius of Tethys's orbit	$2.95 \times 10^8 \text{ m}$

- Calculate the gravitational field strength on the surface of Titan. **2 marks**
- Determine the period of Tethys's orbit. **3 marks**
- Find the mass of Saturn. **3 marks**
- What is the orbital speed of Titan? **2 marks**

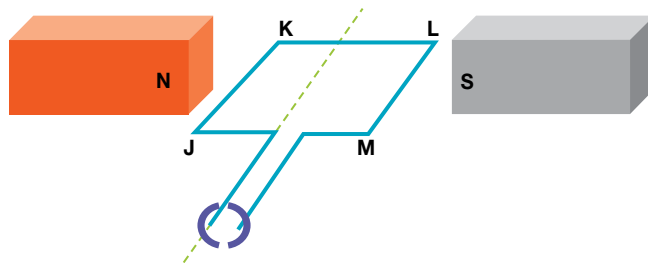
Question 2 (8 marks)

Electrons are 'liberated' from a hot filament, and are then accelerated across a vacuum by a potential difference of 120 V applied between two plates that are 15 cm apart. The electric field between the two plates may be considered to be uniform in strength.

- Determine the electric field strength between the plates. **2 marks**
- Calculate the acceleration of the electrons between the plates. **2 marks**
- What is the gain in kinetic energy by the electrons as they cross between the two plates? **2 marks**
- Assuming the initial velocity of the electrons is zero, what is the final velocity attained by the electrons? **2 marks**

Question 3 (7 marks)

A student builds a model DC motor with 40 turns of wire, and places the coil entirely within a magnetic field as shown in the following diagram. She connects the commutator to a battery, and the coil rotates clockwise when viewed from the position of the commutator.



- At one moment as the coil is rotating, the coil is in the position shown in the diagram. What is the direction of the current in the coil? **1 mark**
- The current in the coil is 3.2 A, and the length of the side JK is 2.9 cm. The force on the side JK is measured to be 1.2 N. What is the magnitude of the magnetic field? **2 marks**
- The motor is stopped and the coil is positioned again as shown in the diagram. The student replaces the commutator with a slip ring commutator. She then reconnects the battery. Carefully explain what happens to the motion of the coil. **2 marks**
- Another student decides to alter his own motor and instead uses only 17 turns of wire. He wants to ensure that the current and the force stay the same as the first student's motor. What would the length of the side JK need to be to enable this? **2 marks**

ASSESSMENT TASK — THE OPERATION OF A DEVICE

In this task, you will be required to analyse gravitational, electric and magnetic fields to explain the operation of a type of particle accelerator, the Pelletron.

- This practice SAC requires you to describe the operation of a device; a structured set of questions is supplied to assist you to write your description. You may choose to present your explanation as a report, or break it down and answer question by question.
- You may use the VCAA Physics formula sheet and a scientific calculator for this task.

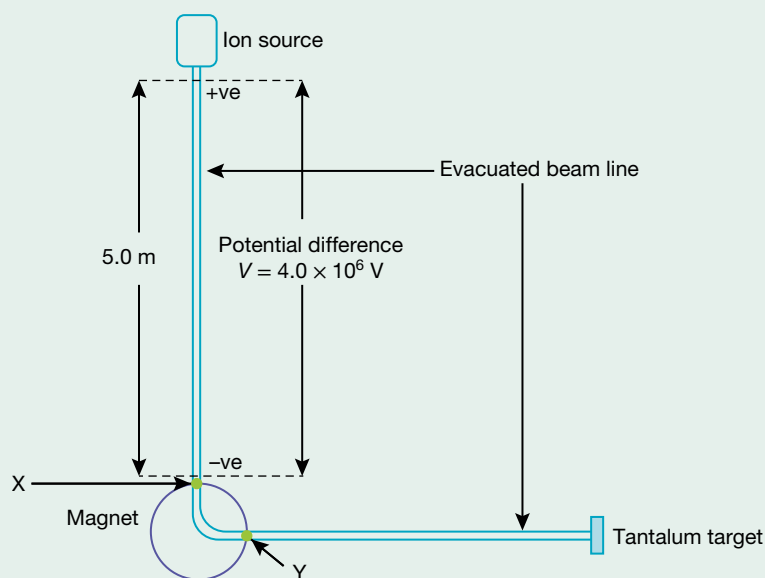
Total time: 55 minutes (5 minutes reading, 50 minutes writing)

Total marks: 46 marks

EXPLORING THE OPERATION OF 5U PELLETRON

The University of Melbourne houses a particle accelerator, the 5U Pelletron, which is capable of accelerating positively charged particles. These charged particles can be directed at targets used for research purposes ranging from fundamental nuclear physics through to medical research projects and the analysis of materials.

The Pelletron consists of an ion source that provides particles capable of being accelerated, and a device similar to a Van de Graaff generator to provide a variable potential difference V . At the base of the accelerator, a large magnet is used to direct beams of charged particles towards samples to be analysed. In essence, the machine is capable of directing positive ions of a specific kinetic energy at a target. A schematic of the machine is shown in the following diagram.



Relevant data:

- mass of a proton: 1.67×10^{-27} kg
- charge of a proton: 1.60×10^{-19} C
- mass of an alpha particle: 6.68×10^{-26} kg
- charge of an alpha particle: 3.20×10^{-19} C

In one experiment, protons are produced by the ion source and accelerated by the potential difference, V .

- Why is it necessary for the ions produced by the ion source to be positively charged and not negatively charged?

The accelerated ions travel along an evacuated beam line from the ion source to the target.

- Why is it important for the beam line to be evacuated — that is, for the beam line to be a vacuum?
- Determine the work done on these protons and hence their kinetic energy when they arrive at point X after leaving the ion source and being accelerated.
- Use your value for the kinetic energy of the proton to determine its speed at point X directly above the magnet.

Consider now if the ion source produced alpha particles instead of protons.

5. Would the speed of the alpha particles be greater than, the same, or less than the speed of the protons at point X? Explain your answer.
6. Calculate the strength of the electric field in the region between the positive and negative plates of the Pelletron. Give the direction of the electric field in this region (up or down) and explain why you have chosen it.
7. Calculate the size of the electric force acting on a proton moving from the ion source to point X and hence its acceleration down the beam line.

Protons moving from the ion source of the Pelletron to point X also undergo a loss of gravitational potential energy.

8. Explain why this transformation of energy can be ignored for protons moving from the ion source to point X. A calculation would assist in your answer. Use $g = 9.8 \text{ N kg}^{-1}$ down.

At point X, the protons enter a region where there is a uniform magnetic field. This field is used to exert a force on the protons so they move in the arc of a circle. They exit the magnetic field at point Y from which they are directed towards a target situated at the end of a beam line.

9. Explain why the magnetic field interacting with the protons causes them to move in the arc of a circle as they move from point X to point Y and why this could not be achieved with a uniform electric field.
10. Determine the direction of the magnetic field, clearly explaining your method.
The radius of the circle that the protons travel is 0.80 m.
11. Calculate the magnitude of the magnetic field of the magnet.
12. Use your results for questions 4 and 11 to determine the size of the magnetic force acting on a proton as it moves from X to Y.
13. After the proton has been deflected by the magnetic field, it is travelling at the same speed as at point X, yet the proton has been accelerated by the magnetic force. Explain how this is so.

The beam of protons now travels from Y to the end of the beam line to collide with a target. In this particular instance, the target is made of tantalum. Each tantalum nucleus has 73 protons. Protons fired at the target are capable of colliding with a tantalum nucleus.

In one collision, a proton is approaching a tantalum nucleus head-on. When the separation between the proton and the tantalum nucleus is 10 nm, the electric force acting on the proton is $1.68 \times 10^{-8} \text{ N}$.

14. Calculate the strength of the electric field due to the tantalum nucleus at a distance 10 nm from its centre.
15. Sketch a diagram showing this collision, clearly showing the size and direction of the electric force acting on the proton. Explain if the proton will speed up, slow down or travel at a constant speed.
A university student operating the Pelletron decides that she would like protons of a higher speed.
16. What two adjustments must she make to the parameters of the machine to ensure that protons of higher speed still hit the target? Relate each adjustment to the motion of the proton as it travels from the ion source to the target.
17. The Pelletron described discusses the acceleration of positive particles. Would the device be able to accelerate negative particles? What would need to be done to allow this?

Resources



Digital document School-assessed coursework (doc-32256)

4 Generation of electricity

4.1 Overview

Numerous **videos** and **interactivities** are available just where you need them, at the point of learning, in your digital formats, learnON and eBookPLUS at www.jacplus.com.au

4.1.1 Introduction

Hans Christian Oersted's discovery that a current-carrying wire induces a magnetic field was the first indication of the relationship between electricity and magnetism. Following this, scientists started to investigate the relationship in more detail. In 1831, Michael Faraday completed the link between electricity and magnetism when he found that electricity could be produced from magnetism. This discovery was monumental, allowing the generation of the massive amounts of electricity that society now relies on.

In this topic, you will be introduced to the concept of magnetic flux and apply Faraday's findings to create devices that generate electricity.

FIGURE 4.1 A generator inside a wind turbine



4.1.2 What you will learn

KEY KNOWLEDGE

After completing this topic you will be able to:

- calculate magnetic flux when the magnetic field is perpendicular to the area, and describe the qualitative effect of differing angles between the area and the field, $\Phi_B = \mathbf{B}_{\perp} A$
- investigate and analyse theoretically and practically the generation of electromotive force (emf) including AC voltage and calculations using induced emf, $\varepsilon = -N \frac{\Delta \Phi_B}{\Delta t}$, with reference to:
 - rate of change of magnetic flux
 - number of loops through which the flux passes
 - direction of induced emf in a coil.
- explain the production of DC voltage in DC generators and AC voltage in alternators, including the use of split ring commutators and slip rings respectively
- compare sinusoidal AC voltages produced as a result of the uniform rotation of a loop in a constant magnetic field with reference to frequency, period, amplitude, peak-to-peak voltage (V_{p-p}) and peak-to-peak current (I_{p-p})
- compare alternating voltage expressed as the root-mean-square (rms) to a constant DC voltage developing the same power in a resistive component
- convert between rms, peak and peak-to-peak values of voltage and current.

Source: VCE Physics Study Design (2017–2021) extracts © VCAA; reproduced by permission.

PRACTICAL WORK AND INVESTIGATIONS

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

on Resources

 **Digital documents** Key science skills — VCE Physics Units 1–4 (doc-32112)

Key terms glossary (doc-32252)

Practical investigation logbook (doc-32253)

studyon

To access key concept summaries and past VCAA exam questions download and print the **studyON: Revision and past VCAA exam question booklet** (sonr-0053).

4.2 BACKGROUND KNOWLEDGE Generating voltage and current with a magnetic field

BACKGROUND KNOWLEDGE

- Explain how voltage and current is generated with a magnetic field.
- Investigate and analyse the electromotive force (emf) induced in a moving conductor: $\varepsilon = B/v$.

4.2.1 Generating voltage

What should happen when a metal rod moves through a magnetic field? Imagine a horizontal rod falling down through a magnetic field as shown in figure 4.2.

As the rod falls, the electrons and the positively charged nuclei in the rod are both moving down through the magnetic field. (It is important to recall that velocity, v , is perpendicular to the direction of the magnetic field. If the velocity is parallel to the magnetic field, the force will be zero.) The magnetic field will exert a magnetic force on the electrons, and on the nuclei. The magnitude of this force, F , is equal to the charge, q , multiplied by the velocity, v , multiplied by the strength of the magnetic field, B .

In which direction will the magnetic force act on the electrons and the nuclei?

The hand rules from topic 3 can be used for both the electrons and the nuclei, keeping in mind that the hand rules use conventional current, so electrons moving down are equivalent to positive charges moving up.

The force on the electrons will be towards the far end of the rod (into the page), while the force on the nuclei will be to the near end of the rod (out of the page), as is shown in figure 4.3.

FIGURE 4.2 A metal rod falling down through a magnetic field

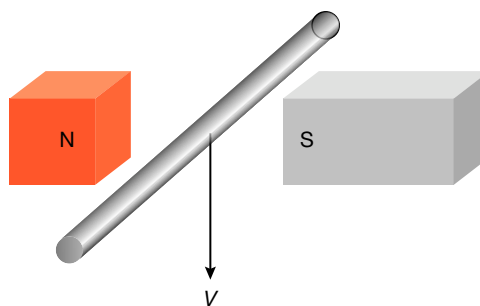
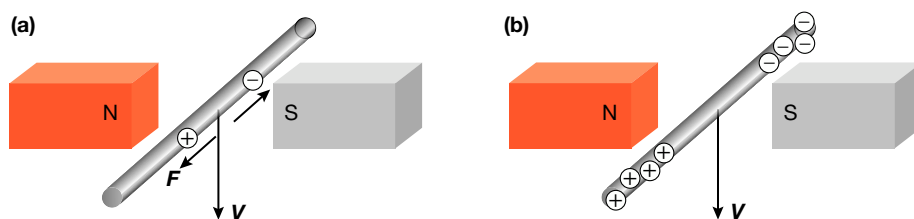


FIGURE 4.3 The magnetic field forces electrons to the far end of the falling rod.



The atomic structure of the metal restricts the movement of the positively charged nuclei. The negatively charged electrons, on the other hand, are free to move. The electrons move towards the far end of the rod, leaving the near end deficient in electrons and thus positively charged.

Not all electrons move to the far end. As the far end becomes more negative, there will be an increasingly repulsive force on any extra electrons at this end of the rod. Similarly, there will be an increasingly attractive force from the positively charged near end, attempting to keep the remaining electrons at that end. This process is similar to the charging of a capacitor.

The movement of the metal rod through the magnetic field has resulted in the separation of charge, causing a potential difference, or voltage drop, between the ends. This is called **induced voltage**. As long as the rod keeps moving, the charges will remain separated. As soon as the rod stops falling (at which point the velocity equals zero), the magnetic force is reduced to zero; electrons are then attracted back to the positive end and soon the electrons return to being distributed evenly in the rod.

The charge in the moving rod is separated by the magnetic field, but the charge has nowhere to go. A source of voltage, an **emf** (electromotive force), has been produced. It is like a DC battery with one end positive and the other negative.

What determines the size of this induced emf? The size depends on the number of electrons shifted to one end. The electrons are shifted by the magnetic force until their own repulsion balances this force. So, the larger the magnetic force pushing the electrons, the more electrons are shifted to one end of the rod.

The size of this pushing magnetic force depends on the size of the magnetic field and the current. The magnetic field is constant in this case, so the size of the force depends on how fast the electrons are moving down with the rod (which is, of course, how fast the rod is falling). So the faster the rod falls, the larger the induced emf.

An expression for the size of the induced emf can be obtained by combining the expression for the force on a moving charge with the definition of voltage. When the rod is moving down with velocity v , each electron experiences a force along the rod equal to qvB . This force pushes the electron along the length l of the rod and so is doing work in separating charge. The amount of work done, in joules, is equal to the force times the distance:

$$W = \text{force} \times \text{distance} = qvB \times l$$

However, the definition of emf (or the voltage drop across the rod) is energy supplied per unit of charge, measured in joules per coulomb, or volts. So the induced emf ($\mathcal{E}$) is given by $\mathcal{E} = \frac{W}{q} = \frac{Blqv}{q}$, which gives:

$$\mathcal{E} = Blv$$

where: $\mathcal{E}$ is the induced emf measured, in V

B is the magnetic field strength, in T

l is the length of the conductor, in m

v is the velocity of the conductor perpendicular to the magnetic field, in m s^{-1}

SAMPLE PROBLEM 1

A 5.0 cm metal rod moves at right angles across a magnetic field of strength 0.25 T at a speed of 40 cm s^{-1} . What is the size of the induced emf across the ends of the rod?

 Teacher-led video: SP1 (tlvd-0136)

THINK

Recall the formula for the induced emf of a conductor: $\mathcal{E} = Blv$

where: $l = 0.05 \text{ m}$, $v = 0.4 \text{ m s}^{-1}$ and $B = 0.25 \text{ T}$.

Ensure that the units have been converted to those required in the formula.

WRITE

$$\mathcal{E} = Blv$$

$$= 0.25 \times 5.0 \times 10^{-2} \times 0.4$$

$$= 5.0 \times 10^{-3} \text{ V}$$

$$= 5.0 \text{ mV}$$

PRACTICE PROBLEM 1

At what speed would the rod need to move to induce an emf of 1.0 V?

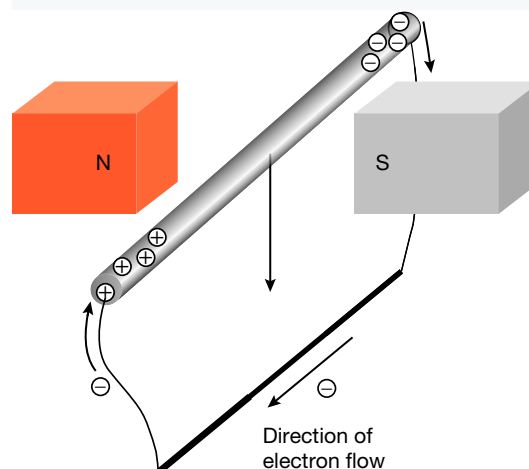
4.2.2 Generating a current

Emfs can be used to produce a current by attaching a wire to each end of the metal rod and connecting these wires outside the magnetic field, producing a closed circuit. Now the electrons have the path of a low-resistance conductor to move to the positively charged end of the rod.

Once the electrons reach the positive end, they will be back in the magnetic field, falling down through the magnetic field with the metal rod, and will again experience a magnetic force pushing them to the far end of the rod. The electrons will then move around the circuit for a second time.

The electrons will continue to flow around the circuit as long as the wire is falling through the magnetic field. An electric current has been generated (see figure 4.4)!

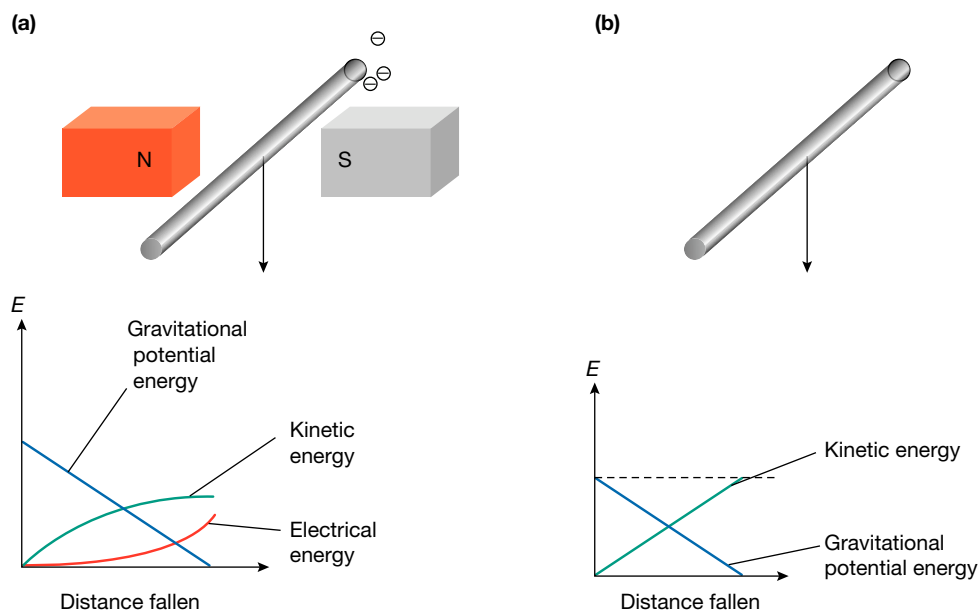
FIGURE 4.4 The accumulated electrons at the far end of a rod move to the positive end through the connecting wire.



4.2.3 The source of a current's electrical energy

Electric current has electrical energy. Where did this energy come from? Before the rod was released, it had gravitational potential energy. If it is dropped outside the magnetic field (see figure 4.5b), this gravitational potential energy is converted into kinetic energy. If it is dropped inside the magnetic field (see figure 4.5a), the potential energy is converted to kinetic energy and electrical energy. Since energy is conserved (that is, it cannot be created or destroyed), there must be less kinetic energy in the rod falling in the magnetic field than the rod falling outside of the magnetic field. That is, the rod in the magnetic field is falling at a slower speed. Why?

FIGURE 4.5 (a) Inside the magnetic field, the gravitational potential energy of the falling rod is converted into both kinetic energy and electrical energy, whereas (b) outside the magnetic field, it is converted only into kinetic energy.



The induced current in the falling rod means that, when the electrons are in the rod, they are moving in two directions — downwards with the rod and along the rod.

The downward movement of the rod through the magnetic field produces the sideways force along the rod that keeps the current flowing. But if the electrons are moving along the rod, how does the magnetic field respond to this?

The movement of electrons along the rod means there is a current-carrying conductor in the magnetic field, causing the field to exert a second force on the rod. The direction of this force is once again given by the hand rule; the magnetic field is directed to the right, the conventional current directed to the near end of the rod (out of the page), and so the force is directed upwards. This magnetic force opposes the accelerating force due to gravity on the rod.

The size of the upward magnetic force depends on the size of the current. This current will depend, in turn, on the size of the voltage drop between the ends of the rod. Voltage will increase as the rod moves faster.

When the rod first starts falling, the magnetic force opposing the force due to gravity is small but, as the rod falls faster, the opposing magnetic force increases until it equals the force due to gravity on the rod. At this point the rod has reached a maximum steady speed. This situation is identical to the terminal velocity experienced by objects falling through the air.

As the metal rod falls through the magnetic field at constant speed, its kinetic energy remains constant, so the loss in gravitational potential energy is converted to electrical energy as the generated emf drives the current through the circuit.

This effect is difficult to demonstrate in practice; a magnetic field large enough for the rod to achieve terminal velocity is too difficult to construct. However, it is possible to drop a magnet through a cylindrical conductor (as shown in figure 4.7). With a sufficiently strong magnet, a measurable decrease in speed against the acceleration due to gravity can be observed. Therefore, the rod falls with an acceleration less than 9.8 m s^{-2} because it experiences a retarding magnetic force.

FIGURE 4.6 The magnetic force opposes the weight of the rod.

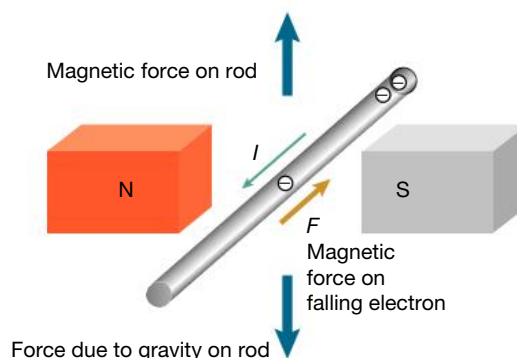
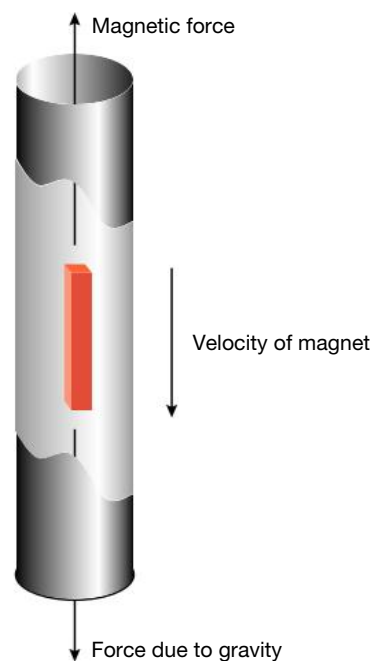


FIGURE 4.7 A magnet falling through a metal tube

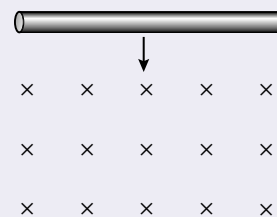


4.2 EXERCISE

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

1. A 10 cm long rod is being moved at a speed of 0.20 m s^{-1} perpendicularly to a magnetic field of strength 0.70 T. Calculate the induced emf in the rod.
2. A 14.3 cm long rod is being moved perpendicularly to a magnetic field of strength 0.850 T. It generates an emf of 100 mV. Determine the speed at which the rod is moving.
3. A rod is being moved at a speed of 0.18 m s^{-1} perpendicularly to a magnetic field of strength 0.60 T. It generates an emf of 90 mV. Determine the length of the rod.

- A rod of length 15 cm is held stationary in a vertical position and then dropped downwards through a magnetic field of strength 100 T. The magnetic field is directed vertically downwards. Determine the induced emf in the rod 4.0 s after it was dropped.
- An aeroplane with a wingspan of 30 m is flying at right angles to the Earth's magnetic field at a speed of 2200 km h^{-1} . If the strength of the Earth's magnetic field is $5.0 \times 10^{-5} \text{ T}$, determine the size of the induced emf between the tips of the aeroplane's wings.
- As the metal rod in the diagram at right falls through the magnetic field, charge is separated and a voltage is established between the two ends of the rod. This requires energy. Where did the energy come from?
- Explain what happens to the voltage between the ends of the rod in question 6 as the rod falls faster.
- A magnet falling through a metal tube can achieve terminal velocity. Why?



Fully worked solutions and sample responses are available in your digital formats.

4.3 Magnetic flux

KEY CONCEPT

- Calculate magnetic flux when the magnetic field is perpendicular to the area, and describe the qualitative effect of differing angles between the area and the field: $\Phi_B = B_{\perp}A$.

Magnetic flux is the amount of magnetic field passing through an area, such as a coil.

The stronger the magnetic field going through an area, the larger the magnetic flux. Similarly, the larger the area the magnetic field is going through, the larger the magnetic flux. Due to this definition, the magnetic field strength is sometimes referred to as the **magnetic flux density**.

Magnetic flux can be calculated as the product of the strength of the magnetic field and the area that is perpendicular to the field lines.

$$\Phi_B = B_{\perp}A$$

where: Φ_B is the magnetic flux, in Wb

B is the strength of the magnetic field, in T

A is the area perpendicular to the magnetic field, in m^2

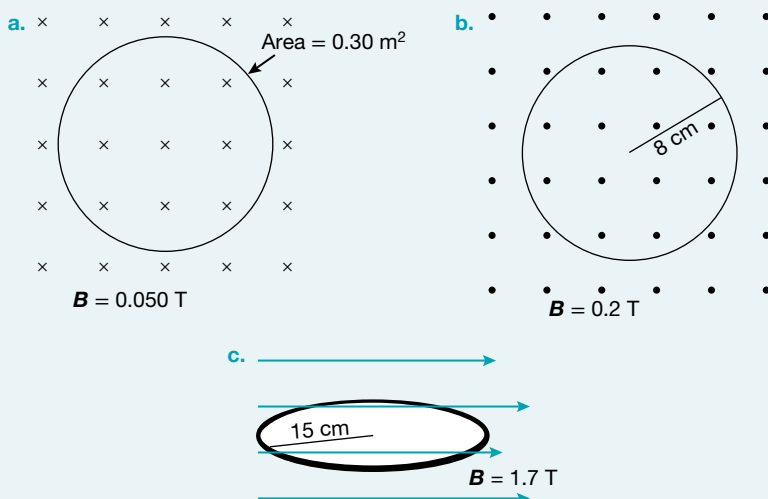
$\perp$ indicates that the area referred to in the formula is the area perpendicular to the magnetic field.

Magnetic flux is measured in webers (named after Wilhelm Eduard Weber). One weber (Wb) is the amount of magnetic flux from a uniform magnetic field with a strength of 1.0 tesla passing through an area of 1.0 square metre. The magnetic flux can also take on positive and negative values, depending on which side of the area the magnetic field is coming from.

This description has assumed that the area is at right angles to the magnetic field, as shown in figure 4.8a. This leads to a maximum value for BA . If the magnetic field went through the area at an angle less than 90° , as shown in figure 4.8b, the amount of magnetic flux passing through the area would be less. In fact, if the magnetic field is parallel to the area, the amount of magnetic flux will be zero, as shown in figure 4.9. None of the magnetic field lines pass through the area from one side to the other.

Diagram illustrating magnetic flux through a surface. A light blue oval represents the surface, labeled "Area A (parallel to the magnetic field)". Four horizontal blue arrows, representing the magnetic field B , point to the right and pass through the surface.

Calculate the magnetic flux in each of the following situations.



THINK

- a. The magnetic field is perpendicular to the area, so use the formula $\Phi_B = \mathbf{B}_\perp A$ to determine the flux, where $\mathbf{B} = 0.05 \text{ T}$ and $A = 0.30 \text{ m}^2$.

WRITE

$$\begin{aligned}\text{a. } \Phi_B &= B_{\perp} \times A \\ &= 0.050 \text{ T} \times 0.30 \text{ m}^2 \\ &= 0.015 \text{ Wb}\end{aligned}$$

b. 1. First calculate area A . (Don't forget to convert the radius to metres.)

$$\begin{aligned} b. A &= \pi r^2 \\ &= \pi \times 0.08^2 \\ &= 0.02 \text{ m}^2 \end{aligned}$$

2. The magnetic field is perpendicular to the area, so use the formula $\Phi_B = B_{\perp} A$ to determine the flux, where $B = 0.2 \text{ T}$ and $A = 0.020106 \text{ m}^2$.

$$\begin{aligned} \Phi_B &= B_{\perp} \times A \\ &= 0.2 \text{ T} \times 0.02 \text{ m}^2 \\ &= 0.004 \text{ Wb} \end{aligned}$$

c. The plane of the loop is parallel to the magnetic field, hence there are no field lines passing through the area.

$$\begin{aligned} c. B_{\perp} &= 0 \\ \Phi_B &= B_{\perp} \times A \\ &= 0 \times A \\ &= 0 \text{ Wb} \end{aligned}$$

PRACTICE PROBLEM 2

A vertical square coil of wire of side length 6.0 cm is placed into a horizontal magnetic field of strength 0.15 T. Calculate the amount of flux through the coil.

CALCULATING THE MAGNETIC FLUX QUANTITATIVELY

In general, the magnetic flux can be expressed in terms of the magnetic field strength, the area and the angle (θ) between the magnetic field and a normal to the area:

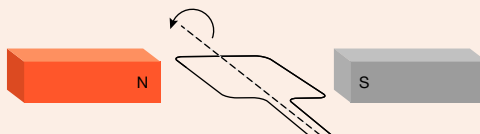
$$\Phi_B = BA \cos \theta$$

For example, if the plane of the loop is parallel to the magnetic field, the angle between the field and the normal to the area is 90° . As $\cos(90^\circ) = 0$, using the formula $\Phi_B = BA \cos \theta$ will determine the flux to be 0 Wb.

4.3 EXERCISE

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

1. What is the difference between magnetic flux and magnetic field strength?
2. Calculate the maximum magnetic flux passing through:
 - (a) a single coil of area 0.050 m^2 in a magnetic field of strength 3.0 T
 - (b) a single coil of area 4.5 cm^2 in a magnetic field of strength 0.4 T
 - (c) a single coil with a radius of 0.3 m in a magnetic field of strength 0.025 T.
3. A square loop of wire of side length 5.0 cm is placed in a magnetic field of strength 0.030 T, as shown in the following diagram. The loop is free to rotate about its horizontal axis.



- (a) What is the magnetic flux passing through the loop when it is in the position shown in the diagram?
- (b) The loop is now rotated 90° about its axis from its original position. What is the magnetic flux passing through the loop when it is in its new position?
- (c) Draw a graph of the magnetic flux passing through the loop as it is rotated anticlockwise through one revolution from the position shown in the diagram.

4.4 Generating emf from a changing magnetic flux

KEY CONCEPTS

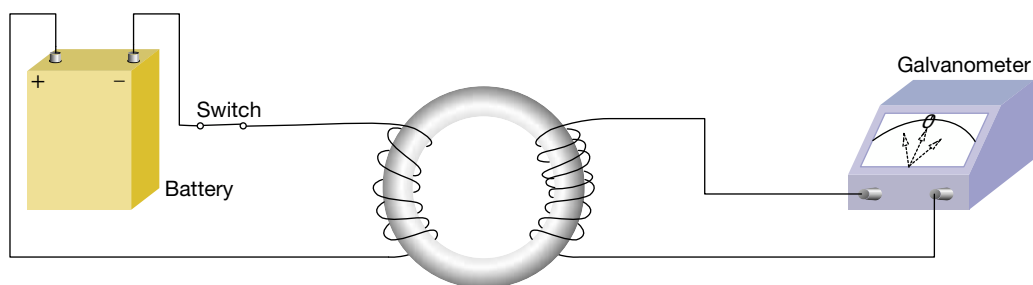
- Investigate and analyse theoretically and practically the generation of electromotive force (emf) including AC voltage and calculations using induced emf, $\varepsilon = -N \frac{\Delta \Phi_B}{\Delta t}$, with reference to:
 - rate of change of magnetic flux
 - number of loops through which the flux passes
 - direction of induced emf in a coil.

4.4.1 Faraday's discovery of electromagnetic induction

Michael Faraday was aware of the magnetic effect of a current and he spent six years searching for the reverse effect — that is, the electrical effect of magnetism.

His equipment consisted of two coils of insulated wire, wrapped around a wooden ring. One coil was connected to a battery, the other to a **galvanometer**, a sensitive current detector. Faraday observed that the galvanometer needle gave a little kick as the battery switch was opened and a little kick the opposite way as the switch was closed. The rest of the time, when the switch was either open or closed, the needle was stationary, reading zero. The current was momentary, not the constant current he was looking for. What Faraday had observed came to be called **electromagnetic induction**.

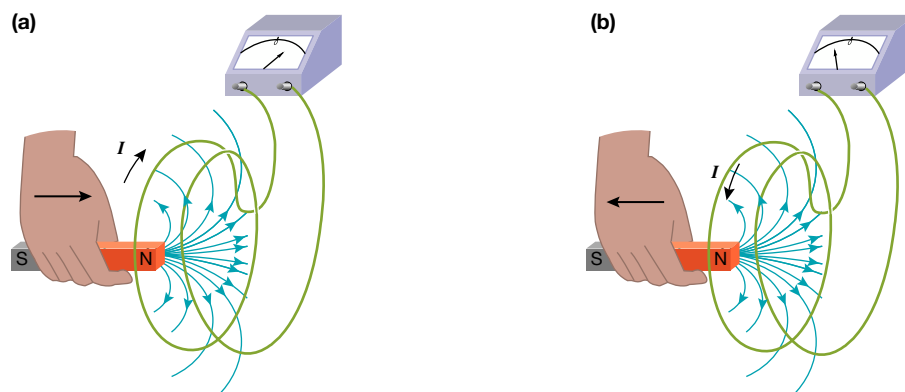
FIGURE 4.10 When the switch in the battery circuit is opened or closed, there is a momentary current through the galvanometer.



Investigating further, Faraday found that using an iron ring instead of a wooden one increased the size of the current. He concluded that when the magnetic field of the battery coil was changing, there was a current induced in the other coil.

He therefore replaced the battery coil with a magnet. Moving the magnet through the other coil changed the magnetic field and produced a current. The faster the magnet moved, the larger the current. When the magnet was moved back away from the coil, current flowed in the opposite direction.

FIGURE 4.11 Magnet (a) moving into a coil and (b) away again



If there was an induced current, there must have been an induced emf. An emf, $\mathcal{E}$, gives energy to a charge to move it through the wire, and the resistance of the wire limits the size of the current. So it is more correct to say that the changing magnetic field induced an emf.



Resources



Digital document Investigation 4.1 Generating a current (doc-31592)

4.4.2 Factors that affect induced emf

Rate of change of magnetic flux

The concept of magnetic flux can be used to explain the induced emf. The two principles are described here.

1. An emf is induced in a coil when the amount of magnetic flux passing through the coil changes.
2. The size of the emf depends on how quickly the amount of magnetic flux changes.

These two statements can be written formally as follows:

$$\mathcal{E}_{\text{average}} = \frac{\Delta\Phi_B}{\Delta t}$$

This statement is known as Faraday's Law. The word 'average' is included because the change in magnetic flux takes place over a finite interval of time.

Lenz's Law states:

The direction of the induced current is such that its magnetic field is in the opposite direction to the change in magnetic flux.

In other words, a coil responds to a change in magnetic flux in such a way as to keep its magnetic environment constant. If the coil experiences an increase in flux, it will compensate by inducing a magnetic field in the opposite direction to the flux. If the coil experiences a decrease in flux, it will compensate for the loss by inducing a magnetic field in the same direction as the flux.

This can be incorporated in the equation as a minus sign:

$$\mathcal{E} = \frac{-\Delta\Phi_B}{\Delta t}$$

Number of loops

Examples concerning emf have been previously discussed when there is a single coil of wire. When there are multiple turns (or loops) in the coil, the emf produced will be the sum of all the individual turns. Therefore, if the coil consists of several turns of wire, the equation can be generalised further:

$$\varepsilon = -N \frac{\Delta\Phi_B}{\Delta t}$$

where: ε is the induced emf, in V

N is the number of turns (or loops) in the coil

$\Delta\Phi_B$ is the change in magnetic flux, in Wb

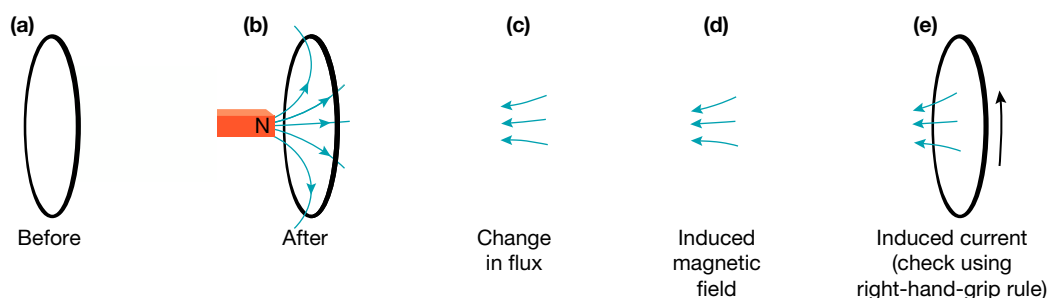
Δt is the time interval, in s

Direction of induced emf in a coil

There is no magnetic flux passing through the loop in figure 4.12a. When the magnet approaches the coil from the left (figure 4.12b), there is an increase in the amount of magnetic field passing through the coil from left to right. The loop has experienced a change in the magnetic flux passing through it (figure 4.12c), and the direction of this change is from left to right. The change in magnetic flux induces a current in the coil, and the current in the coil then induces a magnetic field. The direction of the induced magnetic field due to the induced current in the loop must be such that it opposes the change in the magnetic flux. This means its direction will be from right to left (figure 4.12d). To achieve an induced magnetic field from right to left, the induced current, using the right-hand-grip rule, must be travelling up the front of the loop (figure 4.12e).

The coil responds in such a way as to keep its magnetic environment constant. In the example shown in figure 4.12, there is an increase in flux from left to right, so the induced magnetic field opposes this increase by going from right to left. When the magnet is pulled back, the flux that is still going from left to right is decreasing, so the induced magnetic field adds to the existing flux to compensate for the loss; therefore, this induced field points from left to right.

FIGURE 4.12 The loop (a) before and (b) after; (c) change in flux, (d) direction of induced field and (e) direction of current

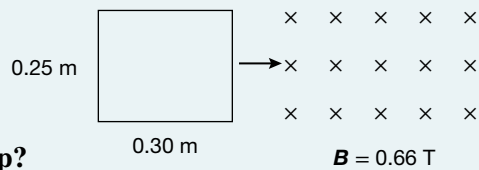


To determine the direction of the induced current in a coil according to Lenz's Law, the problem needs to be broken down into several steps:

1. Determine the change in flux: is it increasing or decreasing (and in which direction)?
2. Determine the direction of the induced magnetic field such that it compensates for the increase or decrease in flux.
3. Determine the direction that the induced current must flow in order to produce the induced magnetic field in step 2.

SAMPLE PROBLEM 3

The rectangular loop shown in the following diagram takes 2.0 s to fully enter a perpendicular magnetic field of strength 0.66 T. The loop has a resistance of 0.5 Ω .



- What is the magnitude of the emf induced in the loop?
- In which direction does the current flow around the loop?
- What is the average induced current in the loop?

Teacher-led video: SP3 (tlvd-0138)

THINK

1. First calculate the area of the loop.
2. Now find the change in flux.
3. Use Faraday's Law to determine the induced emf.

WRITE

$$\begin{aligned}
 \text{a. } A &= L \times W \\
 &= 0.25 \text{ m} \times 0.30 \text{ m} \\
 &= 0.075 \text{ m}^2 \\
 \Delta\Phi_B &= \Phi_{B \text{ final}} - \Phi_{B \text{ initial}} \\
 &= (BA)_{\text{final}} - (BA)_{\text{initial}} \\
 &= (0.66 \text{ T} \times 0.075 \text{ m}^2) - (0 \text{ T} \times 0.075 \text{ m}^2) \\
 &\quad \text{(The initial field strength through the coil is zero.)} \\
 &= (0.050 \text{ T m}^2) - (0 \text{ T m}^2) \\
 &= 0.050 \text{ Wb into the page}
 \end{aligned}$$

$$\begin{aligned}
 \varepsilon &= -N \frac{\Delta\Phi_B}{\Delta t} \\
 &= -1 \times \frac{0.050 \text{ Wb}}{2.0 \text{ s}} \\
 &= -0.025 \text{ V}
 \end{aligned}$$

The magnitude of the induced voltage is 0.025 V.
(The minus sign indicates that the induced emf opposes the change in magnetic flux.)

1. Determine the direction of the flux, and whether the flux is increasing or decreasing.
2. Use Lenz's Law to determine the direction of the induced magnetic field.
3. Use the right-hand-grip rule to determine the direction of the induced current.
- c. Use Ohm's Law, $V = IR$, to calculate the average current in the loop, where $V = 0.025 \text{ V}$ and $R = 0.5 \Omega$.

- The flux increases from 0 Wb to 0.050 Wb into the page as the loop moves into the field.

Lenz's Law states that the induced magnetic field opposes the change in flux. Because the flux is increasing, the direction of the induced magnetic field will be in the opposite direction to the flux. Hence the direction of the induced field will be out of the page.

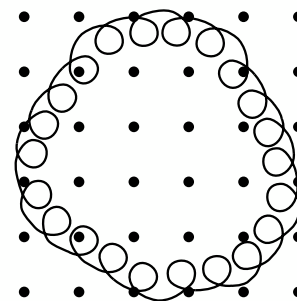
In order for the induced magnetic field to be directed out of the page, the induced current must flow in an anticlockwise direction around the loop.

$$\begin{aligned}
 \text{c. } V &= IR \\
 0.025 \text{ V} &= I \times 0.5 \Omega \\
 I &= \frac{0.025 \text{ V}}{0.5 \Omega} \\
 &= 0.05 \text{ A}
 \end{aligned}$$

PRACTICE PROBLEM 3

A spring is bent into a circle and stretched out to a radius of 5.0 cm. It is then placed in a magnetic field of strength 0.55 T. The spring is released and contracts down to a circle of radius 3.0 cm. This happens in 0.15 seconds. The spring has a resistance of 0.4 Ω .

- What is magnitude of the induced emf?
- In what direction does the current move?
- What is the average induced current in the spring?



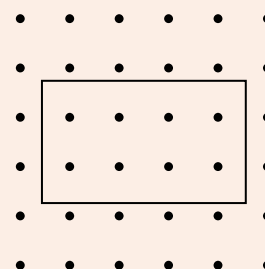
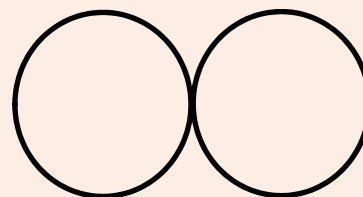
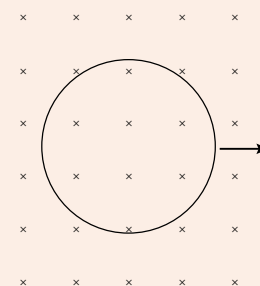
on Resources

-  **Digital documents** Investigation 4.2 Inducing a current in a coiled conductor (doc-31593)
Investigation 4.3 Direction of induced currents (doc-31594)
-  **Teacher-led video** Investigation 4.3 Direction of induced currents (tlvd-0231)
-  **Video eLesson** Magnetic flux and Lenz's Law (eles-0026)
-  **Interactivities** Magnetic flux and Lenz's Law (int-0050)
Generating an emf (int-0116)

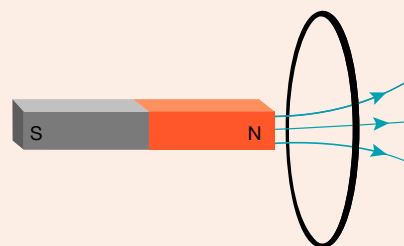
4.4 EXERCISE

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- Why did Faraday use coils with many turns of copper wire?
- The loop of wire shown in the diagram is quickly withdrawn from the magnetic field. Which way does the current flow in the loop?
- Two coils are stacked one on top of the other with their centres in line.
 - If a battery is switched on in the bottom coil, producing a clockwise current seen from above, what happens in the top coil?
 - Would the effect be different if the battery was connected to the top coil?
 - Would the effect be different if the battery was switched off?
- Two coils are placed side by side on a page with their centres in line, as in the diagram.
 - If a battery is switched on in the left coil, producing a clockwise current (seen from the left), what happens in the right coil?
 - Would the effect be different if the current was anticlockwise?
- The diagram shows a confined uniform magnetic field coming out of the page with a wire coil in the plane of the page. Is there an induced current in the coil as it is moved:
 - to the right
 - upwards
 - into the page
 - out of the page?
 Give a reason for each answer. If there is a current, indicate the direction.



6. Calculate the average induced emf in each of the following situations.
 - (a) A circular loop of wire with a 5.0 cm radius is removed from a magnetic field of strength 0.40 T in a time of 0.20 s.
 - (b) The magnetic flux through a coil changes from 60 Wb to 35 Wb in 1.5 s.
 - (c) The magnetic flux through a coil changes from 60 Wb to -35 Wb in 2.5 s.
7. Calculate the average induced current in each of the following situations.
 - (a) A circular loop of wire, 10 cm long with a resistance $0.40\ \Omega$, is removed from a magnetic field of strength 0.60 T in a time of 0.30 s.
 - (b) The magnetic field strength perpendicular to a square loop, of side length 0.26 m and resistance $2.5\ \Omega$, is increased from 0.20 T to 1.20 T in 0.50 s.
 - (c) A stretched circular spring coil with an 8 cm radius and resistance $0.2\ \Omega$ is threaded by a perpendicular magnetic field of strength 2.0 T. The coil shrinks back to a radius of 4 cm in 0.8 s.
8. (a) Use the relationship for the size of induced emf to show that the unit for the magnetic field, the tesla, can be written as $\text{volt} \times \text{second} \times \text{metre}^{-2}$.
 (b) Now use Ohm's Law and the definition of electric current to show that the tesla can also be written as $\text{ohm} \times \text{coulomb} \times \text{metre}^{-2}$.
 (c) Now use the definition of magnetic flux to show that the unit for magnetic flux, the weber, can be written as $\text{ohm} \times \text{coulomb}$.
9. An orbiting satellite has a small module tethered to it by a 5.0 km conducting cable. As the satellite and its module orbit Earth, they cut across Earth's magnetic field at right angles.
 - (a) If the pair are travelling at a speed of $6000\ \text{m s}^{-1}$, how far do they travel in 1.0 s?
 - (b) What area does the conducting cable cross during the 1.0 s period?
 - (c) If the strength of Earth's magnetic field at this distance is 0.1 mT, what is the size of the induced emf?
10. A bar magnet, with its north end down, is dropped through a horizontal wire loop.
 - (a) What is the direction of the induced current when the magnet is:
 - i. just above the loop
 - ii. halfway through the loop (so the north end is below the loop and south end is above the loop)
 - iii. just below the loop?
 - (b) Draw the graph of the induced current against time.
 - (c) Where did the electrical energy of the induced current come from?
 - (d) If the magnet falls from a very long distance above the loop to a very long distance below the loop, what is the overall change in magnetic flux through the loop? What does this imply about the area under the current-time graph?
11. How much charge, in coulombs, flows in a loop of wire of area $1.6 \times 10^{-3}\ \text{m}^2$ and resistance $0.20\ \Omega$ when it is totally withdrawn from a magnetic field of strength 3.0 T over 1 second?
12. A magnet passes through two loops, one wire and the other plastic. Compare the induced emfs and the induced currents of the two loops.
13. Lenz's Law is an illustration of the conservation of energy. Explain why the reverse of Lenz's Law (the direction of the induced current reinforces the change in magnetic flux) contravenes the law about the conservation of energy. Use the example of a north end of a magnet approaching a loop of conducting wire (as shown in the diagram).
14. Calculate the average emf in the axle of a car travelling at $120\ \text{km h}^{-1}$ if the vertical component of the Earth's magnetic field is $40\ \mu\text{T}$ and the length of the axle is 1.5 m.



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4.5 Generators and alternators

KEY CONCEPTS

- Explain the production of DC voltage in DC generators and AC voltage in alternators, including the use of split ring commutators and slip rings respectively
- Compare sinusoidal AC voltages produced as a result of the uniform rotation of a loop in a constant magnetic field with reference to frequency, period, amplitude, peak-to-peak voltage (V_{p-p}) and peak-to-peak current (I_{p-p})
- Compare alternating voltage expressed as the root-mean-square (rms) to a constant DC voltage developing the same power in a resistive component
- Convert between rms, peak and peak-to-peak values of voltage and current.

4.5.1 Induced emf in a rotating loop

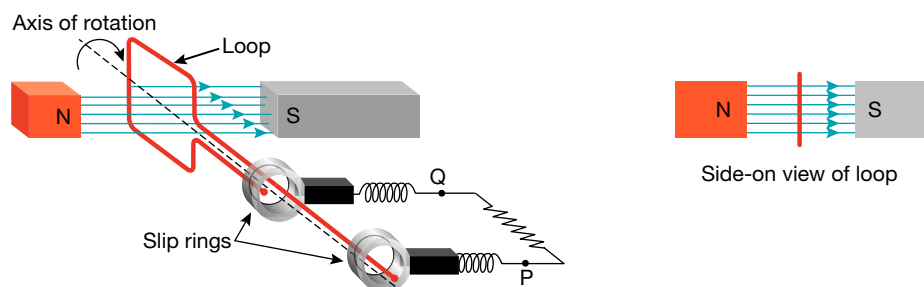
A magnet moving in and out of a coil to generate a current is not a very efficient means of converting the mechanical energy of the moving magnet into the electrical energy of a current in the coil. It does not have much technological potential; an alternative is needed.

Another way of changing the amount of magnetic flux passing through a loop is to rotate a loop in a magnetic field, as shown in figure 4.13.

When the loop is ‘face on’ to the magnetic field, the maximum amount of magnetic flux is passing through the loop: $\Phi_B = BA$. As the loop turns, the amount of flux decreases. When it has turned 90° and is parallel to the field, there is no flux passing through it at all: $\Phi_B = 0$. As the loop continues to turn between 90° and 180° , the magnetic field passes through the loop from the other side: a negative amount of flux, from the point of view of the loop.

As seen in figure 4.13, the magnitude of the magnetic flux passing through the loop increases to a maximum again, but in the opposite direction: $\Phi_B = -BA$. Then it decreases back to zero when the loop has rotated 270° , and finally passes through the original face of the loop.

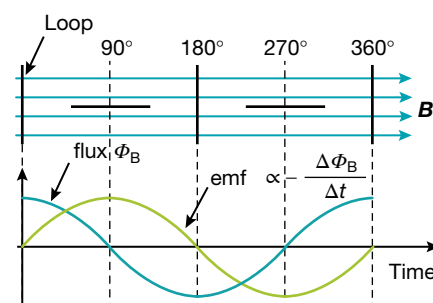
FIGURE 4.13 A loop ‘face on’ to a magnetic field has maximum magnetic flux.



The amount of magnetic flux passing through the loop varies in the form of a sine wave, as shown in figure 4.14. The induced emf across the ends of the loop is equal to the change of magnetic flux with time. Since $\varepsilon \propto -\frac{\Delta\Phi_B}{\Delta t}$, the induced emf is shown on the graph as the negative gradient function of the magnetic flux–time graph, and hence is also a sine wave.

The emf graph is the same shape as the flux graph but shifted sideways, so that when the flux is a maximum, the emf is zero. When the flux is at a maximum (or minimum) the flux–time graph is flat, so the gradient is zero and hence the emf is zero.

FIGURE 4.14 Flux–time graph



Similarly, when the flux is zero, the flux–time graph is steepest, so the gradient is a maximum (or minimum) and hence the emf is a maximum (or minimum).

4.5.2 AC alternators

Which way does the current travel when a rotating loop is placed in a magnetic field? Consider again figure 4.13. From which connection, P or Q, does the current leave the loop to go around the external circuit? This is not easy to determine. It can be worked out using Lenz's Law or using the magnetic force of electrons in the loop. Both methods are explained as follows (Note — in VCE Physics you only need to understand one explanation, so use the one in which you feel most confident.)

Using Lenz's Law

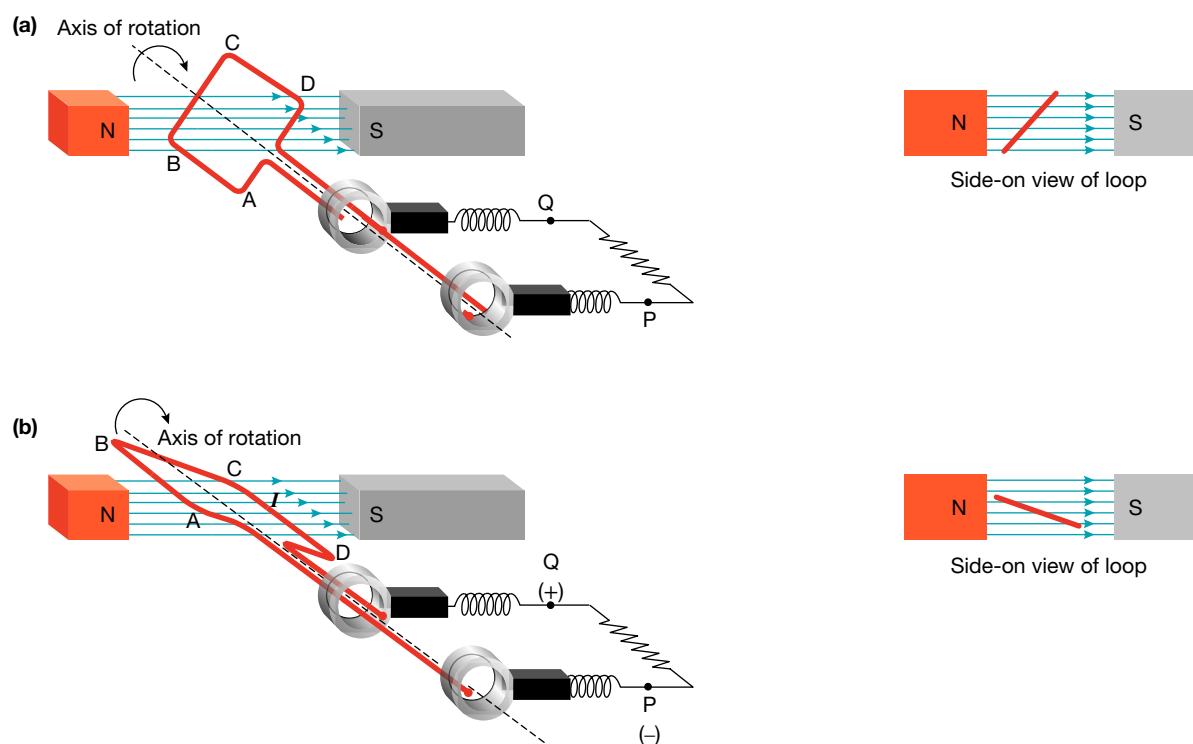
As the loop rotates, the magnetic flux changes from passing through one side to passing through the other.

In figure 4.15a, the magnetic flux is entering the loop from left to right above the edge AB. As the coil rotates clockwise to a horizontal position, the flux decreases to zero, inducing a current through the coil. The induced current induces a magnetic field from left to right to restore the decreasing flux.

In figure 4.15b, the loop continues to rotate in a clockwise direction from the horizontal position to the vertical position. The magnetic flux increases from zero, entering the loop from the other side below the edge AB. The induced magnetic field will now be from right to left to counteract the increase in flux.

To produce this field, the conventional current needs to run in the direction $A \rightarrow B \rightarrow C \rightarrow D$.

FIGURE 4.15 Direction of current flow as loop passes through the horizontal position



At this point in the rotation, the current will enter the external circuit from the slip ring at Q and return to the loop by the slip ring at P. So, for the time being, the current flows through the external circuit from Q to P, with Q being the positive terminal and P the negative.

In the diagrams in figure 4.15, the wire from A is attached to the front metal ring, the one connected to P, and the wire from D is attached to the back ring, the one connected to Q. These connections are fixed. When the loop rotates about its axis, the two slip rings also rotate about the same axis. The black blocks are made of graphite. They are being held in place against the spinning slip rings by the springs.

Graphite is used because it not only conducts electricity but is also a lubricant. The spinning slip rings easily slide past the fixed block. The blocks are also called ‘brushes’ because early designs used thin metal strips that rested against the slip rings.

Consider the loop as it continues to rotate clockwise from the position shown in figure 4.15b through the vertical position. The flux is increasing from left to right through the loop as it moves to the vertical position. The induced current flows through $A \rightarrow B \rightarrow C \rightarrow D$ in order to induce a magnetic field from right to left through the loop to counteract the increasing flux. When the loop rotates past the vertical position and begins to move again towards the horizontal position, the flux from left to right decreases, inducing a magnetic field from left to right through the loop, below the edge AB. For this to be possible, the induced current must now move in the direction $D \rightarrow C \rightarrow B \rightarrow A$. The current in the external circuit will now flow from P to Q, that is, in the opposite direction! The direction of the induced current will reverse every time the loop passes through the vertical position (when the plane of the loop is perpendicular to the field), or every half-turn.

The sinusoidal emf drives current through the external circuit first one way, then the opposite way, and is thus called **alternating current** (AC).

This design of a rotating coil in a magnetic field is called a **generator**. If the ends of the coil are connected to slip rings, then the voltage across the external connections is alternating in direction, producing an alternating current. The device is now called an **alternator**.

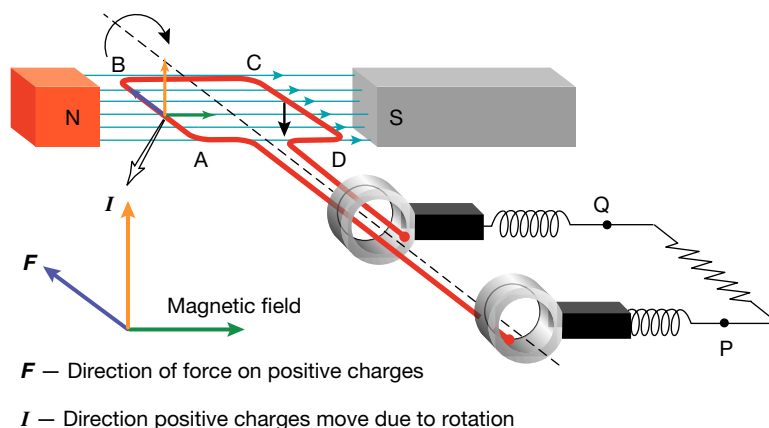
Using magnetic force on the charges in the wire

As the loop rotates through the horizontal plane, the left side of the loop, AB (see figure 4.16), is moving up, and the right side, CD, is moving down. The force of the magnetic field on the positive charges in AB will be towards B, while the force on the electrons in AB will be towards A.

Similarly, the positive charges in CD will be pushed to D, while the electrons will be pushed towards C.

This means that conventional current will flow in the direction $A \rightarrow B \rightarrow C \rightarrow D$, while the electrons will travel around the loop in the order $D \rightarrow C \rightarrow B \rightarrow A$. The conventional current will enter the external circuit from the slip ring at Q and return to the loop by the slip ring at P.

FIGURE 4.16 Using the left-hand rule to determine current direction in a rotating loop

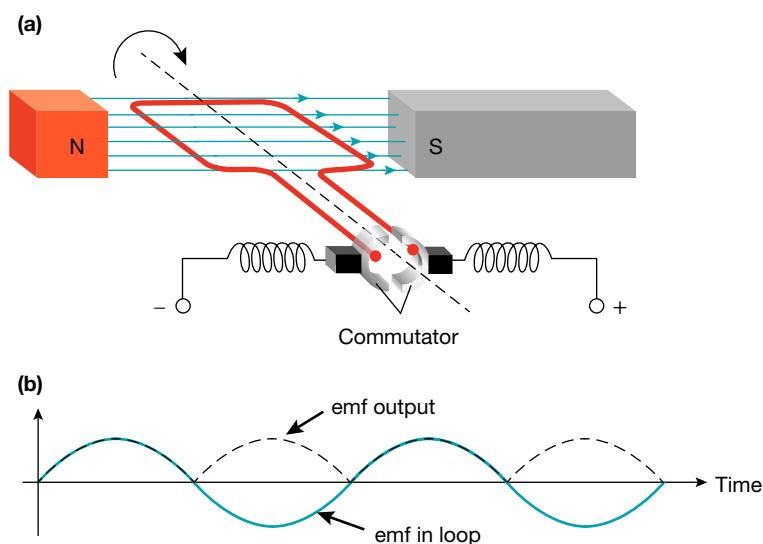


Once the loop passes through the vertical plane, AB will move downwards and CD will move upwards. The force of the magnetic field on the positive charges in AB will be towards A, while the force on the electrons in AB will be towards B, and the conventional current will now flow in the opposite direction, that is $D \rightarrow C \rightarrow B \rightarrow A$, entering the external circuit at P and returning to the loop at Q. This is the same result obtained as with the previous method.

4.5.3 DC generators

Now, take a look at what happens if the slip rings are replaced with split rings like those used in a DC motor. When the current in the loop reverses every half-cycle as the loop rotates through the vertical position, the ends of the coil swap to the other side of the split ring so that the direction of the current flowing through the external circuit remains the same. Essentially, the direction of the output to the external circuit is changed by the commutator, and so the alternating current in the loop is converted into pulsating **direct current** (DC) in the external circuit. The device is now called a DC generator.

FIGURE 4.17 AC voltage coming from loop, and DC coming from commutator



4.5.4 Comparison of motors and generators

Recall from topic 3 that a motor consists of a coil connected to a power supply in the presence of a magnetic field. The magnetic field induces a force on the electrons moving through the coil, causing the coil to turn. A motor converts electrical energy into mechanical energy.

A generator consists of a coil in the presence of a magnetic field. By manually rotating the coil, the magnetic flux through the coil changes, inducing a current through the coil. If connected to an external circuit, the current through the coil can provide electricity to the circuit. A generator converts mechanical energy into electrical energy.

**Motors convert electrical energy into mechanical energy.
Generators convert mechanical energy into electrical energy.**

Back emf

Considering what you have learned in this topic, the current in the loop of a motor induces its own magnetic field. By Lenz's Law, this magnetic field acts in the direction opposite to the change in flux, meaning that the current induces an emf, in the opposite direction, known as a **back emf**. This results in the net emf in the motor being less than the supplied emf when the motor is rotating.

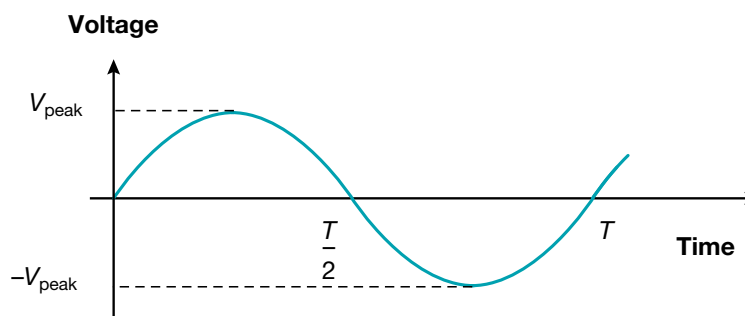
4.5.5 Peak, RMS and peak-to-peak voltages

The voltage output of an AC generator varies with time, producing a sinusoidal signal. This signal, shown in figure 4.18, can be described in terms of the physical quantities listed here.

- The **period**, T , is the time taken for one complete cycle.
- The **frequency**, f , is the number of full cycles completed in one second. The frequency is related to the period by the equation:

$$T = \frac{1}{f}$$

FIGURE 4.18 Sinusoidal signal from voltage output of an AC generator



The frequency of the power supplied to households is 50 Hz (1 hertz is one cycle per second). The period is therefore $\frac{1}{50}$ per second = 0.02 s.

- The **amplitude** is the maximum variation of the voltage output from zero. It is called the **peak voltage**, V_{peak} . Similarly, the amplitude of the current is called the **peak current**, I_{peak} .
- The **RMS** (root mean square) **voltage**, V_{RMS} , is the value of the constant DC voltage that would produce the same power as the AC voltage across the same resistance. The RMS voltage is related to the peak voltage by the equation:

$$V_{\text{RMS}} = \frac{V_{\text{peak}}}{\sqrt{2}}$$

The peak voltage of a 240 V_{RMS} household power supply is 339 V. A 240 V_{RMS} output from a generator delivers the same amount of power as a 240 V DC power supply across the same resistance. Similarly, I_{RMS} is the value of a DC current that generates the same power as an AC current through the same resistance:

$$I_{\text{RMS}} = \frac{I_{\text{peak}}}{\sqrt{2}}$$

- The **peak-to-peak voltage**, V_{p-p} , is the difference recorded between the maximum and minimum voltages. In the case of a symmetrical AC voltage:

$$V_{p-p} = 2V_{\text{peak}}$$

$$I_{p-p} = 2I_{\text{peak}}$$

SAMPLE PROBLEM 4

A digital multimeter gives a measurement of 6.3 V for the RMS value of an AC voltage. A CRO is used to measure the peak-to-peak voltage. What value do you expect?

 Teacher-led video: SP4 (tlvd-0139)

THINK

1. Calculate the peak voltage when $V_{\text{RMS}} = 6.3 \text{ V}$.

WRITE

$$V_{\text{RMS}} = \frac{V_{\text{peak}}}{\sqrt{2}}$$

$$6.3 = \frac{V_{\text{peak}}}{\sqrt{2}}$$

$$V_{\text{peak}} = 6.3\sqrt{2}$$

$$V_{\text{p-p}} = 2V_{\text{peak}}$$

$$= 2 \times 6.3 \times \sqrt{2} \text{ V}$$

$$= 18 \text{ V}$$

2. Calculate the peak-to-peak voltage.

PRACTICE PROBLEM 4

A toaster is rated at 230 V_{RMS} and 1800 W. (Recall that $P = IV$.) What are the values of the RMS and peak currents?

4.5.6 Producing a greater emf

The AC voltage produced by a generator has a substantial technological application because it is easy to make things spin. Hydroelectricity is produced when water falls under gravity through pipes and hits the vanes of a propeller connected to a generator. In coal and gas-fired turbines, the burning fuel heats up water to a high temperature and pressure to direct against the vanes of the turbine.

The emf that is produced by a generator has a frequency that is the same as the frequency of the rotation of a coil in a magnetic field.

Using the Faraday equation for average emf:

$$\varepsilon = \frac{-N\Delta\Phi_B}{\Delta t} = \frac{-N\Delta(B_{\perp}A)}{\Delta t}$$

and ignoring the $-$ sign (which relates to direction), the ways to produce a larger emf can be deduced, as follows:

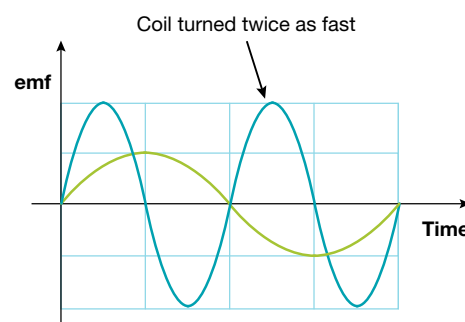
- increase the number of turns
- increase the strength of the magnetic field
- increase the area of each coil
- decrease the time for one turn (that is, increase the frequency of rotation).

(Note that turning the coil twice as fast doubles both the induced emf and the frequency — that is, it halves the period.)

FIGURE 4.19 Vanes of a turbine



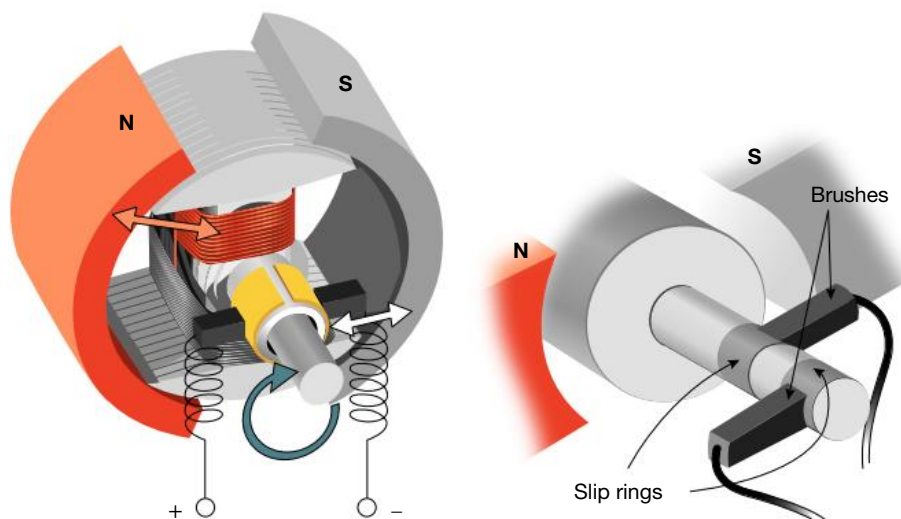
FIGURE 4.20 Doubling the frequency doubles the induced emf.



Other technological strategies can also increase the emf:

- The pole ends of the magnet can be curved so that the coils are close to the magnets for more time during the rotation.
- An iron core can be placed inside the coils to strengthen the magnetic field.
- The coils can be wound onto the iron core in grooves cut into the outer surface so that the iron core is as close as possible to the magnetic poles to increase the magnetic field.

FIGURE 4.21 Improvements to the design of a DC motor and an alternator



4.5 EXERCISE

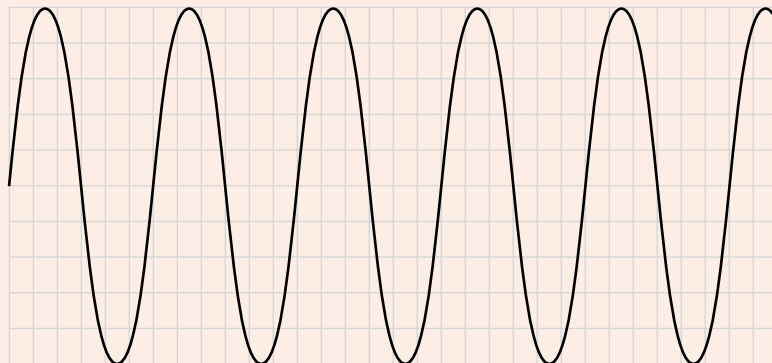
To answer questions online and to receive **immediate feedback** and **sample responses** for every question, go to your learnON title at www.jacplus.com.au.

1. A coil with an area of 0.04 m^2 of 100 turns spins at a rate of 50 Hz in a magnetic field of strength 2.5 T.
 - (a) What is the average emf induced as the coil turns from parallel to the field to perpendicular to the field?
 - (b) What is the average emf as the coil does one complete turn?
2. How can a motor operate as a DC generator?
3. A DC motor has a coil rotating in a magnetic field. This rotation produces a 'back emf' that opposes the current from the battery.
 - (a) How does the back emf vary with the speed of the motor?
 - (b) How then would the current vary with the speed of the motor?
 - (c) If the DC motor is used to lift masses, the speed of the motor is less for heavier masses. Why is there a risk that a heavy mass would burn out the motor?
4. In the past, electronic valves were powered by $6.3 V_{\text{RMS}}$ AC. What was the maximum voltage received by a valve?

5. A CRO shows the following trace. The settings are:

Y: 10 mV per division

X: 5 ms per division.



For this AC signal, what are the:

- (a) period
 - (b) frequency
 - (c) peak voltage
 - (d) peak-to-peak voltage
 - (e) RMS voltage
6. Some appliances are designed to run off either AC or batteries. The size of the batteries is equivalent to the peak of the AC voltage. If the appliance can run off 9 V DC, what RMS voltage would it also run off?

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4.6 Review

4.6.1 Summary

- A metal rod moving across a magnetic field experiences an induced voltage across its ends.
- The induced voltage across the ends of a moving conductor in a magnetic field will produce an electric current if the ends are connected by a wire outside the magnetic field.
- Magnetic flux is a measure of the amount of magnetic field passing through an area. It is measured in webers (Wb). Its magnitude is the product of the component of the area, A , and the magnetic field strength, B , that is perpendicular to the area.
- An emf is induced in a loop if the magnetic flux passing through the loop changes. The emf induced in a single loop is given by $\text{emf} = \frac{-\Delta\Phi_B}{\Delta t}$, where Φ_B is the magnetic flux. The negative sign in the equation acknowledges Lenz's Law, which states that the induced current (and hence emf) is such that it creates a magnetic field that opposes the change in flux.
- The emf generated in N loops threaded by a magnetic flux, Φ_B , is given by $\text{emf} = \frac{-N\Delta\Phi_B}{\Delta t}$.
- In an alternator, a coil rotates in a magnetic field to induce a sinusoidal voltage and therefore an alternating current. Slip rings are used at the end of the coil to allow the alternating current to flow in an external circuit.
- In a DC generator, the slip rings are replaced with a commutator to allow a direct current to flow in an external circuit.
- The voltage output of an AC generator can be described in terms of its amplitude, frequency and period. The amplitude of the voltage output is known as the peak voltage, V_{peak} . The peak-to-peak voltage, $V_{\text{p-p}}$, is the difference between the maximum and minimum voltages of the output.
- The RMS (root mean square) voltage, V_{RMS} , is the value of the constant DC voltage that would produce the same power as AC voltage across the same resistance. Similarly, I_{RMS} is the value of the constant direct current that would produce the same power as alternating current through the same resistance.
- The emf produced by a generator can be increased by increasing the number of turns in the coil, increasing the strength of the magnetic field, increasing the area of each coil or increasing the frequency of rotation of the coil.

Resources

studyON

To access key concept summaries and past VCAA exam questions download and print the **studyON: Revision and past VCAA exam question booklet** (sonr-0053).

4.6.2 Key terms

An **alternating current** is an electric current that reverses direction at short, regular intervals.

An **alternator** is a device in which the ends of the coil are connected to slip rings, causing the voltage to alternate in direction, inducing an alternating current (AC).

The **amplitude** of a periodic disturbance is the maximum variation from zero.

A **back emf** is an electromagnetic force that opposes the main current flow in a circuit. When the coil of a motor rotates, a back emf is induced in the coil due to its motion in the external magnetic field.

A **direct current** is an electric current that flows in one direction only.

Electromagnetic induction is the generation of an electric current in a coil as a result of a changing magnetic field or as a result of the movement of the coil within a constant magnetic field.

An **emf** is a source of voltage that can cause an electric current to flow.

The **frequency**, f , of a periodic wave is the number of times that the wave repeats itself every second.

A **galvanometer** is an instrument used to detect small electric currents, as well as being able to detect the direction of current (such as in AC).

A **generator** is a device in which a rotating coil in a magnetic field is used to induce a voltage.

An **induced voltage** is a voltage that is caused by the separation of charge due to the presence of a magnetic field.

Magnetic flux is a measure of the amount of magnetic field passing through an area. It is measured in webers (Wb).

Magnetic flux density, B , is the strength of a magnetic field, which is measured in tesla (T) or weber per square metre (Wb m^{-2}).

The **peak current**, I_{peak} , is the amplitude of an alternating current.

The **peak voltage**, V_{peak} , is the amplitude of an alternating voltage.

The **peak-to-peak voltage**, $V_{\text{p-p}}$, is the difference between the maximum and minimum voltages of a DC voltage.

The **period**, T , of a periodic wave is the time it takes a source to produce a complete wave. This is the same as the time taken for a complete wave to pass a given point.

The **RMS** (root mean square) **voltage**, V_{RMS} , is the value of the constant DC voltage that would produce the same power as AC voltage across the same resistance.



Resources



Digital document Key terms glossary (doc-32252)

4.6.3 Practical investigation

Investigation 4.1

Generating a current

Aim:

- To investigate the direction of a current in a conductor that is moving relative to a magnetic field
- To investigate the factors affecting the magnitude of a current in a conductor that is moving relative to a magnetic field.

Digital document: doc-31592

Investigation 4.2

Inducing a current in a coiled conductor

Aim: To investigate how a current can be induced in a coiled conductor, and to determine factors that affect the size of the induced current

Digital document: doc-31593

Investigation 4.3

Direction of induced currents

Aim: To predict the direction of an induced current in a conducting coil and verify Lenz's Law

Digital document: doc-31594

Teacher-led video: tlvd-0231



Resources



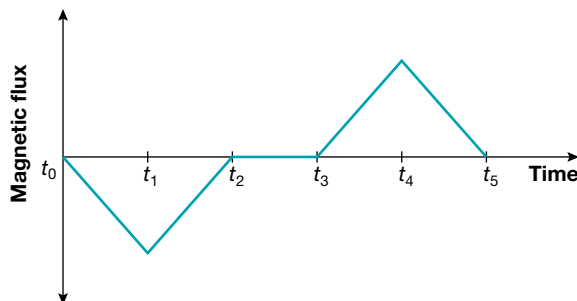
Digital document Practical investigation logbook (doc-32253)

4.6 Exercises

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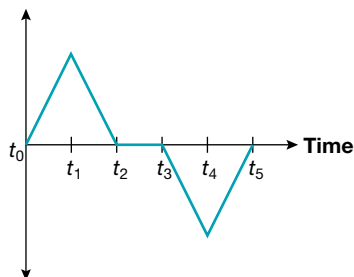
4.6 Exercise 1: Multiple choice questions

1. The variation of magnetic flux through a coil is shown in the following diagram:

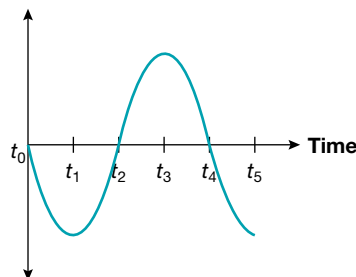


Which one of the following graphs best represents the corresponding induced EMF in the coil?

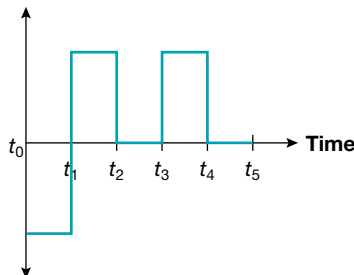
A. EMF



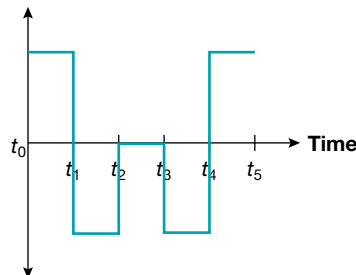
B. EMF



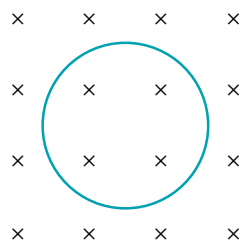
C. EMF



D. EMF



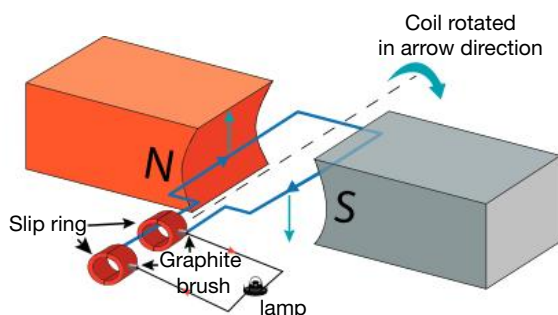
2. A coil consisting of 12 turns of a wire is held perpendicularly to a magnetic field as shown in the following diagram:



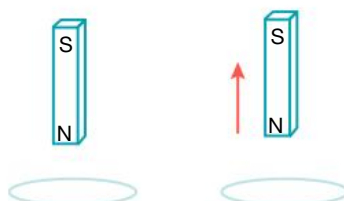
Which of the following actions would produce a current flowing clockwise in the coil?

- A. Stretching the coil
- B. Increasing the magnetic field strength
- C. Reversing the direction of the magnetic field
- D. Pulling the coil outside the magnetic field to the left

3. An AC generator is set up as in the following diagram. The coil is rotated continuously in a clockwise direction. Which one of the following best describes the effect that replacing the slip rings with a split ring commutator will have on the current through the external circuit?

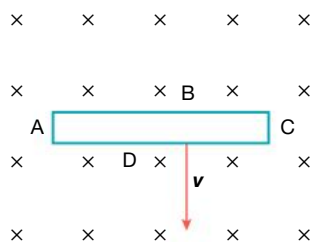


- A. The commutator will have no effect; an alternating current will flow through the coil and the external circuit, where the direction of the current changes with every half turn of the coil.
 - B. No current flows as the circuit is not connected to a power source.
 - C. The commutator will convert the AC current induced in the coil into a direct current through the external circuit.
 - D. The commutator will cause the induced current in the coil to flow in one direction only.
4. A bar magnet is pulled away from a copper ring as shown in the following diagram:



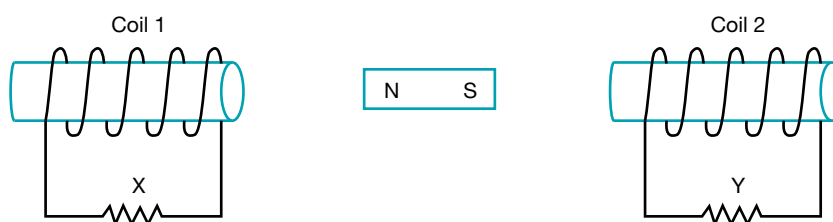
If a person was to view the ring from above, the current would flow in which one of the following ways?

- A. Clockwise
 - B. Anticlockwise
 - C. Clockwise followed by anticlockwise
 - D. Anticlockwise followed by clockwise
5. A thin, solid conductor with sides A, B, C, D is moving with a constant velocity through a magnetic field as depicted by the following diagram. Which side of the conductor will have the greatest concentration of electrons?



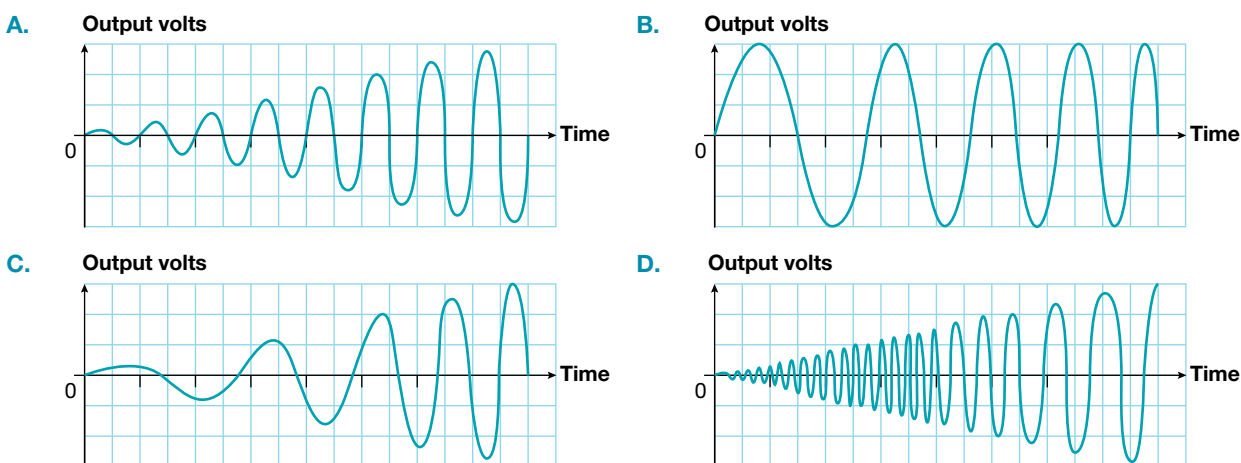
- A. Side A
- B. Side B
- C. Side C
- D. Side D

6. A magnet is placed between 2 coils as illustrated in the following diagram:

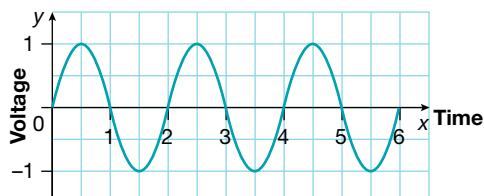


If the magnet is moved towards coil 1, in which direction will the induced currents flow through resistors X and Y respectively?

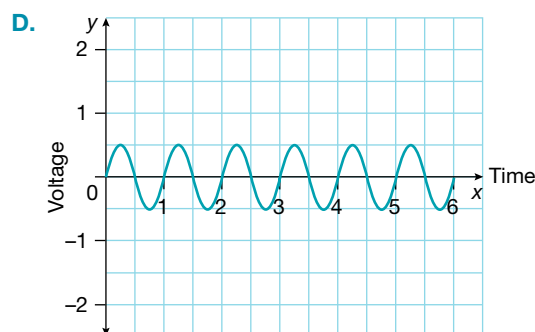
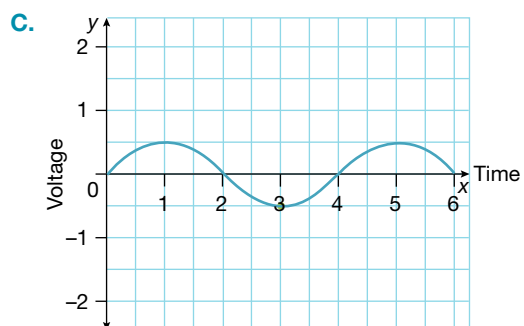
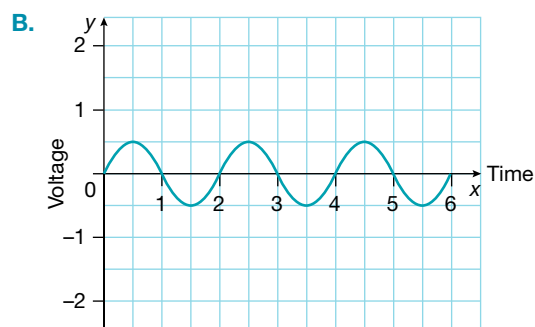
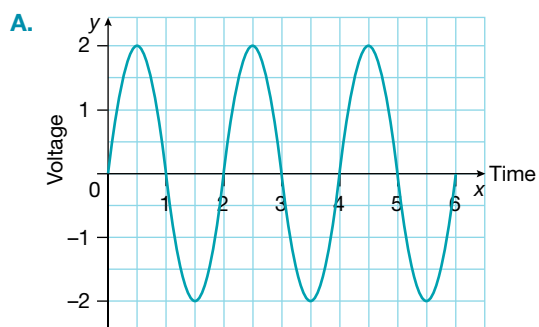
- A. X: from page right to page left, Y: from page right to page left
 - B. X: from page left to page right, Y: from page left to page right
 - C. X: from page left to page right, Y: from page right to page left
 - D. X: from page right to page left, Y: from page left to page right
7. An alternator speeds up gradually with time, starting at rest. Which one of the following graphs best represents the output voltage of this alternator?



8. A simple AC generator had its output voltage measured with a cathode ray oscilloscope. The coil was rotated at a constant velocity and the voltage–time graph produced can be seen in the following graph:



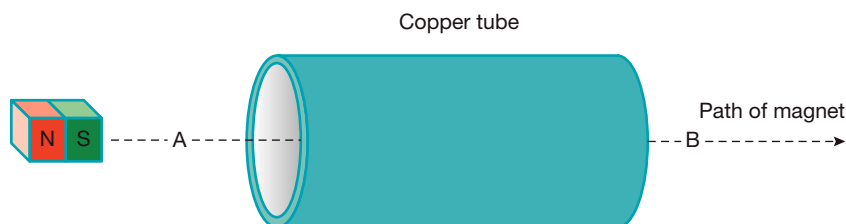
If the velocity of the turning coil was reduced to half of this input, which one of the following graphs would represent the output voltage?



9. A CRO is used to measure the peak-to-peak voltage, which is determined to be 24 V. The value for V_{RMS} is:
- A. 8.5 V
 - B. 12 V
 - C. 17 V
 - D. 9.6 V
10. A coil of wire with 50 turns was found to have an initial magnetic flux of 3.0 Wb. After 0.10 seconds, the induced emf was calculated as 2500 V. What would the magnetic flux have been after 0.10 seconds?
- A. 5.0 Wb
 - B. -5.0 Wb
 - C. -2.0 Wb
 - D. 2.0 Wb

4.6 Exercise 2: Short answer questions

1. A magnet passes through a copper tube at constant velocity along the path shown. A current is induced in the tube by the motion of the magnet.

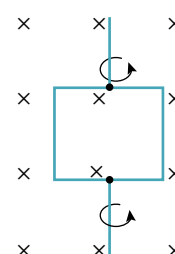


- a. Describe the force acting between the tube and the magnet at point A and justify your answer.
- b. Describe the force acting between the tube and the magnet at point B and justify your answer.

2. This figure shows a single loop of wire placed completely within a region of uniform magnetic field ($B = 3.2 \times 10^{-2} \text{ T}$) directed into the page. The loop of wire has an area of 8.0 cm^2 and is mounted so that it can be turned about the vertical axis as shown.

The loop rotates at a constant rate of 10 turns each second.

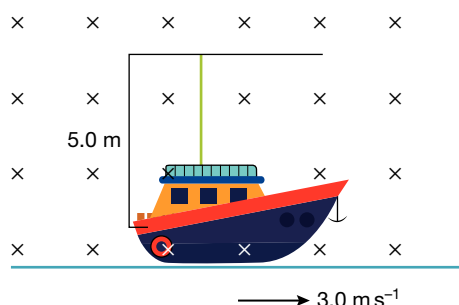
What is the value of the emf induced in the loop at the instant when the plane of the loop is first perpendicular to the direction of the magnetic field if the coil begins parallel to the field?



3. Veronica and Ron are investigating electromagnetic induction using a square coil. They place the coil between the poles of a magnet. The sides of the coil are 0.020 m long. The uniform magnetic field between the poles is $5.0 \times 10^{-2} \text{ T}$, and elsewhere in air it is assumed to be zero. Calculate the magnetic flux through the coil when it is entirely within and perpendicular to the magnetic field.
4. A coil consisting of 10 turns of wire is held at right angles to a uniform magnetic field, and the coil is completely within and perpendicular to the magnetic field.

The area enclosed by the coil is A . The magnetic field is decreased from B to $\frac{B}{3}$ in time t . Write an expression for the induced emf in the 10-turn coil in terms of the quantities given.

5. A boat sails at 3.0 m s^{-1} due east, where the Earth's magnetic field is $5.0 \times 10^{-5} \text{ T}$ due north and horizontal. The boat carries a vertical aerial 5.0 m long.



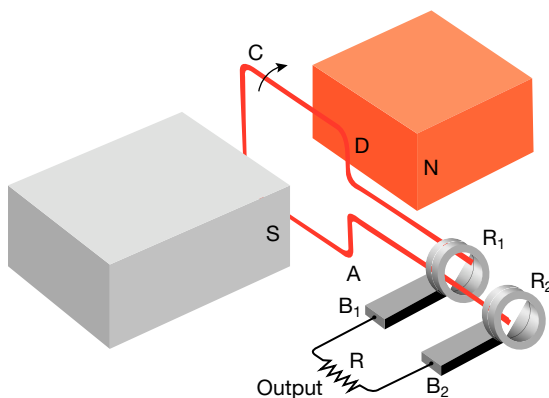
What will be the magnitude of the emf induced in the aerial?

6. An AC supply of 100 Hz is connected to a circuit, resulting in an RMS current of 2.0 A being observed. Sketch the graph of this current over time, showing at least one complete period.

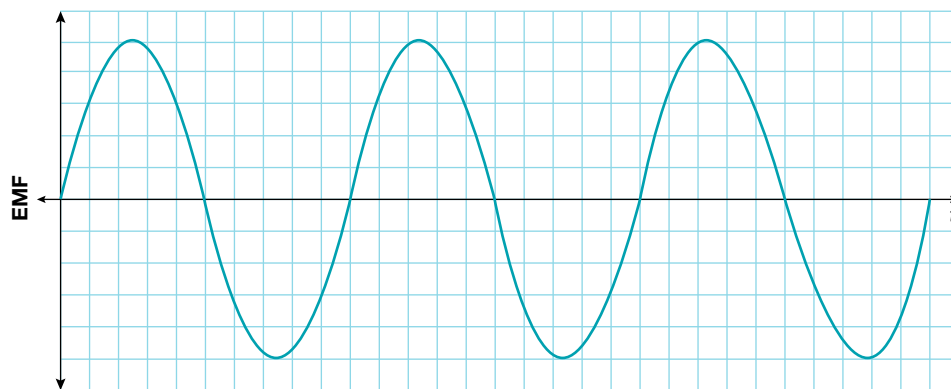
4.6 Exercise 3: Exam practice questions

Question 1 (6 marks)

Jake and Jenny have constructed a simple alternator. It consists of a single rectangular coil of wire, $0.60\text{ m} \times 0.40\text{ m}$, which is connected to slip rings, as shown in the following diagram. The coil is in a uniform magnetic field of 0.15 T and can be turned in the direction as shown in the diagram. Jake and Jenny test this alternator by rotating the loop 90 degrees for a period of 0.30 s .



- a. What is the magnitude of flux through the coil when orientated as shown in the diagram? **2 marks**
- b. What is the average voltage measured through the slip rings? **2 marks**
- c. Jenny now rotates the coil at a constant rate of 5 revolutions per second, and the students observe that the voltage between the slip rings varies with time as shown in the following diagram.

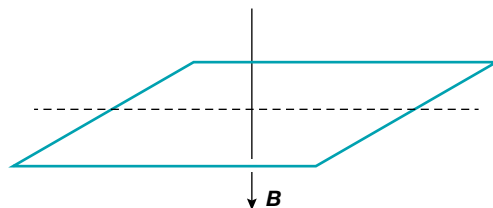


Jake decides to test the effect of rotation speed and turns the coil at a rate of 10 revolutions per second. Copy the graph shown and sketch the effect this would now have on the variation of voltage with time.

2 marks

Question 2 (6 marks)

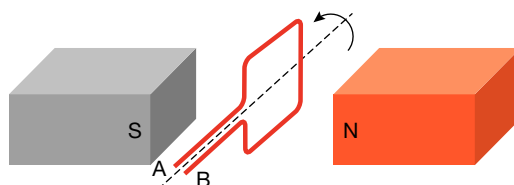
The following diagram shows a square loop of metal in a horizontal plane, situated in a uniform magnetic field $\mathbf{B}$ that is directed vertically downwards. The side length of the square is 0.25 m. The magnitude of $\mathbf{B}$ is 9.0×10^{-5} T.



- a. How much flux is threading the loop? 2 marks
- b. If the loop was rotated 90° about the horizontal axis, what would be the magnitude of flux now threading the loop? 2 marks
- c. If this 90° rotation took place in a time of 0.50 seconds, what would be the average EMF generated during this period of time? 2 marks

Question 3 (8 marks)

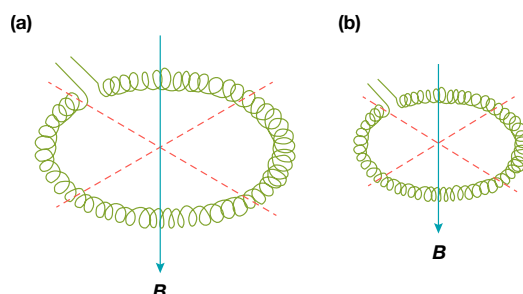
A single, circular coil of wire is placed perpendicularly to a magnetic field as shown in the following diagram. The magnetic field strength is 0.70 T and the flux threading the coil is 4.0×10^{-3} Wb.



- a. Calculate the area of the loop. 2 marks
- b. The loop is now rotated anticlockwise as shown in the diagram. If it is rotated at a rate of 10 revolutions per second, calculate the average emf generated in the loop. 2 marks
- c. On one set of axes, sketch the graphs of flux and emf generated over one complete rotation of the coil. 2 marks
- d. State two ways to increase the size of the emf generated in the loop. 2 marks

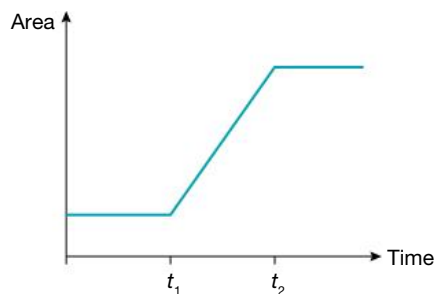
Question 4 (6 marks)

A wire spring is made into a circular loop of area 0.30 m^2 and is placed in a uniform magnetic field, $\mathbf{B}$, of 0.82 T, normal to the plane of the loop, as in part (a) of the following diagram.



- a. What is the magnetic flux through the loop shown in diagram (a)? 2 marks
- b. The area enclosed by the loop shrinks from 0.30 m^2 in diagram (a) to 0.10 m^2 in diagram (b) in a time of 0.10 seconds. What is the average emf induced? 2 marks

At time t_0 , the loop has an area of 0.10 m^2 , as in diagram (b). At time t_1 , the loop is made to expand back to its original size, which it reaches at time t_2 , in such a way that its area grows at a steady rate, as shown in the following graph:

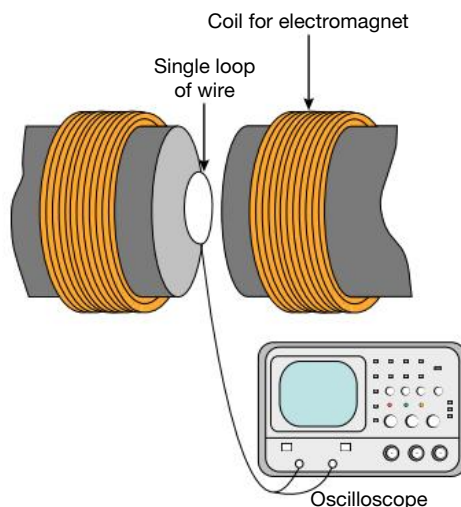


- c. Sketch a graph that represents the emf in the loop as a function of time.

2 marks

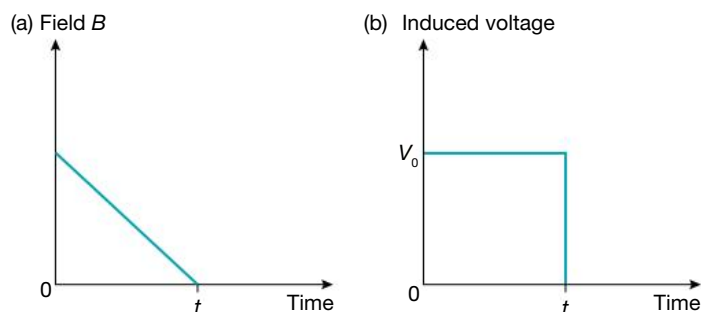
Question 5 (4 marks)

A student investigates electromagnetic induction using a single loop of wire and an electromagnet. As shown in the following diagram, the loop is placed between the pole pieces of the electromagnet, perpendicular to the magnetic field, and connected to an oscilloscope so that any induced voltage can be measured.



The current in the electromagnet's coil is reduced so that the magnetic field, B , decreases to zero at a constant rate over a time, t , as shown in part (a) of the following diagram. The induced voltage measured on the oscilloscope is shown in diagram (b).

- a. Explain why the induced voltage varies with time as shown. **2 marks**
- b. The magnetic field is found to have an initial value of 1.7 T and it takes $5.0 \times 10^{-3} \text{ s}$ to reduce to 0 T . If the magnitude of voltage generated is equal to 1.2 V , find the area of the loop of wire. **2 marks**



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5 Transmission of power

5.1 Overview

Numerous **videos** and **interactivities** are available just where you need them, at the point of learning, in your digital formats, learnON and eBookPLUS at www.jacplus.com.au.

5.1.1 Introduction

Without reliable electricity, everyone's lives would be drastically different. It is easy to take for granted the work that goes into ensuring that households and classrooms get a constant supply of electricity, safely. Electricity is produced at power stations, which are often far away from the towns and cities in which it is consumed. To reduce power loss, electricity must be transmitted sustainably. In this topic you will learn about transformers and their role in limiting power loss in the long-distance transmission of electricity.

FIGURE 5.1 High-voltage power lines are used to transmit electricity over long distances.



5.1.2 What you will learn

KEY KNOWLEDGE

After completing this topic you will be able to:

- Analyse transformer action with reference to electromagnetic induction for an ideal transformer:

$$\frac{N_1}{N_2} = \frac{V_1}{V_2} = \frac{I_2}{I_1}$$

- analyse the supply of power by considering transmission losses across transmission lines
- identify the advantage of the use of AC power as a domestic power supply.

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PRACTICAL WORK AND INVESTIGATIONS

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

on Resources

 **Digital documents** Key science skills — VCE Physics Units 1–4 (doc-32112)

Key terms glossary (doc-32254)

Practical investigation logbook (doc-32255)

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To access key concept summaries and past VCAA exam questions download and print the **studyON: Revision and past VCAA exam question booklet** (sonr-0054).

5.2 Transformers

KEY CONCEPTS

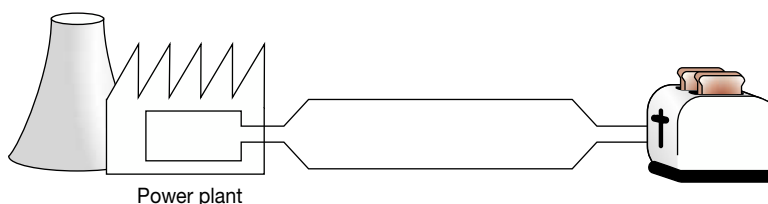
- Analyse transformer action with reference to electromagnetic induction for an ideal transformer:

$$\frac{N_1}{N_2} = \frac{V_1}{V_2} = \frac{I_2}{I_1}$$

5.2.1 Electric power

Electric power is generated for a purpose — to provide lighting in streets and homes, and to operate motors in domestic and industrial appliances. But electric power is often generated very far from where it is consumed. This problem *appears* to be simply overcome: make the connecting wires from the generator to the light or motor longer and longer, even stretching to hundreds of kilometres, and you have your basic transmission line.

FIGURE 5.2 Why not just extend the wires from your toaster all the way back to the power plant generator?



This simple solution might work on the laboratory bench where the connecting wires are so short that their resistance is a very small fraction of the overall resistance in the circuit. However, when the wires extend over kilometres, their resistance becomes significant. So, too, does the power loss in them. The power dissipated in the wires is equal to:

$$P_{\text{loss}} = VI = I^2R$$

where: P_{loss} is the power dissipated in the wires, in W

V is the voltage drop across the wires (not to be confused with the supply voltage), in V

I is the current through the wires, in A

R is the resistance of the wires, in Ω

Hence, the higher the resistance of the wires, the more power is lost in transmission along those wires. In addition, so much of the supply voltage now drops along the wires that the remaining voltage across the devices is insufficient for them to operate properly.

UNITS OF POWER

Electric power is normally discussed in terms of watts or megawatts — for example, when comparing electrical generators or deciding between vacuum cleaners. However, the generator supplies *energy*, the vacuum cleaner consumes *energy*, and it is ultimately people who pay for *energy*. The **power rating**, or wattage, of an electrical appliance indicates the rate at which it uses electricity. The longer the appliance is powered on, the more energy is used and the more the process costs. By definition:

$$1 \text{ watt} = 1 \text{ joule per second}$$

$$1 \text{ joule} = 1 \text{ watt} \times 1 \text{ second} = 1 \text{ watt second}$$

So,

As 1 watt second is equivalent to 1 joule, then

$$1000 \text{ watt seconds} = 1000 \text{ J}$$

$$1 \text{ kilowatt second} = 1 \text{ kJ.}$$

If a 1 kW heater was turned on for 1 s, it would use 1 kilowatt second or 1 kilojoule of electrical energy. If it was turned on for 60 seconds, it would use 60 kilowatt seconds or 60 kilojoules.

The common unit for energy supply and consumption in electricity is the kilowatt hour, which is the amount of energy consumed, for example, by a one-kilowatt heater for one hour. This unit is abbreviated to kWh (e.g. 60 kWh).

The conversion from kilowatt hour to joules is as follows:

$$\begin{aligned} 1 \text{ kWh} &= 60 \times 60 \text{ kilowatt seconds} \\ &= 3600 \text{ kilowatt seconds} \\ &= 3\,600\,000 \text{ watt seconds} \\ &= 3.6 \times 10^6 \text{ joules} \\ &= 3.6 \text{ megajoules (MJ)} \end{aligned}$$

5.2.2 Why use a transformer?

The transmission line transmits electrical energy from the generator to the appliance. The electrical energy is generated at a voltage set by the generator. Using Ohm's Law, if the voltage supplied from the generator is constant, then the current drawn from the generator depends on the resistance in the appliances connected to the generator: $I = \frac{V}{R}$. Appliances are connected in parallel so that they can all have the same voltage. Plugging in additional appliances is the same as adding extra resistances in parallel, with

each appliance drawing its own current from the supply. The extra appliances in parallel reduce the total resistance in the circuit.

With more appliances connected, the overall resistance of the circuit is reduced, drawing a larger current from the generator and therefore greater energy is supplied. The amount of energy supplied by the generator every second, or the electrical power supplied, is equal to the product of the voltage supplied by the generator and the current drawn from the generator, $P = VI$.

If the transmission lines are long, the energy wasted due to their resistance becomes a significant fraction of the energy supplied by the generator. If the same amount of energy produced every second (that is, the same power) can be sent along the lines but at a lower current, the energy loss will be less. In fact, since the power loss is given by I^2R (current² $\times$ resistance of the lines), halving the current through the lines reduces the power loss by a factor of four. This power loss can be reduced with the use of **transformers**.

SAMPLE PROBLEM 1

A 100 W light globe uses 100 J of energy every second when the voltage across it is 230 V_{RMS}.

- a. Calculate the current through the globe.**
- b. Calculate the resistance of the globe for this current and voltage.**
- c. i. If the globe was connected to a 230 V_{RMS} power supply by 2.00 m of copper wire, what would be the total resistance of the circuit? The wire has a resistance of $0.0220 \Omega \text{ m}^{-1}$.**
 - ii. What would be the voltage drop across the globe?**
- d. i. If the globe was connected by 100 km of copper wire, what would be the total resistance of the circuit?**
 - ii. What would be the voltage drop across the globe now?**
- e. Comment on how the light globe would respond when there is 100 km of wire.**

THINK

- a.** Use the formula $P = VI$ to determine the current through the globe, where $P = 100 \text{ W}$ and $V = 230 \text{ V}$.
- b.** Recall and use Ohm's Law, $V = IR$, to determine the resistance of the globe.
- c. i.** The globe and the wire are connected in series, so add their resistances to determine the total resistance of the circuit.
- ii. 1** Determine the current through the series circuit using Ohm's Law, $V = IR$, where $V = 230 \text{ V}$ (supplied to the circuit) and $R = 529 \Omega$ (total resistance of the circuit).

WRITE

- a.** $P = VI$
 $100 = 230I$
 $I = \frac{100}{230}$
 $= 0.435 \text{ A}$
- b.** $V = IR$
 $230 = 0.435R$
 $R = \frac{230}{0.435}$
 $= 529 \Omega$
- c. i.** $R_{\text{total}} = R_{\text{copper}} + R_{\text{globe}}$
 $= (2.00 \text{ m} \times 0.0220 \Omega \text{ m}^{-1}) + 529 \Omega$
 $\approx 529 \Omega$
- ii.** $V = IR$
 $I = \frac{V}{R}$
 $= \frac{230}{529}$
 $= 0.435 \text{ A}$

- 2 Determine the voltage drop across the globe using Ohm's Law, $V = IR$.

$$\begin{aligned} V &= IR \\ &= 0.435 \text{ A} \times 529 \Omega \\ &= 230 \text{ V} \end{aligned}$$

The voltage drop across the globe is 230 V.

- d. i. The globe and the wire are connected in series, so add their resistances to determine the total resistance of the circuit.

$$\begin{aligned} \text{d. i. } R_{\text{total}} &= R_{\text{copper}} + R_{\text{globe}} \\ &= (100 \times 10^3 \text{ m} \times 0.0220 \Omega \text{ m}^{-1}) + 529 \Omega \\ &\approx 2729 \Omega \end{aligned}$$

The total resistance of the circuit is 2730 Ω .
The resistance of the copper wire is not negligible.

- ii. 1 Determine the current through the series circuit using Ohm's Law, $V = IR$, where $V = 230 \text{ V}$ (supplied to the circuit) and $R = 2729 \Omega$ (total resistance of the circuit)

$$\begin{aligned} \text{ii. } V &= IR \\ I &= \frac{V}{R} \\ &= \frac{230}{2729} \\ &= 0.0843 \text{ A} \end{aligned}$$

- 2 Determine the voltage drop across the globe using Ohm's Law, $V = IR$.

$$\begin{aligned} V &= IR \\ &= 0.0843 \text{ A} \times 529 \Omega \\ &= 44.6 \text{ V} \end{aligned}$$

- e. Most of the 230 V supplied to the circuit is dissipated in the copper wire, with only a small amount across the globe.

- e. The globe would not light up.

PRACTICE PROBLEM 1

An 800 W toaster uses 800 joules of energy every second when the voltage across it is 230 V_{RMS}.

- Calculate the current through the toaster.
- Calculate the resistance of the toaster for this current and voltage.
- If the toaster was connected to a 230 V power supply by 1.00 m of copper wire, what would be the total resistance of the circuit? The wire has a resistance of $0.0350 \Omega \text{ m}^{-1}$.
 - What would be the voltage across the toaster?
- If the toaster was connected by 20 km of copper wire, what would be the total resistance of the circuit?
 - What would be the voltage across the toaster now?
- Comment on how the toaster would respond.

5.2.3 How do transformers work?

In 1831 Michael Faraday constructed a device to achieve this when he demonstrated that an electric current in one circuit had a magnetic effect that could produce an electric current in another circuit.

Faraday's transformer consisted of two sets of wire coils wrapped around a ring of iron. One coil, the primary coil, was connected to a battery by a switch, while the other, the secondary coil, was connected to a galvanometer (a sensitive current detector). (Faraday's transformer is discussed in section 4.4.1.)

As with other examples of electromagnetic induction, the transformer works only when there is a change in magnetic flux in the coils and the connecting iron core (which is the case with modern transformers).

To sum up, transformers are devices that act to increase or decrease AC voltages, and they are used in various appliances.

If an AC voltage is applied to the primary coil, an alternating magnetic field will be set up in the iron core. This alternating magnetic field will propagate through the iron core to the secondary coil. Here, the alternating magnetic field will induce an alternating voltage in this coil of the same frequency as the primary AC voltage. Transformers do not work with a constant DC current supply. There will be a brief induced current when the switch is turned off or on, but the constant DC supply does not produce a changing magnetic flux in the primary coil and, hence, no induced current in the secondary coil.

An AC voltage supplied to the primary coil produces an AC voltage at the secondary coil, even though there is no electrical connection between the two coils. How do the sizes of the two voltages compare? In other words, how do the RMS voltages compare?

FIGURE 5.3 Circuit diagram symbol for a transformer

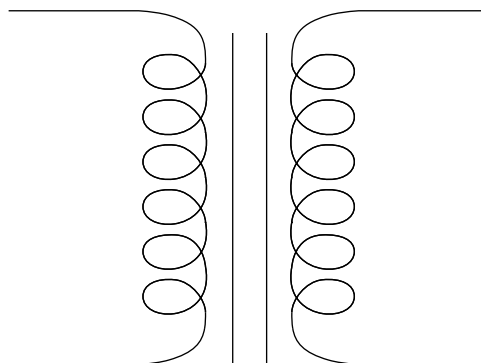
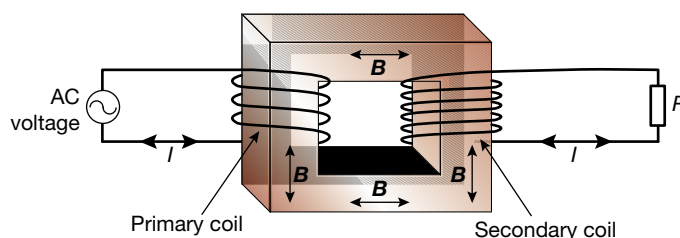


FIGURE 5.4 A changing current, I , in the primary coil produces a changing magnetic field, $\mathbf{B}$, in the iron core, which is propagated through the iron core to the secondary coil, where the changing magnetic field induces a changing emf in the secondary coil.



5.2.4 Comparing voltages

When an AC voltage supply, V_1 , is connected to the primary coil, the current will be limited by the resistance in the coil — which will be proportional to the number of turns, N_1 , in the coil.

The iron core has constantly changing magnetic flux throughout, which is created by the primary coil. This magnetic flux then passes through the secondary coil, producing an AC voltage at the terminals of the secondary coil. So, applying Faraday's Law to the primary coil gives:

$$V_1 = N_1 \times \frac{\Delta\Phi_B}{\Delta t}$$

Applying it to the secondary coil gives:

$$V_2 = N_2 \times \frac{\Delta\Phi_B}{\Delta t}$$

Combining these equations gives:

$$\frac{\Delta\Phi_B}{\Delta t} = \frac{V_1}{N_1} = \frac{V_2}{N_2}$$

or

$$\frac{V_1}{V_2} = \frac{N_1}{N_2}$$

where: V_1 is the RMS voltage in the primary coil
 V_2 is the RMS voltage in the secondary coil
 N_1 is the number of turns in the primary coil
 N_2 is the number of turns in the secondary coil

This relationship means that three types of transformers can be built. One type, which produces a secondary voltage greater than the primary, is called a **step-up transformer**. In this, the number of secondary turns is greater than the number of primary turns.

The other type is a **step-down transformer**, which features more primary turns than secondary turns. It produces a smaller secondary voltage than the primary voltage. Both types are used in the distribution of electricity from generator to home, and also inside the home. The third type of transformer involves voltage on either side, but this type is not useful in transmission systems as explored in this topic.

AS A MATTER OF FACT

Low-voltage lighting is now quite common in instances where 230 V AC would present a safety risk (for example, Christmas tree lights or external garden lighting). In these cases, a step-down transformer converts the 230 V AC down to a safer 12 V AC.

If there is no energy loss as the energy is transferred from the primary to the secondary side, then the *power in* to the primary coil will equal the *power out* of the secondary coil, and the transformer is considered an **ideal transformer**. Since power = voltage $\times$ current, this can be written as:

$V_1 \times I_1 = V_2 \times I_2$, and hence:

$$\frac{N_1}{N_2} = \frac{V_1}{V_2} = \frac{I_1}{I_2}$$

where: V_1 is the RMS voltage in the primary coil
 V_2 is the RMS voltage in the secondary coil
 I_1 is the current in the primary coil
 I_2 is the current in the secondary coil
 N_1 is the number of turns in the primary coil
 N_2 is the number of turns in the secondary coil

As this is looking at a relationship, the units used do not matter, as long as they are the same for both the primary and secondary coil. This also applies to the voltage used — it needs to be consistent as RMS, peak, or peak-to-peak (as mentioned previously in section 4.5.5 of the last topic).

SAMPLE PROBLEM 2

A step-down transformer is designed to convert 230 V_{RMS} AC to 12 V_{RMS} AC. If there are 190 turns in the primary coil, how many turns are in the secondary coil?

 Teacher-led video: SP2 (tlvd-0141)

THINK

1 List the known information.

WRITE

$V_1 = 230 \text{ V}; V_2 = 12 \text{ V}; N_1 = 190 \text{ turns}$

- 2 Use the relationship $\frac{V_1}{V_2} = \frac{N_1}{N_2}$ to determine the number of turns in the secondary coil.

$$\begin{aligned}\frac{V_1}{V_2} &= \frac{N_1}{N_2} \\ \frac{230}{12} &= \frac{190}{N_2} \\ N_2 &= \frac{12 \times 190}{230} \\ &= 9.9\end{aligned}$$

The secondary coil consists of approximately 10 turns.

PRACTICE PROBLEM 2

A generator supplies 10 kW of power to a transformer at 1.0 kV. The current in the secondary coil is 0.50 A. What is the turns ratio of the transformer? Is it a step-up or a step-down transformer?

5.2.5 Household use of transformers

Australian houses are provided with AC electricity that has a value of 230 V_{RMS}. Most electronic circuits are designed to operate at low DC voltages of between 3 V and 12 V. Therefore, household appliances that have electronic circuits in them will either have a ‘power-cube’ transformer that plugs directly into the power outlet socket, or have transformers built into them.

Power-cube transformers can be found in rechargeable appliances such as mobile phone chargers, electric keyboards, answering machines, cordless telephones and laptop computers. You can probably find more in your own home. These transformers also have a rectifier circuit built into them that converts AC to DC.

The RMS value of an AC voltage is a way of describing a voltage that is continuously changing. The voltage actually swings between –339 V and +339 V at a frequency of 50 Hz. This voltage has the same heating effect on a metal conductor as a DC voltage of 240 V; hence, it is usually described as 240 V.

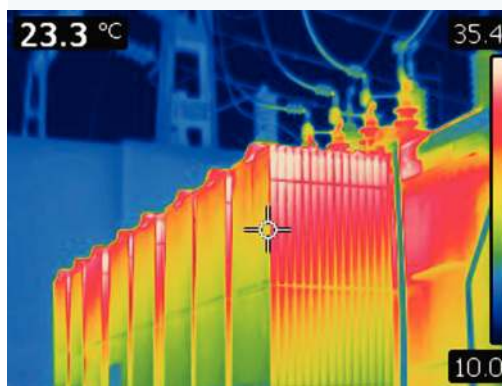
on Resources

 **Weblink** Transformer applet

5.2.6 Ideal versus real transformers

In an ideal transformer, the transformer is assumed to be 100% efficient and energy losses can be ignored. In reality, all transformers lose some energy in transferring electric power from the primary side to the secondary. This energy loss occurs in two areas. The first area is in the wires that make up the primary and secondary coils. This loss is called either *copper loss* (because the wires are usually copper), or *resistive* or I^2R loss. This is resistive heat from the wires heating up, so energy and power are lost in the coils. The heat generated from a transformer can be seen in figure 5.5. The loss is usually quite minor. If the transformer is being designed to take large currents, the wires on that side would be made thicker to take the high current and minimise the resistance.

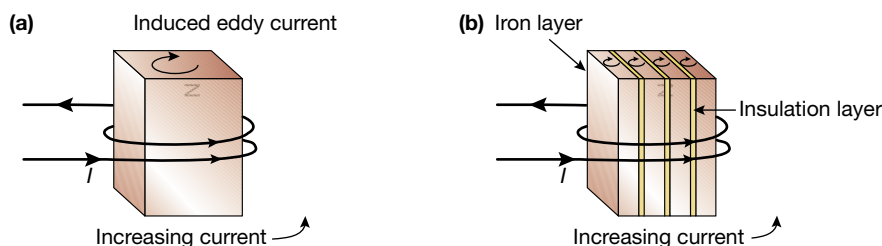
FIGURE 5.5 This infra-red photo shows the heat generated from a transformer. The red areas are the hottest.



The other area of energy loss in the transformer is in the iron core. This loss is due to induced currents in the iron core. These currents are called **eddy currents**, because they are like the swirls, or eddies, left in the water after a boat has gone by. Eddy currents are an application of Lenz's Law. The magnetic fields set up by eddy currents oppose the changes in the magnetic field acting in the regions of the metal objects.

The changing magnetic flux in the iron core produces a changing voltage in each of the turns of the secondary coils. Iron is an electrical conductor, so it will behave in the same way as the turns of wire. A circular current will be induced in the iron in a plane at right angles to the direction of the changing magnetic flux.

FIGURE 5.6 (a) An eddy current induced in an iron core by a changing magnetic field, and (b) putting the iron core into layers reduces the currents.



If the iron core was one solid piece of iron, these induced eddy currents would be quite substantial. As iron has a low resistance, it would lead to large energy loss.

To minimise this loss, the iron core is constructed of layers of iron sandwiched between thin layers of insulation. These layers, called laminations, significantly reduce the energy loss. In practice, transformers used to transmit large quantities of energy are about 99% efficient.

on Resources

-  **Digital documents** Investigation 5.1 Linking coils (doc-31595)
Investigation 5.2 Transformer ins and outs (doc-31596)
-  **Teacher-led video** Investigation 5.2 Transformer ins and outs (tlvd-0233)
-  **Interactivity** Transforming voltage and current (int-0118)
-  **Video eLesson** Electricity distribution system (med-0198)

5.2 EXERCISE

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

1. An ideal transformer has 100 turns in the primary coil and 2000 turns in the secondary coil. If the primary coil was connected to $230 \text{ V}_{\text{RMS}}$ AC, what would be the voltage across the secondary coil?
2. A transformer has 300 turns in the primary coil and six turns in the secondary coil.
 - (a) If $230 \text{ V}_{\text{RMS}}$ AC is connected to the primary coil, what will be the voltage across the secondary coil?
 - (b) If the secondary voltage is $9.0 \text{ V}_{\text{RMS}}$ AC, what is the voltage across the primary coil?
3. Christmas tree lights need a transformer to convert the $230 \text{ V}_{\text{RMS}}$ AC to $12 \text{ V}_{\text{RMS}}$ AC.
 - (a) If there are 50 coils on the 12 V secondary coil, how many turns are there in the primary coil?
 - (b) If there are 20 globes connected in parallel to the secondary coil, each of 12 V and 5 W , what is the current in the secondary coil?
 - (c) What is the current in the primary coil, assuming the transformer is ideal?
4. Explain why a transformer does not work with a constant DC input voltage.
5. Why is the core of transformers made of an alloy of iron that is easy to magnetise?
6. A transformer is used to change $10\,000 \text{ V}_{\text{RMS}}$ to $230 \text{ V}_{\text{RMS}}$. There are 2000 turns in the primary coil.
 - (a) What type of transformer is this?
 - (b) How many turns are there in the secondary coil?

7. An ideal transformer has 400 turns in the primary coil and 900 turns in the secondary coil. The primary voltage is $60 \text{ V}_{\text{RMS}}$ and the current in the secondary coil is 0.30 A .
- What is the voltage across the secondary turns?
 - What is the power delivered by the secondary coils?
 - What is the current in the primary coil?

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5.3 Power distribution and transmission line losses

KEY CONCEPTS

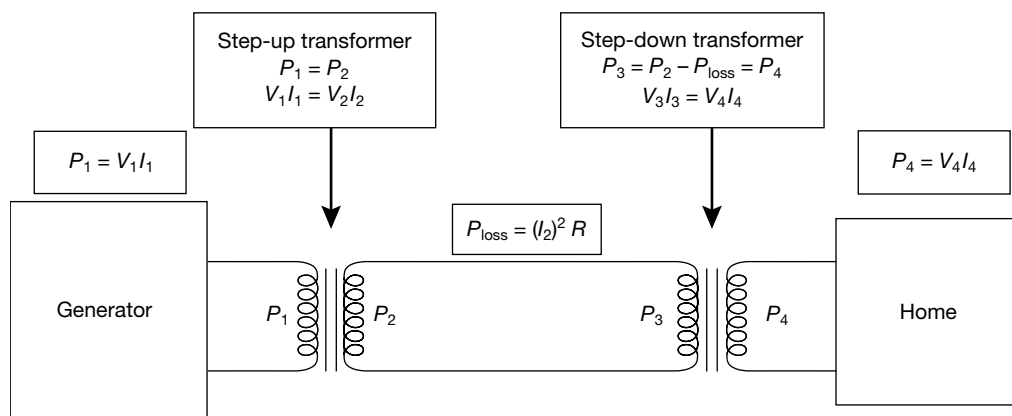
- Analyse the supply of power by considering transmission losses across transmission lines
- Identify the advantage of the use of AC power as a domestic power supply.

5.3.1 Transmission of power

The power loss in the transmission lines is equal to $P_{\text{loss}} = VI = I^2R$, where V is the voltage drop across the lines, I is the current through the lines and R is the resistance of the wires. Be careful not to confuse the voltage drop in the transmission lines with the voltage supplied from the generator. In order to minimise power loss in the transmission wires, large amounts of power produced by the generator need to be transmitted using a very low current. Development of the transformer meant that the AC supply voltage from the generator could be connected to a step-up transformer, allowing transmission lines to increase the voltage supplied by the generator and decrease the current, and so reduce energy loss in the transmission lines.

However, at the other end of the transmission line, the high voltage supplied would be unsuitable, and possibly dangerous, for domestic appliances. So a step-down transformer is used to bring the voltage back down to a safe level for home use.

FIGURE 5.7 Supplying power from a generator to the home



In Victoria, electricity is generated at a variety of voltages. In Yallourn, the voltage is 20 000 V (20 kV). In Newport, the generating voltage is 24 000 V. From the various generators around Victoria, the voltage is stepped up to 500 kV to transmit the electrical energy over the long distances to Melbourne. In Victoria, there are five main companies that distribute electricity across different regions: Powercor Australia (for western Victoria), Ausnet Services (for outer north and eastern Victoria), United Energy Distribution (for southern Victoria and the Mornington Peninsula), Citipower (for the city and inner suburbs) and Jemena (for the northern and north-western suburbs).

Because of the very high voltage, there is an increased risk of electrical discharge to the ground or the frame of the cable support, so tall towers are needed to hold the transmission cables high off the ground. Several porcelain discs are used to insulate the cables from the steel frame of the tower.

When the cables reach the outskirts of Melbourne, the high voltage is stepped down to 66 kV for distribution within the suburban area. In each suburb, the voltage is then further stepped down to 11 kV, either for delivery to yet another step-down transformer or to a neighbourhood power pole. There it is reduced to 230 V for connection to all the houses in the immediate neighbourhood.

The high-voltage transmission line feeds several outer suburban terminal stations, each of which passes the current to several zone substations, which again, step down the voltage using transformers and split the distribution voltage to go in different directions. These substations can also be disconnected from the transmission grid, allowing for sections to be turned off when required. These substations each connect to hundreds of pole transformers, which then connect to hundreds of homes. As the distribution system spreads further and further down to the domestic consumer, the voltage in the transmission line at each stage gets less and less. Finally, pole transformers step down the voltage to 230 V for domestic use.

FIGURE 5.8 A transformer at a substation



FIGURE 5.9 A pole transformer



TABLE 5.1 Typical voltages in different sections of the transmission system

Section of transmission system	Voltages
Major power tower or switchyard to terminal substation	220 kV, 330 kV or 500 kV
Terminal substation to zone substation	66 kV
Zone substation to pole-type transformer or underground transformer	22 kV
Pole-type transformer to house	230 V single phase, or 400 V for a three-phase supply

This means that the cables in each section need to be designed to handle the current in that section in a cost-effective way, maximising energy transfer while minimising the cost of doing so. To minimise energy loss, the resistance of the cable needs to be made as small as possible.

FIGURE 5.10 Victoria's power system — a representation

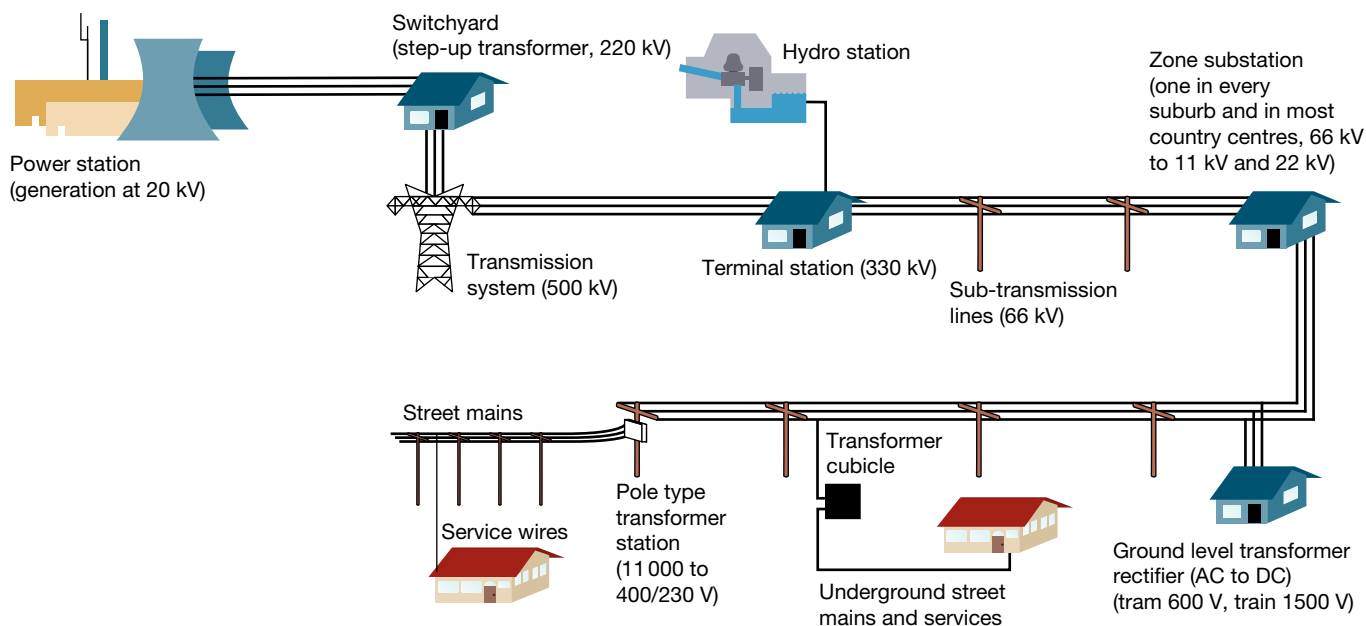


TABLE 5.2 Ways to reduce resistance

Method	Effect
Make the wires fatter	This increases the cost of the material in the wire and the cost of the pole to hold up the heavier wire.
Use a better conductor	Metals differ in their electrical conductivity and in their economic value as a metal. Very good conductors such as gold and silver are too expensive to use as wires.

Imagine that 400 MW of power was available to be transmitted along a transmission line of $4.0\ \Omega$. How would the power losses due to the resistance of the transmission line vary with the voltage across the transmission line? The following table shows some typical values.

TABLE 5.3 Transmission of 400 MW at different voltages

Transmission voltage	1000 kV	500 kV	220 kV	66 kV
Current $\left(I = \frac{P_{\text{tot}}}{V}\right)$	400 A	800 A	1800 A	6100 A
Power loss $\left(P_{\text{loss}} = I^2 R\right)$	640 kW	2.6 MW	13 MW	150 MW
Power loss (%)	0.2%	0.6%	3.3%	37%

HISTORY OF POWER TRANSMISSION

Electric power was first transmitted in 1882 by Thomas Edison in New York and by St George Lane-Fox in London, both using a DC system (connected to a DC generator) for street lighting. The transmission was at low voltage with considerable transmission power line losses, and so limited to short distances.

Later that decade, George Westinghouse purchased patents for AC generators. His company also improved the design of transformers, and developed an AC-based transmission system. In 1886, these new developments allowed power to be transmitted over a distance of a kilometre, stepping up the voltage to 3000 V and then stepping it down to 500 V.

In the 1800s, there was much debate on the relative efficiency of the AC and DC transmission systems as well as on their environmental effects. Currently, AC systems are mostly used. By 1898, there was a 30 000 V 120 km line and, by 1934, the voltage was up to 287 000 V over 430 km. During World War II, German scientists developed 380 000 V and overcame the effect of electrical discharge by using double cables.

During the 1960s, transmission voltages reached 765 000 V. Future voltages are expected to be at 1 000 000 V.

SAMPLE PROBLEM 3

- a. A 20.0 kW, 400 V_{RMS} diesel generator supplies power for the 400 V_{RMS} lights on a film set at an outside location. The 500 m transmission cables have a resistance of 5.00 Ω .
- What is the current in the cables?
 - What is the voltage drop across the transmission cables?
 - What is the power loss in the cables as a percentage of the power supplied by the generator?
 - What is the voltage supplied to the lighting?
- b. Repeat the calculations in part (a), but this time increase the generator voltage by a factor of 20 and, prior to connection to the lights, reduce the voltage by a factor of 20.

 Teacher-led video: SP3 (tlvd-0142)

THINK

- a. i. 1 Draw a diagram showing all known information.

- 2 The current in the cables is equal to the current coming from the generator.
For the generator: $P = 20\,000\text{ W}$;
 $V = 400\text{ V}$ Use $P = VI$ to determine the current through the cables.
(Note: Using $V = IR$ with $V = 400\text{ V}$ and $R = 5.0\ \Omega$ is incorrect because 400 V is the voltage supplied by the generator, it is not the voltage drop across the cables.)

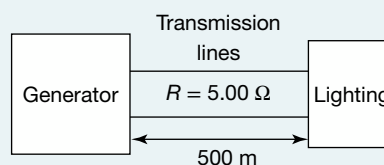
- ii. In the cables, $I = 50\text{ A}$ and $R = 5.0\ \Omega$.
Use $V = IR$ to determine the voltage drop across the cables.

- iii. 1 In the cables, $I = 50\text{ A}$ and $R = 5.0\ \Omega$.
Use $P_{\text{loss}} = I^2 R$ to determine the power lost in the cables.
(Note: This answer could have been obtained by using $P = VI$, with $V = 250\text{ V}$ from solution ii; however, there is a risk that 400 V may be used by mistake, so it is better to use $I^2 R$.)

- 2 Determine the power loss as a percentage of the power supplied by the generator.

WRITE

- a. i.



$$V = 400\text{ V}$$

$$P = 20.0\text{ kW}$$

$$P = VI$$

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

$$= \frac{20\,000}{400}$$

$$= 50.0\text{ A}$$

The current through the cables is 50.0 A.

$$\text{ii. } V = IR$$

$$= 50.0 \times 5.00$$

$$= 250\text{ V}$$

The voltage drop across the cables is 250 V.

$$\text{iii. } P_{\text{loss}} = I^2 R$$

$$= 50.0 \times 50.0 \times 5.00$$

$$= 12\,500\text{ W}$$

$$\%P_{\text{loss}} = \frac{12\,500}{20\,000} \times \frac{100}{1}$$

$$= 62.5\%$$

- iv. The voltage supplied by the generator is shared between the transmission cables and the lights:

$$V_{\text{generator}} = V_{\text{cables}} + V_{\text{lights}}$$

$$\text{where } V_{\text{generator}} = 400 \text{ V and}$$

$$V_{\text{cables}} = 250 \text{ V.}$$

- b. i. 1 Draw a diagram showing all known information.

- 2 Determine the voltage in the secondary coil of the step-up transformer.

- 3 The current in the cables is equal to the current coming from the secondary coil of the step-up transformer.

Use $P = VI$ to determine the current in the secondary coil of the transformer, and hence the cables, assuming an ideal transformer.

- ii. In the cables, $I = 2.50 \text{ A}$ and $R = 5.00 \Omega$. Use $V = IR$ to determine the voltage drop across the cables.

- iii. 1 In the cables, $I = 2.50 \text{ A}$ and $R = 5.00 \Omega$. Use $P_{\text{loss}} = I^2 R$ to determine the power loss

- 2 Determine the power loss as a percentage of the power supplied by the generator.

$$\text{iv. } V_{\text{generator}} = V_{\text{cables}} + V_{\text{lights}}$$

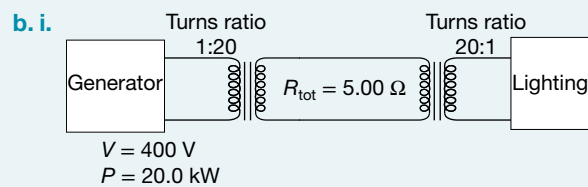
$$V_{\text{lights}} = V_{\text{generator}} - V_{\text{cables}}$$

$$= 400 \text{ V} - 250 \text{ V}$$

$$= 150 \text{ V}$$

At this distance, the voltage drop across the cables is too much to leave sufficient voltage to operate the lights at their designated voltage.

Given the noise of the generators, they cannot be moved closer. Therefore, step-up and step-down transformers with turns ratios of 20 are used to reduce the power loss in the cables and increase the voltage at the lights.



$$\frac{V_1}{V_2} = \frac{N_1}{N_2}$$

$$\frac{400}{V_2} = \frac{1}{20}$$

$$V_2 = 20 \times 400$$

$$= 8000 \text{ V}$$

$$P_1 = P_2 = 20\,000 \text{ W}; V_2 = 8000 \text{ V}$$

$$P_1 = P_2 = V_2 I_2$$

$$I_2 = \frac{P_1}{V_2}$$

$$= \frac{20\,000}{8000}$$

$$= 2.50 \text{ A}$$

ii. $V = IR$

$$= 2.50 \times 5.00$$

$$= 12.5 \text{ V}$$

The voltage drop across the cables is 12.5 V.

iii. $P_{\text{loss}} = I^2 R$

$$= 2.50 \times 2.50 \times 5.00$$

$$= 31.3 \text{ W}$$

$$\% P_{\text{loss}} = \frac{31.25}{20\,000} \times \frac{100}{1}$$

$$= 0.156\%$$

This is $\left(\frac{1}{20}\right)^2$ or $\frac{1}{400}$ of the original power loss! This is an impressive reduction.

iv. 1 The voltage supplied to the primary coil of the step-down transformer is the voltage from the secondary coil of the step-up transformer minus the voltage drop across the cables.

2 Determine the voltage in the secondary coil of the step-down transformer.

iv. Voltage supplied to the step-down transformer is therefore:
 $8000 \text{ V} - 12.5 \text{ V} = 7988 \text{ V}$

$$\begin{aligned}\frac{V_1}{V_2} &= \frac{N_1}{N_2} \\ \frac{7988}{V_2} &= \frac{20}{1} \\ V_2 &= \frac{7988}{20} \\ &\approx 400 \text{ V}\end{aligned}$$

PRACTICE PROBLEM 3

- a. A remote community uses a 50.0 kW, 250 V_{RMS} generator to supply power to its hospital. The power is delivered by a 100 m cable with total resistance of 0.200 Ω.
- What is the current in the cables?
 - What is the voltage drop across the transmission cables?
 - What is the power loss in the cables as a percentage of the power supplied by the generator?
 - What is the voltage supplied to the hospital?
- b. Transformers with a turns ratio of 10:1 are installed. Repeat (a) with this new ratio.

TRANSMISSION LINES

In transmission lines, the current actually flows through the outer surface of the line to a depth of about 1 mm. This is called the skin effect. It happens because the voltage is applied to the surface of the transmission line and the effect of the voltage decreases exponentially with distance from the surface.

Transmission lines are bare, multi-layered, concentrically stranded aluminium cables with a core of steel or reinforced aluminium for tensile strength. The advantages of having wires in a bundle over a single conductor of the same area include lower resistance to AC currents, lower radio interference and audible noise, and better cooling.

The smaller the sag in a transmission line, the greater will be the tension in the line. As the transmission lines cool, they contract, producing greater tension. High winds also increase tension.

The cost of building a transmission line is very nearly proportional to the input voltage and to the length of the line. The cost to transmit each unit of power is proportional to the length and inversely proportional to the square root of the power. That is, if the power to be transmitted is quadrupled, it can be transmitted twice as far for the same unit cost. It is therefore uneconomical to transmit power over a long distance unless a large quantity of power is involved.

The cost of constructing a line underground rather than above ground ranges from eight times as much (at 69 kV) to 20 times as much (at 500 kV). Underground cables are usually stranded copper, insulated with layers of oil-soaked paper tape. Superconductive cables may make this a more economical proposition.

Basslink uses subsea cables to transmit high-voltage DC between Victoria and Tasmania.

5.3.2 Using Ohm's Law wisely

The relationship $V = IR$ (Ohm's Law) is very useful. It can be applied in many situations in the same problem. This usefulness can lead to error if Ohm's Law is not applied wisely. The errors occur when students assume that, having calculated a value for V , the same value can be used every time $V = IR$ is used.

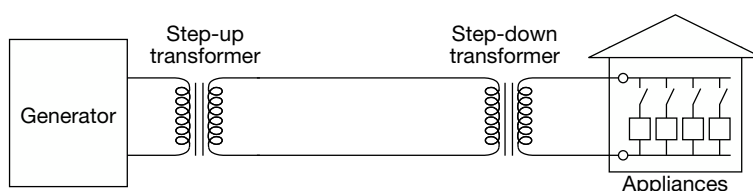
Rather, $V = IR$ should be remembered as:

Voltage across a section = current through the section $\times$ resistance of the section

So, in transmission line problems, the voltage across the output of the generator is different from the voltage across the transmission lines, which is different, in turn, from the voltage across the load at the end of the lines.

A well-labelled diagram can help avoid this confusion.

FIGURE 5.11 An electric circuit with step-up and step-down transformers



In any electric circuit, the total resistance determines how much current is drawn from the power supply. If there are transformers in the circuit, this statement is still true, but there are different currents and voltages on each side of the transformer.

As more appliances are turned on, there is a larger secondary current, which causes a larger primary current to be drawn from the power supply. This means the secondary current drives the primary current. When all the appliances are turned off, there is no secondary current and, so, no primary current.

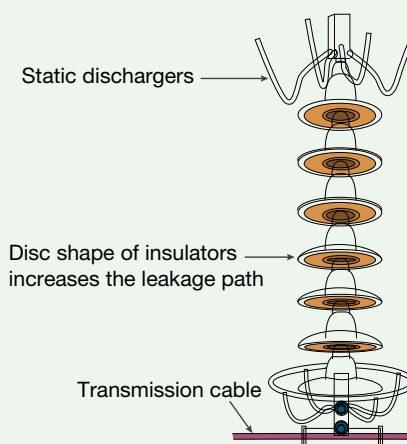
However, the primary voltage determines the secondary voltage through the ratio of turns in the transformer.

With more appliances turned on, the current in the transmission lines between the transformers increases. The increased voltage drop across these lines means there will be slightly less voltage across the primary turns of the step-down transformer. This will result in a slight drop in the voltage for each of the appliances. This is a scenario where Ohm's Law can lead to errors in calculations, due to this additional voltage drop.

INSULATING TRANSMISSION LINES

In dry air, sparks can jump a distance of 1 cm for every 10 000 V of potential difference. Therefore, a 330 kV line will spark to a metal tower if it comes within a distance of 33 cm. In high humidity conditions, the distance is larger. To prevent sparks jumping from transmission lines to the metal support towers, large insulators separate them from each other. It is important that these insulators are strong and have high insulating properties. Suspension insulators, as shown in figure 5.12, are used for all high-voltage power lines operating above 33 kV, where the towers or poles are in a straight line. Note that the individual sections of the insulators are disc shaped. This is because dust and grime collect on the insulators, making them conductive when wet. Many wooden poles catch fire after the first rain following a prolonged dry period because a current flows across wet, dirty insulators. The disc shape of the insulator sections increases the distance that a current has to pass over the surface of the insulator and so decreases the risk. There is also less chance that dirt and grime will collect on the undersides of the sections, and these are also less likely to get wet.

FIGURE 5.12 Suspension insulators are used in high-voltage transmission lines



5.3.3 The advantage of using AC power as a domestic power supply

AC power allows for the use of transformers to increase supply voltages. Transmitting the same power at a higher voltage means less current through the transmission lines and hence less power lost in transmission. Remember that transformers don't work with batteries providing DC voltage (they can work if there is a varying DC power supply), as there is no change in magnetic flux. In order to decrease the power lost in transmission using DC power, the resistance of the transmission would need to be significantly reduced. This can be achieved by increasing the cross-sectional area of the transmission wires, making them heavier and more expensive.



Resources



Digital documents Investigation 5.3 Modelling power transmission (doc-31597)

Investigation 5.4 Modelling power transmission using a spreadsheet (doc-31598)



Interactivity

Losing power (int-0119)

5.3 EXERCISE

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

1. An isolated film set uses a 50 kW generator to produce electricity for lighting and other purposes at 250 V_{RMS}. The generator is connected to lights approximately 100 m away by transmission cables with a combined resistance of 0.30 Ω.
 - (a) When the generator is operating at full capacity, what current does it supply?
 - (b) What is the power loss in the transmission cables?
 - (c) What is the total drop in voltage across the two cables connected by the generator?
 - (d) What is the voltage supplied to the lights?
 - (e) Two transformers with a turns ratio of 20 are used to first step up the voltage from the generator to the cables, and then to step it down from the cables to the lights. Using this new information, answer (b) to (d) again.
2. The appliances in a house would, if all turned on and connected to a power supply of 230 V_{RMS}, draw a current of 40 A.
 - (a) What is the effective resistance of the appliances in the house when they are all turned on?
However, the house is some distance from the power lines and the connecting cables have a resistance of 0.20 Ω.
 - (b) What is the total resistance of the circuit connected to the power lines?
 - (c) If the voltage at the power lines is 230 V AC, what is the voltage at the house?
 - (d) A 20 kW workshop that operates off the 230 V supply is installed in the garage in parallel to the house.
Answer parts (b) and (c) again for the new situation.
The owners now decide to install a step-up transformer and a step-down transformer, each with a turns ratio of 10:1, at either end of the transmission lines.
 - (e) If the system draws 120 A from the grid at 230 V, will the voltage at the house and the garage be within 1% of 230 V for the appliances to work properly?
 - (f) At night, the workshop is turned off. Will the voltage at the house increase, decrease or remain unchanged? Give reasons.
3. A generator at a power station produces 220 MW at 23 kV. The voltage is then stepped up to 330 kV. The power passes along transmission lines with a total resistance of 0.40 Ω.
 - (a) What is the current in the transmission lines?
 - (b) What is the power loss in the transmission lines?
 - (c) What is the voltage drop across them?
 - (d) What voltage and power is available to the step-down transformer located at the end of the lines?
4. The maximum electrical power that the generator at a power station can deliver is 500 MW at a voltage of 40 kV. This power is to supply the electricity needs of a distant city. Transmission lines connecting the station to the city have a total resistance of 0.80 Ω. At the city, the transmission lines are connected to a series of step-down transformers that reduce the voltage to 230 V. The city wants a two-step evaluation of the transmission system.

- (a) What percentage of the power delivered by the power station is lost in the transmission lines?
The power loss can be reduced by stepping up the voltage at the generator with a transformer. At the substations on the city's outskirts, the voltage is stepped down. The voltage could be stepped up to 400 kV using a transformer with a turns ratio of 10:1. The same transmission lines could be used, but they would need to be raised higher off the ground and be better insulated at each pole.
- (b) What would be the effect on the power loss in the transmission lines?

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5.4 Review

5.4.1 Summary

- A transformer is a device in which two multiple-turn coils are wound around an iron core. One coil, the primary coil, acts as an input; the other, the secondary coil, acts as an output.
- In a transformer, the iron core transfers the changing magnetic flux produced by an AC current in the primary coil to the secondary coil. The changing magnetic flux in the secondary coil induces an alternating voltage, producing an alternating current.
- The purpose of the transformer is to produce an output AC voltage that is different from the input AC voltage.
- A step-up transformer produces an output (secondary) voltage that is greater than the input (primary) voltage. A step-down transformer produces an output (secondary) voltage that is less than the input (primary) voltage.
- The relationship between the primary voltage and secondary voltage of a transformer is given by the equation:

$$\frac{V_1}{V_2} = \frac{N_1}{N_2}$$

- An ideal transformer does not lose energy. The power output of the secondary coil is equal to the power input of the primary coil and given by the equation:

$$V_1 I_1 = V_2 I_2$$

- Real transformers lose energy in transferring electric power from the primary coil to the secondary coil. Some is lost in the wires that make up the coils. Some energy is lost due to induced currents (eddy currents) in the iron core.
- When AC electric power is transmitted over long distances, some energy is lost due to the resistance of the transmission lines. The rate at which energy is lost can be calculated using the formula $P = I^2 R$.
- The power losses in long-distance transmission lines can be reduced by using step-up transformers to increase the transmission voltage, thereby reducing the transmission current. Step-down transformers are then used to reduce the voltage supplied to homes and industrial customers.

on Resources

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5.4.2 Key terms

An **eddy current** is an electric current induced in the iron core of a transformer by changing magnetic fields.
An **ideal transformer** is a transformer that is 100% efficient. Its input power is equal to its output power.
The **power rating**, or wattage, of an electrical appliance indicates the rate at which it uses electrical energy.
A **step-down transformer** produces an output (secondary) voltage that is less than the input (primary) voltage.
A **step-up transformer** produces an output (secondary) voltage that is greater than the input (primary) voltage.
A **transformer** is a device in which two multi-turn coils may be wound around an iron core. One coil acts as an input while the other acts as an output. The purpose of the transformer is to produce an output AC voltage that is different from the input AC voltage.



Resources



Digital document Key terms glossary (doc-32254)

5.4.3 Practical work and investigations

Investigation 5.1

Linking coils

Aim: To investigate how the magnetic field of a current-carrying coil can induce a current in another coil

Digital document: doc-31595

Investigation 5.2

Transformer ins and outs

Aim: To use an AC input voltage across a primary coil to produce an AC output voltage in a secondary coil, and to compare their values.

Digital document: doc-31596

Teacher-led video: tlvd-0233



Investigation 5.3

Modelling power transmission

Aim:

- a. To investigate power loss through transmission lines
- b. To investigate how the use of transformers in power distribution systems can minimise power loss

Investigation 5.4

Modelling power transmission using a spreadsheet

Aim:

- a. To investigate power loss through transmission lines
- b. To investigate how the use of transformers in power distribution systems can minimise power loss

Digital document: doc-31598



Resources



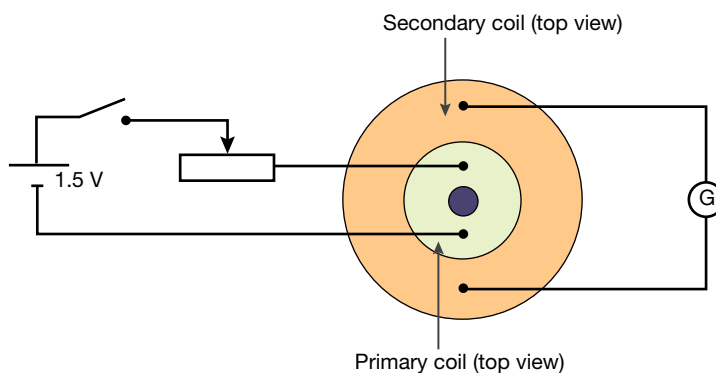
Digital document Practical investigation logbook (doc-32255)

5.4 Exercises

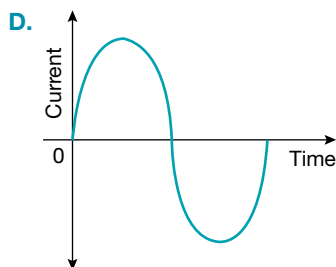
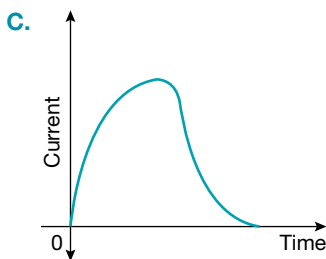
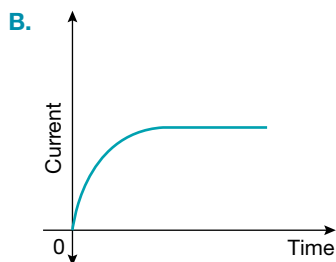
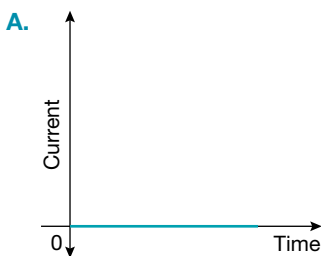
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5.4 Exercise 1: Multiple choice questions

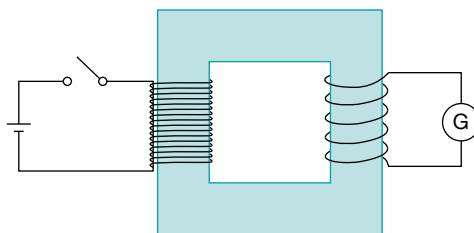
1. A transformer has 50 turns in the primary coil and 500 turns in the secondary coil. An AC input voltage of 10.0 V is applied. What is the output voltage, and what type of transformer is this?
 - A. 1.00 V, step-down
 - B. 600 V, step-up
 - C. 100 V, step-up
 - D. 100 V, step-down
2. A transformer with 40 turns in the primary coil is used to convert an input of 5 V into an output of 20 V. Which description best fits this transformer?
 - A. Step-up, 10 turn in secondary coil
 - B. Step-down, 160 turns in secondary coil
 - C. Step-up, 160 turns in secondary coil
 - D. Step-down, 10 turn in secondary coil
3. The primary coil of a transformer is connected to a battery, a resistor and a switch. The secondary coil is connected to a galvanometer (a sensitive ammeter), as shown in the following diagram.



Which of the following graphs, A, B, C or D, best shows the current flow in the galvanometer when the switch is closed?



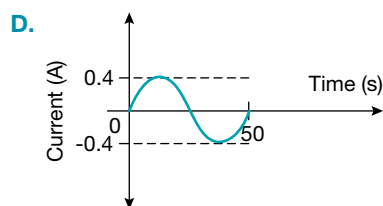
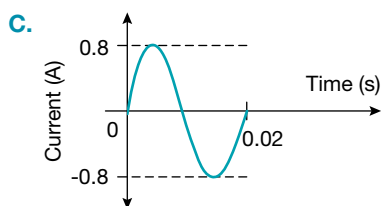
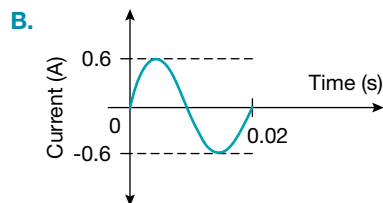
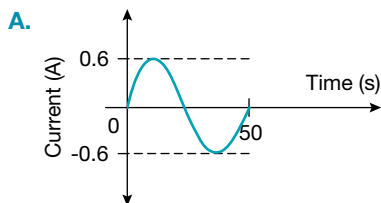
4. The following diagram shows an ideal transformer:



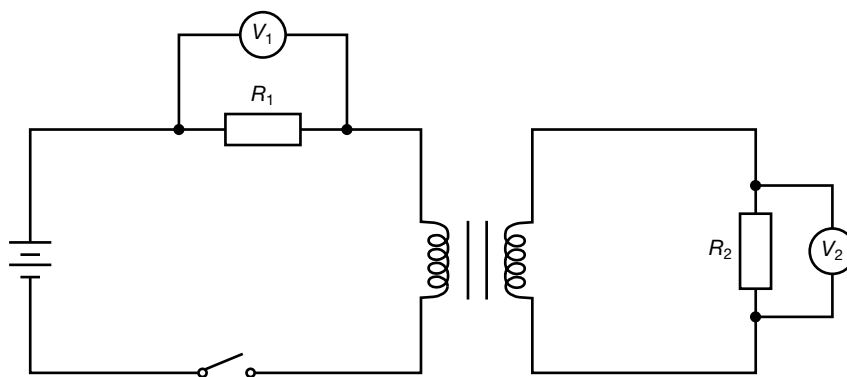
When the switch is closed, the needle on the galvanometer deflects.

How could the size of the deflection be increased?

- A. Place a resistor in series with the galvanometer.
 - B. Decrease the number of turns in the secondary coil.
 - C. Decrease the number of turns in the primary coil.
 - D. Decrease the input voltage.
5. A handheld electronic device operates from the 230 V AC household supply and will not operate properly if a voltage less than 230 V is supplied to it. Sarah wants to use the device in her home. This is a problem since the electricity supply comes to Sarah's home from the town generator, which is 1 km away. The cables that run from the town generator to her home have a total resistance of $0.026\ \Omega$. Because of the resistance of the cables, some power is lost in transmission and the voltage at Sarah's home is less than 230 V. A transformer is required at the generator to increase the voltage transmitted through the cables, and hence reduce the power loss in the cables.
- Which of the following statements is a correct explanation for why high voltages should be used?
- A. High transmission voltages require high current through the transmission cables.
 - B. For transmission of a given power, a larger transmission voltage requires a larger current.
 - C. High transmission voltages make electricity reach the home faster.
 - D. To minimise power loss in the wires, the current must be small.
6. A circuit is connected to a 50 Hz AC supply causing an RMS current of 0.6 A to flow. Which graph below best represents the variation of current with time through the circuit?



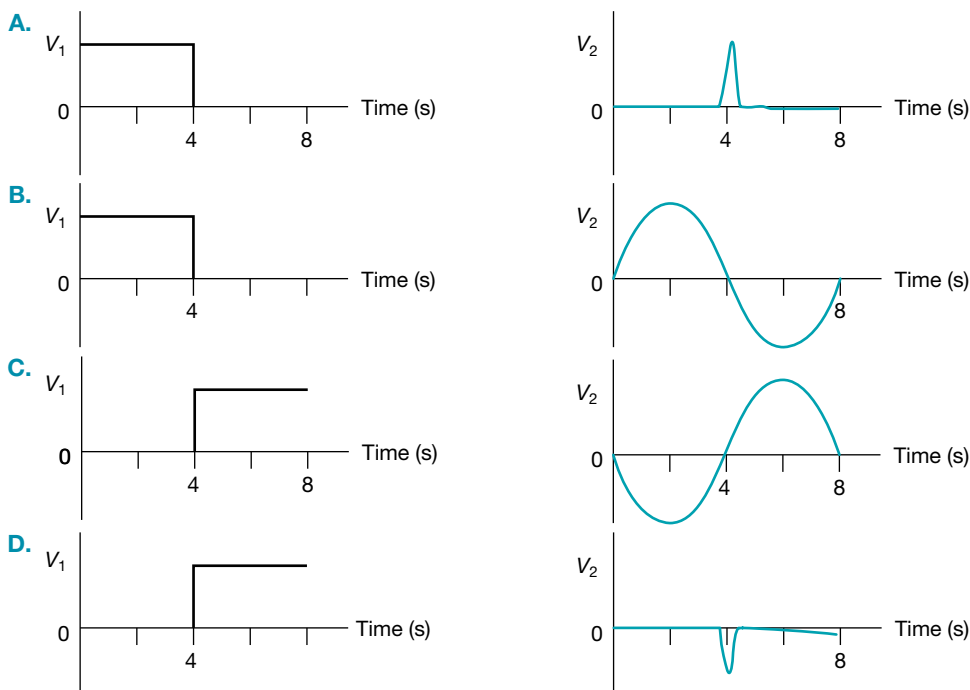
7. A step-down transformer has an input voltage of 100 V with 400 turns in the primary coil. If the output voltage is 25.0 V, how many turns are in the secondary coil?
- 25
 - 50
 - 100
 - 200
8. Consider the following circuit:



The switch is initially closed. The voltage drop, V_1 and V_2 , across the resistors, R_1 and R_2 , are measured continuously for 8 s.

After 4 seconds, the switch is opened.

Which pair of the following graphs shows how the values of V_1 and V_2 vary with time over the 8-second interval?



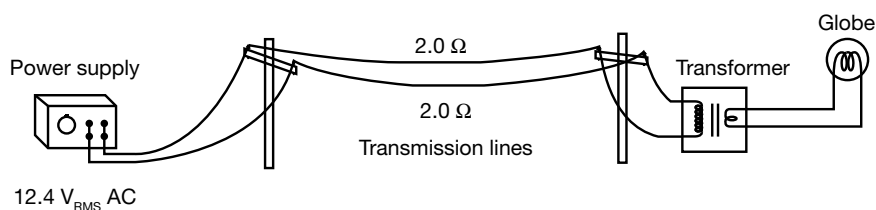
9. Which one of the following states the role of a transformer at an electrical power station?
- To reduce power loss in the transmission lines by stepping up the voltage
 - To reduce power loss in the transmission lines by stepping up the current
 - To increase power loss in the transmission lines by stepping up the voltage
 - To increase power loss in the transmission lines by stepping up the current

10. Which one or more of the following statements best describes how to minimise power losses in transmission lines?
- A. Transmit power at low voltage and high line current. The formula $P = \frac{V^2}{R}$ means that low voltage gives low power loss.
 - B. Transmit power at high voltage and low line current. The formula $P = I^2R$ means that low current gives low power loss.
 - C. Increase the line resistance so it is as large as possible. The formula $P = \frac{V^2}{R}$ means that large resistance gives low power loss.
 - D. Increase the line resistance so it is as large as possible. The formula $P = I^2R$ means that low resistance gives low power loss.

5.4 Exercise 2: Short answer questions

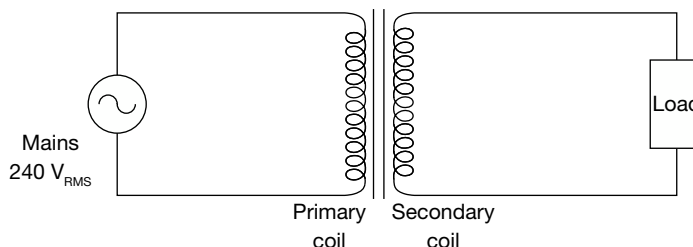
1. A 24 W globe is operated from a 6.0 V_{RMS} alternating current supply.
 - a. Determine the resistance of the globe when it is in operation.
 - b. Determine the peak value of the supply voltage.
2. A device uses a 40 W globe that operates at 18 V_{RMS}. The device is plugged into the 240 V_{RMS} household supply, and an ideal transformer is used to convert the 240 V_{RMS} to 18 V_{RMS} for the globe. The secondary coil of the transformer has 30 turns.
 - a. Determine the number of turns in the primary coil of the transformer.
 - b. Determine the current flowing in the primary coil when the device is operating.
3. A transformer has a primary coil with 30 turns and a secondary coil with 1150 turns. If the primary voltage to the transformer is 110 V_{RMS}, what is the secondary voltage?
4. An electrical appliance requires a 1200 V_{RMS} supply for its operation. A transformer allows the appliance to operate from a 240 V_{RMS} supply. Determine the ratio of the number of turns in the secondary coil to the number of turns in the primary coil for the transformer.
5. In the model of an AC transmission system shown in the following diagram, the ‘transmission lines’ consist of two wires, each with a constant resistance of 2.0 Ω.

The connecting wires from the power supply to the transmission lines and from the transmission lines to the globe have negligible resistance. The output of the power supply is set to 12.4 V_{RMS} AC. A 5:1 step-down transformer (assumed to be ideal) is used at the other end. The output of the transformer is connected to a globe. The globe is operating at 2.0 V_{RMS} and 6.0 W.



- a. The primary coil of the 5:1 step-down transformer has 2000 turns. How many turns does the secondary coil have?
- b. With the experiment set up as shown in the diagram, what is the power loss in the transmission lines?
- c. Determine the power delivered at each of the following points:
 - i. At the input to the primary coil of the transformer
 - ii. At the output of the 12 V_{RMS} power supply.
- d. What would be observed at the globe if the 18 V_{RMS} AC power supply is replaced by an 18 V battery?

6. Consider the following electrical circuit:



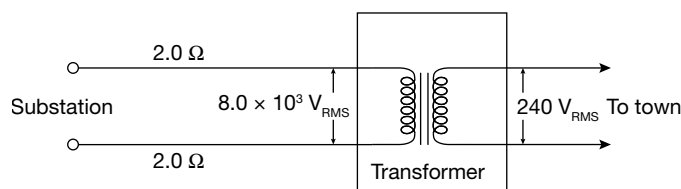
Primary coil: $V_{p\text{ RMS}} = 240\text{ V}_{\text{RMS}}$

Secondary coil: $V_{s\text{ RMS}} = 13\text{ V}_{\text{RMS}}$

$I_{s\text{ RMS}} = 2.7\text{ A}_{\text{RMS}}$

Assuming the transformer is ideal, calculate the RMS current in the primary coil.

7. A transformer is connected to a substation through wires with a total resistance of $4.0\ \Omega$, as shown in the following diagram. This transformer supplies a town with electricity at $240\text{ V}_{\text{RMS}}$, at a rate of 400 kW . The transformer (assumed ideal) has an input voltage of $8.0 \times 10^3\text{ V}_{\text{RMS}}$.



- If the secondary winding of the transformer has 60 turns, how many turns are there on the primary winding?
- Determine the RMS current in the wires from the substation to the transformer.
- What is the power loss in the wires between the substation and the local area transformer?
- At what voltage is electricity supplied from the substation?

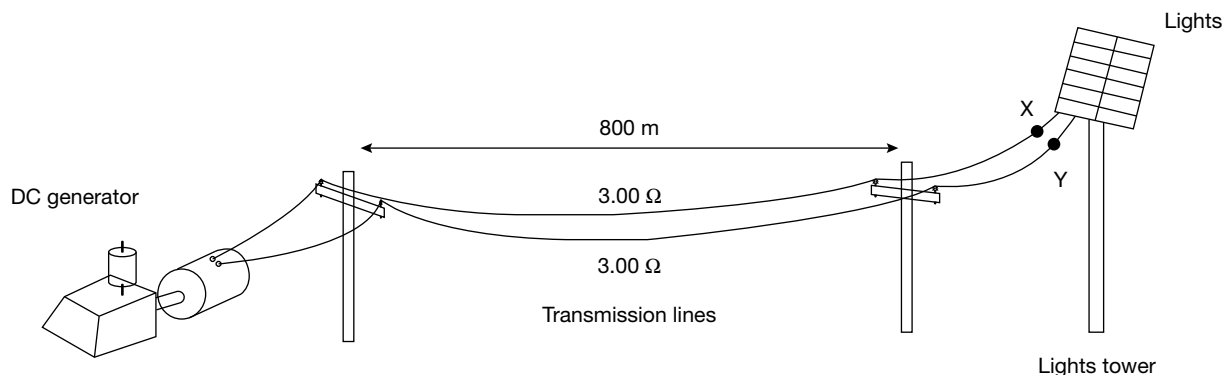
5.4 Exercise 3: Exam practice questions

Use the following information to answer Questions 1 to 7.

A DC generator is used to power lights on a light tower at the showgrounds, as shown in the following diagram.

The generator, which produces a constant $600\text{ V}_{\text{RMS}}$ DC is positioned 800 m from the light tower, and a two-wire transmission line connects the generator to the lights. Each of the wires in the transmission line has a resistance of $3.00\ \Omega$. The resistance of the other connecting wires is considered negligible.

The generator has an output current of 20.0 A when the lights are operating.



Question 1 (1 mark)

Calculate the power output of the generator.

Question 2 (1 mark)

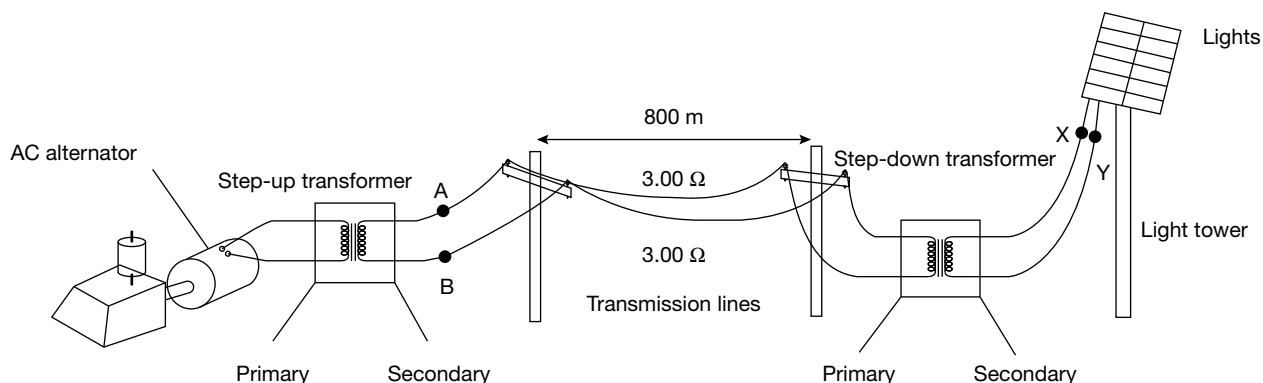
Determine the power loss in the transmission lines.

Question 3 (1 mark)

What is the voltage drop across the terminals of the light tower, XY?

The lights are found to be too dim. The following suggestions are made to fix this problem:

- replace the DC generator with an AC alternator producing $600\text{ V}_{\text{RMS}}$
- insert a 1:10 step-up transformer between the alternator and the power lines, and a 10:1 step-down transformer between the power lines and the light tower, as shown in the following diagram:



The output of the alternator is $20.0\text{ A}_{\text{RMS}}$ when the lights are operating, and the transformers can be considered to be ideal.

Question 4 (1 mark)

Calculate the RMS voltage drop at the input to the transmission lines, AB.

Question 5 (1 mark)

The primary coil of the step-down transformer has 2400 turns. How many turns are in the secondary coil?

Question 6 (2 marks)

Calculate the power loss in the transmission lines now.

Question 7 (3 marks)

Determine the voltage at the output of the step-down transformer, XY.

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UNIT 3 | AREA OF STUDY 2 REVIEW

AREA OF STUDY 2 How are fields used to move electrical energy?

OUTCOME 2

Analyse and evaluate an electricity generation and distribution system.

PRACTICE EXAMINATION

STRUCTURE OF PRACTICE EXAMINATION		
Section	Number of questions	Number of marks
A	20	20
B	4	20
Total		40

Duration: 50 minutes

Information:

- This practice examination consists of two parts. You must answer all question sections.
- Pens, pencils, highlighters, erasers, rulers and a scientific calculator are permitted.
- You may use the VCAA Physics formula sheet for this task.



Resources



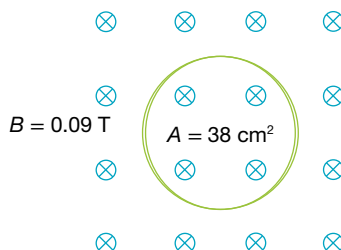
Weblink VCAA Physics formula sheet

SECTION A — Multiple choice questions

All correct answers are worth 1 mark each; an incorrect answer is worth 0.

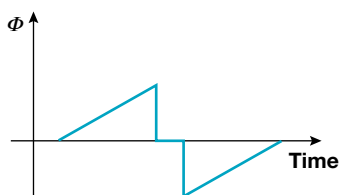
Use the following information to answer questions 1 and 2:

A circular conducting coil with 80 loops is placed inside a magnetic field with a field strength of 0.09 T. The area of the circular coil is 38 cm^2 .

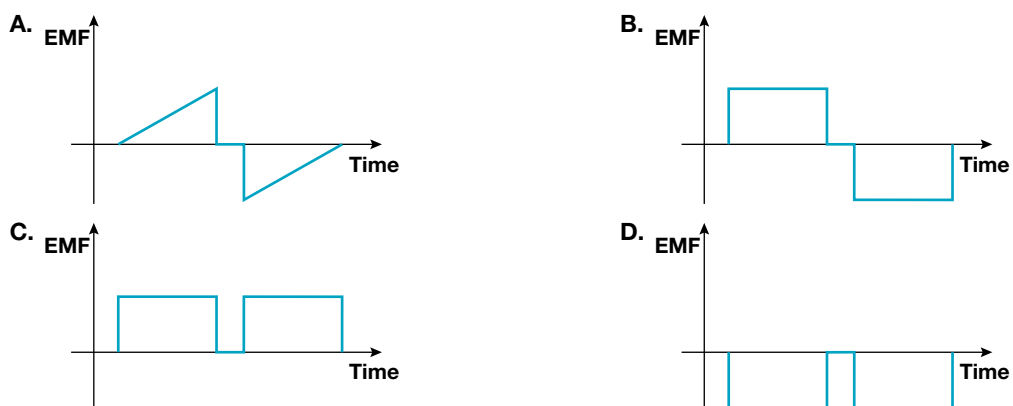


1. What is the magnetic flux through the loop?
- A. $3.4 \times 10^{-4} \text{ Wb}$ B. $2.7 \times 10^{-2} \text{ Wb}$
C. 3.4 Wb D. $2.7 \times 10^2 \text{ Wb}$

2. The coil is moved to the left and taken completely out of the magnetic field in a time of 0.35 s. Calculate the magnitude of the EMF induced in the coil.
 - A. $9.8 \times 10^{-4} \text{ V}$
 - B. $9.6 \times 10^{-3} \text{ V}$
 - C. $7.8 \times 10^{-2} \text{ V}$
 - D. $2.7 \times 10^{-1} \text{ V}$
3. The magnetic flux through a square loop conductor as it changes over time is plotted on a graph as shown in the following diagram:

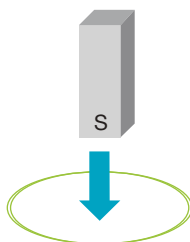


What is the expected graph of the EMF induced in the square loop conductor?



Use the following information to answer questions 4 and 5:

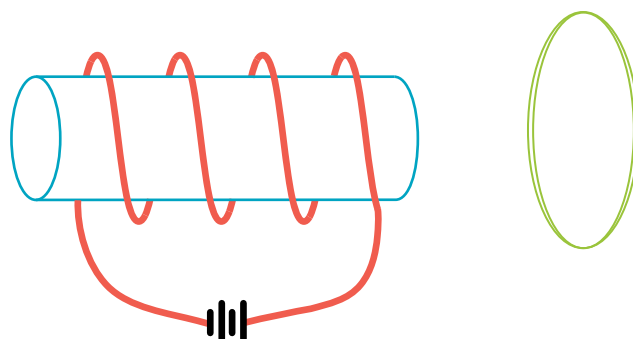
A permanent magnet is allowed to drop, entirely due to gravity, through a circular metal ring with its south pole going down first, as shown in the following diagram:



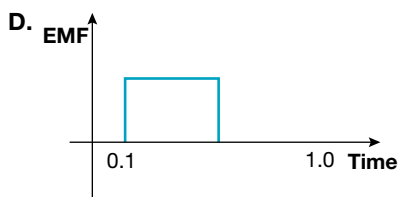
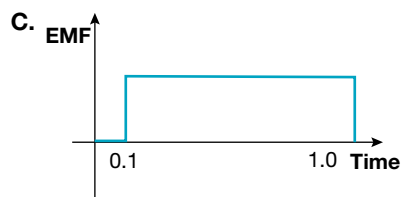
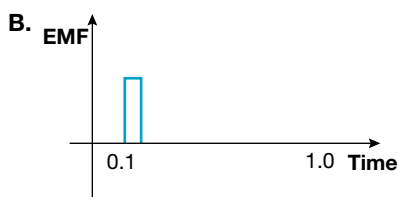
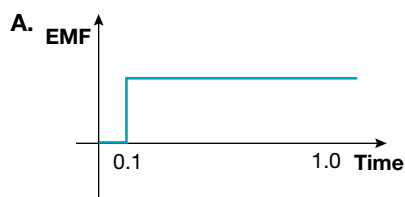
4. All of the following actions will increase the magnitude of the EMF generated in the metal ring except:
 - A. Increasing the strength of the magnet
 - B. Dropping the magnet from a greater height
 - C. Using a different metal with lower electrical resistance
 - D. Increasing the size of the circle
5. Viewed from above the ring, what is the direction of the generated current, if any?
 - A. Clockwise
 - B. Anticlockwise
 - C. No current generated, only an EMF
 - D. Cannot be determined, as additional information needed, for example, the resistance of the metal ring

Use the following information to answer questions 6, 7, and 8:

A solenoid is used to create a magnetic field to the left of a circular metal ring, as shown in the following diagram. When the solenoid circuit is switched on, the solenoid becomes 'active'.



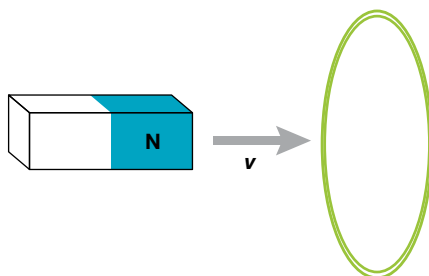
6. The solenoid circuit is initially inactive. At time $t = 0.1$ s, the solenoid circuit is switched on, becomes active and remains active for a long time. Which of the following graphs represents the magnitude of the EMF in the circular metal ring, between the time $t = 0$ and the time $t = 1.0$ s?



7. The solenoid circuit is initially active and then it is switched off. Viewed from the left of the ring, what is the direction of the generated current, if any?
- Clockwise
 - Anticlockwise
 - No current generated as the solenoid is no longer active
 - Cannot be determined, additional information needed, for example, the strength of the solenoid's magnetic field
8. Which of the following actions will *not* induce an EMF in the metal ring?
- Switching on an inactive solenoid circuit
 - Switching off an active solenoid circuit
 - Moving an active solenoid circuit closer to the metal ring
 - Moving an inactive solenoid circuit further away from the metal ring
9. A conducting coil is rotating at a constant rate inside a magnetic field with a constant field strength, producing an EMF. The rate of rotation is now reduced to half the rate it was before. Which of the following options best describes the period and the EMF produced by the new rate of rotation?
- The period is longer and the EMF produced is higher.
 - The period is longer and the EMF produced is lower.
 - The period is shorter and the EMF produced is higher.
 - The period is shorter and the EMF produced is lower.

Use the following information to answer questions 10 and 11:

A bar magnet is travelling to the right at velocity, v , and as it approaches a metal ring, it induces a current in the metal ring.



10. The direction of the induced current may be determined using Lenz's Law. Which of the following statements is the best explanation of Lenz's Law?
- A. The magnetic field of the induced current will oppose the direction of the initial magnetic flux through the ring.
 - B. The magnetic field of the induced current will oppose the direction of the final magnetic flux through the ring.
 - C. The magnetic field of the induced current will be the same direction as the change in magnetic flux through the ring.
 - D. The magnetic field of the induced current will oppose the change in magnetic flux through the ring.
11. All of the following actions will increase the size of the current in the metal ring except:
- A. Increasing the strength of the magnet
 - B. Increasing the velocity of the magnet
 - C. Increasing the resistance of the metal ring
 - D. Increasing the diameter of the metal ring

Use the following information to answer questions 12, 13 and 14:

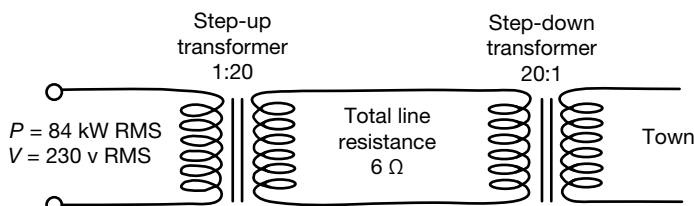
A mobile phone charger is comprised of a step-down transformer from $240 V_{\text{RMS}}$ AC to $18 V_{\text{RMS}}$ AC. The charger consumes $54 W_{\text{RMS}}$ of power when it is charging the phone. Assume that the phone charger is ideal.

12. If the secondary coil has 360 turns, what is the number of turns in the primary coil?
- A. 13 turns
 - B. 27 turns
 - C. 4680 turns
 - D. 4800 turns
13. Calculate the RMS current in the secondary coil.
- A. 0.23 A
 - B. 0.32 A
 - C. 3.0 A
 - D. 4.2 A
14. Determine the peak current in the primary coil.
- A. 0.23 A
 - B. 0.32 A
 - C. 3.0 A
 - D. 4.2 A
15. Which of the following statements best explains why transformers are AC devices and not DC devices?
- A. Direct currents are fixed and cannot be stepped up or stepped down.
 - B. An alternating current may generate a changing magnetic flux.
 - C. A direct current generates a weaker magnetic field than an equivalent alternating current.
 - D. The iron cores of transformers work best with alternating currents.

16. Which of the following statements best describes the role of the iron core in a transformer?
- The iron core enables the primary coil to transfer its voltage over to the secondary coil.
 - The iron core channels the magnetic flux between the primary coil and the secondary coil.
 - The iron core has a higher resistance than the copper conductors used in the primary and secondary coils.
 - The iron core focuses the current from the primary coil to reduce the losses in the secondary coil.

Use the following information to answer questions 17 to 20:

A small rural town is powered by a hydroelectric power station 500 m away. The power station produces 84 kW RMS power at 230 V_{RMS}. The voltage is stepped up with a step-up transformer with a turns ratio of 1:20 before transmission to the town. The total resistance of the transmission line is 6 Ω. At the town, the transmission line voltage is stepped down with a step-down transformer with a turns ratio of 20:1 before distribution to individual homes and businesses.

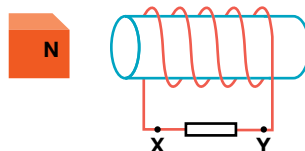


17. Between the power station and the town, which of the following is the expected RMS current in the transmission line closest to?
- 7.3 A
 - 18 A
 - 3.7×10^2 A
 - 7.3×10^2 A
18. Which of the following is the expected voltage available to consumers at the town after the step-down transformer?
- Equal to 230 V
 - Less than 230 V
 - Greater than 230 V
 - Unknown, since there is insufficient information to determine the voltage
19. If the turns ratio for the step-up transformer is changed to 1:30, and the turns ratio for the step-down transformer is changed to 30:1, what is likely to happen to the transmission line current and the voltage available to consumers at the town?
- The transmission line current will increase, while the voltage available will decrease.
 - The transmission line current will increase, while the voltage available will increase.
 - The transmission line current will decrease, while the voltage available will decrease.
 - The transmission line current will decrease, while the voltage available will increase.
20. Which of the following actions will not reduce the transmission line loss?
- Reducing the total resistance of the transmission line
 - Reducing the turns ratio of the step-up transformer
 - Reducing the transmission line current
 - Reducing the length of the transmission line

SECTION B — Short answer questions

Question 1 (7 marks)

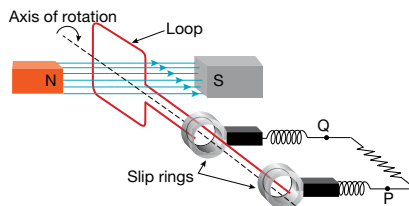
The diagram below shows a permanent magnet near a coil of wire. The coil is connected to a resistor.



- Which way will a current flow through the resistor when the magnet moves towards the coil from the position shown? Explain your answer. **3 marks**
- When the magnet is held stationary inside the coil, no current is detected in the resistor. Explain why this is the case. **2 marks**
- Describe two ways to increase the magnitude of the induced current in the resistor. **2 marks**

Question 2 (4 marks)

A model electric generator similar to that shown in the following diagram is being tested by some students. The coil consists of 50 turns of wire and has an area of $6.0 \times 10^{-3} \text{ m}^2$. The magnetic field between the poles of the magnets is measured to be 0.15 T.



- Calculate the magnitude of the magnetic flux threading the coil when it is in the position shown. **1 mark**
- The students rotate the coil in a clockwise direction as indicated in the diagram. The coil is rotated a quarter turn (90°). Using the points P and Q, identify which direction the current flows through the external resistor. **1 mark**
- As the students rotate the coil through an angle of 90° , the magnitude of the average induced EMF is 40 mV. What time interval is required for this rotation to produce an average induced EMF of 40 mV during a quarter-turn? **2 marks**

Question 3 (6 marks)

A step-up transformer has a primary voltage of 230 V_{RMS} and an output RMS voltage of 1200 V. The primary coil of the transformer has 75 turns of wire and carries a current of 4.0 A.

- How many turns are on the secondary coil of the transformer? **2 marks**
 - What is the current in the secondary coil of the transformer? **2 marks**
- A small 1000 W generator supplies power across some transmission lines. These lines also carry a current of 4.0 A and have a resistance of 3.5Ω .
- Calculate the power loss in the cables and express this as a percentage of the power supplied by the generator. **2 marks**

Question 4 (3 marks)

A transformer is designed to give 6.0 V output from a 240 V input. A 1.0 A fuse is placed in series with the primary coil.

- Find the ratio $\frac{N_{\text{primary}}}{N_{\text{secondary}}}$ where N_{primary} is the number of turns of wire in the primary coil, and $N_{\text{secondary}}$ is the number of turns of wire in the secondary coil. **1 mark**
- What is the maximum power that could be delivered in the primary coil? **1 mark**
- What is the maximum current obtained from the secondary coil? **1 mark**

ASSESSMENT TASK — A REPORT OF A PHYSICS PHENOMENON

In this task, you will be required to report on the physics phenomenon of transformers and AC voltages, linking this to the generation of electricity.

- This practice SAC requires you to report on the phenomenon of transformers and AC voltages; a structured set of questions is supplied to assist you to write your description.
- You may use the VCAA Physics formula sheet and a scientific calculator for this task.

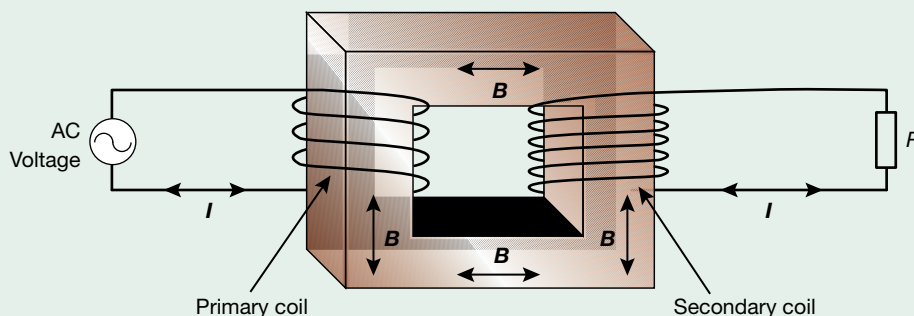
Total time: 55 minutes (5 minutes reading, 50 minutes writing)

Total marks: 46 marks

THE GENERATION OF ELECTRICITY — THE IMPORTANCE OF TRANSFORMERS AND AC VOLTAGES

A student is studying electricity and magnetism, and reads the following extract from an article published on an internet site devoted to physics learning. The extract is as follows:

Transformers can be used in conjunction with AC voltages applied to the primary coil to either increase or decrease the AC potential difference produced at the terminals of the secondary coil. When a step-up transformer is used, the output voltage is larger than the input voltage but with a smaller output current. When a step-down transformer is used, the output voltage is smaller than the input voltage but with a larger output current. Transformers do not work with steady DC voltages applied to the primary coil.



Useful equations:

$$\frac{V_s}{V_p} = \frac{N_s}{N_p}$$

$$V_s I_s = V_p I_p$$

$$V = IR$$

$$P = VI$$

You need to write **a report** on the outlined phenomenon, responding to the following questions.

1. Explain, using Faraday's Law, how a transformer can induce electrical power in one circuit from another circuit.
2. The article also states that transformers do not work with steady DC voltages. Explain why this is the case.

The student reads further into the article, which is now discussing power losses in transmission cables:

In a transmission cable, due to the resistance and the current in the cable, electrical power is dissipated by the cable, resulting in a loss of power available to the electrical device at the end of the cable.

3. In terms of the resistance, R , of the transmission cable and the current, I , in the cable, explain the size of the power dissipated in the cable. Further, suggest two ways in which the power loss can be decreased.

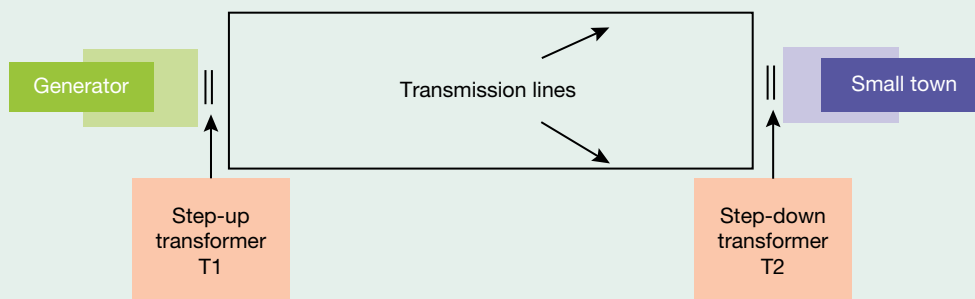
The article continues:

Using a step-up transformer, the power loss in a transmission cable can be substantially lowered without compromising the amount of power delivered to the end user.

4. Comment on the preceding sentence in terms of how a step-up transformer could achieve this outcome.
- A week later, the student is reading an article in an engineering magazine about the development of a small independent power supply to a small, remote town in Victoria. The generator uses an array of solar cells

connected to an inverter to produce a $240\text{ V}_{\text{RMS}}$ AC supply, but at a distance from the small town. The article states the following:

A generator and transmission system is being designed to supply electrical power to a small country town two kilometres away from the generator. The system consists of a generator, two transformers (T1 located close to the generator and T2 located close to the small town) and a transmission line as shown in the following diagram:



During the day, the generator is expected to supply $6.000 \times 10^5\text{ W}$ of power with $240.0\text{ V}_{\text{RMS}}$ at the primary terminals of T1. The power will be transferred via an ideal step-up transformer T1 using transmission lines with a total resistance of $5.000\ \Omega$ and, finally, an ideal step-down transformer T2, with the same turns ratio.

The town engineer is considering which turns ratio to use for both of the transformers and is aware that the RMS voltage to appliances in the town must not exceed $240\text{ V}_{\text{RMS}}$.

In the following questions, give numerical answers to an accuracy of 4 significant figures other than when estimates are required. All values calculated are RMS values.

5. Show that the expected current in the primary coil of transformer T1 is 2500 A. You must show your working to obtain full marks.
6. Why would the turns ratio be chosen to be the same for both the step-up and step-down transformer pair?
7. Using the expected power output of the generator ($6.000 \times 10^5\text{ W}$), the current in the primary coil of transformer T1 is 2500 A.
By determining the current in the transmission line, calculate the power loss in the transmission line for each of the following turns ratios:
(a) 10 (b) 20 (c) 40 (d) 80
8. Graph the power loss in the transmission line versus the turns ratio. Plot the 4 points and draw a smooth curve of best fit by eye.
9. Calculate the voltage supplied to the small town after it has been stepped down for each of the following turns ratios:
(a) 10 (b) 20 (c) 40 (d) 80
10. Graph the voltage supplied to the small town versus the turns ratios 10, 20, 40 and 80. Draw a smooth curve of best fit for the 4 data points on your graph of voltage versus turns ratio.
The engineer realises that 220 V is sufficient to run equipment in the city without loss of performance in the appliances used by the residents.
11. Use your graph of voltage versus turns ratio, graph 2, to estimate the minimum turns ratio that will produce a minimum voltage to the town of 220.0 V. Demonstrate your method on your graph.
12. Now use your graph of power loss versus turns ratio, graph 1, to estimate the power loss for the minimum turns ratio that you estimated in question 8. Use your graph to demonstrate your method.
13. At 10 pm, when people begin to go to bed, the demand for power decreases.
(a) Describe what will happen to the voltage available for the residents of the town as the demand for power decreases?
14. Give a detailed argument for your choice in question 13.

on Resources

 **Digital documents** School-assessed coursework (doc-32300)

6 Newton's laws of motion

6.1 Overview

Numerous **videos** and **interactivities** are available just where you need them, at the point of learning, in your digital formats, learnON and eBookPLUS at www.jacplus.com.au.

6.1.1 Introduction

Backwards and forwards. Faster and slower. Why do objects in motion behave the way they do, and how can such behaviour be consistently described?

Before Sir Isaac Newton published *Principia Mathematica* in 1687, there was no plausible theory that could clearly describe bodies, the forces acting upon them, and their movements in response to those forces. Newton's laws of motion changed humanity's understanding of the entire universe by providing a mathematical description of the universe. They describe everything from a ball rolling down a hill to the position of the planets in our universe.

To this day, more than 300 years later, Newton's laws of motion and gravity remain the foundations on which mechanics and engineering are based. They gave humanity the knowledge needed to put a man on the Moon and send satellites into orbit. Everyday motion, from driving a car and riding a bike, to enjoying a ride on a roller-coaster, are all governed by forces that can be described by Newton's laws.

FIGURE 6.1 Whether you are driving a car, riding a bike or riding a roller-coaster, your motion is controlled by the forces acting on the vehicle.



6.1.2 What you will learn

KEY KNOWLEDGE

After completing this topic, you will be able to:

- investigate and apply theoretically and practically Newton's three laws of motion in situations where two or more coplanar forces act along a straight line and in two dimensions
- investigate and analyse theoretically and practically the motion of projectiles near Earth's surface, including a qualitative description of the effects of air resistance
- investigate and analyse theoretically and practically the uniform circular motion of an object moving in a

horizontal plane: $\left(\mathbf{F}_{\text{net}} = \frac{m\mathbf{v}^2}{r}\right)$, including:

- a vehicle moving around a circular road
- a vehicle moving around a banked track
- an object on the end of a string
- model natural and artificial satellite motion as uniform circular motion
- investigate and apply theoretically Newton's second law to circular motion in a vertical plane (forces at the highest and lowest positions only).

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PRACTICAL WORK AND INVESTIGATIONS

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

on Resources

-  **Digital documents** Key science skills — VCE Physics Units 1–4 (doc-32112)
Key terms glossary (doc-32257)
Practical investigation logbook (doc-32258)

studyon

To access key concept summaries and past VCAA exam questions download and print the **studyON: Revision and past VCAA exam question booklet** (sonr-0055).

6.2 BACKGROUND KNOWLEDGE Motion review

BACKGROUND KNOWLEDGE

- identify parameters of motion as vectors or scalars
- analyse graphically, numerically and algebraically, straight-line motion under constant acceleration:

$$\mathbf{v} = \mathbf{u} + \mathbf{a}t \quad \mathbf{v}^2 = \mathbf{u}^2 + 2\mathbf{a}s \quad \mathbf{s} = \frac{1}{2}(\mathbf{u} + \mathbf{v})t \quad \mathbf{s} = \mathbf{u}t + \frac{1}{2}\mathbf{a}t^2 \quad \mathbf{s} = \mathbf{v}t - \frac{1}{2}\mathbf{a}t^2$$

- graphically analyse non-uniform motion in a straight line
- apply concepts of momentum to linear motion: $\mathbf{p} = m\mathbf{v}$

6.2.1 Describing motion

To explain the motion of objects, it is important to be able to measure and describe the motion clearly. The language used to describe motion must therefore be precise and unambiguous.

The language of motion

The physical quantities used to describe and explain motion fall into two distinct groups: scalar quantities and vector quantities.

Scalar quantities are those that can be described without specifying a direction. Mass, energy, time and temperature are all examples of scalar quantities.

Vector quantities are those that can only be fully described by specifying a direction as well as a magnitude. Force, displacement, velocity and acceleration are all examples of vector quantities. Vectors are notated with bold font or with an arrow above or below the variable.

Distance is a measure of the length of the path taken during the change in position of an object. Distance is a scalar quantity. It does not specify a direction.

Displacement is a measure of the change in position of an object. In order to fully describe a displacement, a direction must be specified as well as a magnitude. Displacement is therefore a vector quantity.

Speed is a measure of the rate at which an object moves over a distance. Because distance is a scalar quantity, speed is also a scalar quantity. The average speed of an object can be calculated by dividing the distance travelled by the time taken:

$$\text{average speed} = \frac{\text{distance travelled}}{\text{time interval}}$$

Velocity is a measure of the rate of displacement of an object. Because displacement (change in position) is a vector quantity, velocity is also a vector quantity. The velocity has the same direction as the displacement. The symbol v is used to denote velocity. (The symbol v is often used to represent speed as well.)

The average velocity of an object, v_{av} , during a time interval can be expressed as:

$$\vec{v}_{av} = \frac{\Delta \vec{x}}{\Delta t}$$

where: $\vec{x}$ represents the displacement
 Δt represents the time interval

Neither the average speed nor the average velocity provide information about movement at any particular instant of time. The speed at any particular instant of time is called the **instantaneous speed**. The velocity at any particular instant of time is called the **instantaneous velocity**. It is only if an object moves with a constant velocity during a time interval that its instantaneous velocity throughout the interval is the same as its average velocity.

The rate at which an object changes its velocity is called its **acceleration**. Because velocity is a vector quantity, it follows that acceleration is also a vector quantity. The average acceleration of an object, a_{av} , can be expressed as:

$$\vec{a}_{av} = \frac{\Delta \vec{v}}{\Delta t}$$

where: $\Delta \vec{v}$ represents the change in velocity ($\vec{v} - \vec{u}$), $\vec{v}$ is the final velocity and $\vec{u}$ the initial velocity
 Δt represents the time interval

The direction of the average acceleration is the same as the direction of the change in velocity. The instantaneous acceleration of an object is its acceleration at a particular instant of time.

A non-zero acceleration is not always caused by a change in speed. The vector nature of acceleration means that it can have a non-zero value when either or both of the magnitude and direction of the velocity change.

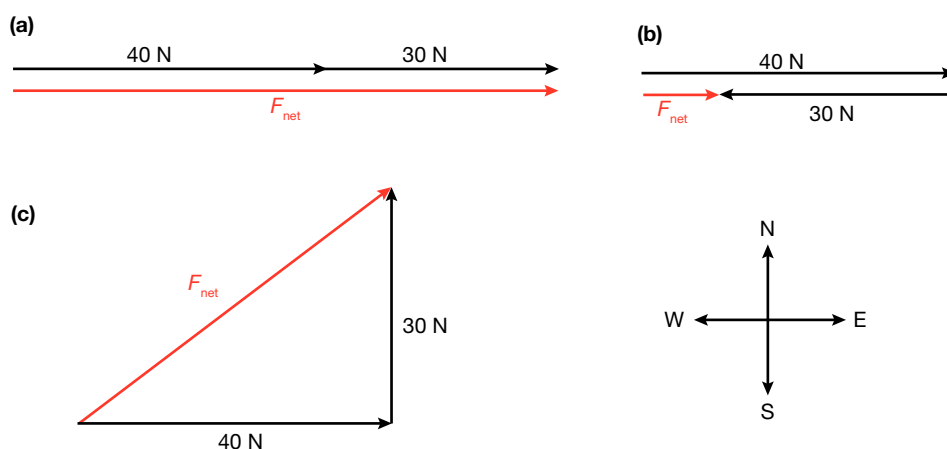
Reviewing vectors

A vector quantity is one that has both direction and magnitude. These are represented diagrammatically using arrows, in which the length of the arrow reflects the magnitude of the quantity and the arrowhead allows the direction to be shown. Vectors are used constantly in physics, particularly in the study of motion, in which many variables are vector quantities.

Adding vectors

When vector quantities such as forces are added together, direction needs to be taken into account as well as magnitude. The labelled arrows that represent vectors can be used to perform the addition by placing them ‘head to tail’. When adding pairs of vectors, the labelled arrows are redrawn so that the ‘tail’ of the second arrow abuts the ‘head’ of the first arrow. The sum of the vectors is represented by the arrow drawn between the tail of the first vector and the head of the second. Figure 6.2 illustrates how this method has been used to determine the net force in the three examples shown. The sum of the vectors (F_{net}) is represented in each case.

FIGURE 6.2 When adding vectors, both magnitude and direction need to be considered.



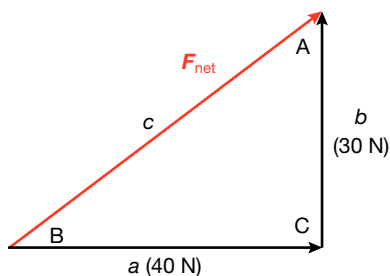
Determining the magnitude of a vector sum

The vectors in figure 6.2 have been drawn to scale. That means that the length of the arrow representing the vector sum can be measured. The magnitude of the vector sum can then be calculated. The direction of the vector sum is given by the direction in which the third arrow points. If the vectors have been drawn to scale, the direction can be determined by measuring the appropriate angle with a protractor.

The magnitude of the vector sum can also be determined by using Pythagoras's theorem. The vector addition shown in figure 6.3 results in a right-angled triangle. The arrow representing the vector sum makes up the hypotenuse of the right-angled triangle. The magnitude that it represents is given by:

$$\begin{aligned}
 c^2 &= a^2 + b^2 \\
 &= (40)^2 + (30)^2 \\
 &= 2500 \text{ (calculating the sum of the squares of both sides)} \\
 \Rightarrow c &= 50 \text{ N (taking the positive square root of the sum of the squares)}
 \end{aligned}$$

FIGURE 6.3 The magnitude and direction of vector addition can be determined using Pythagoras's theorem.



The direction of the net force can be found using trigonometric ratios. In this case, we can use

$$\tan B = \frac{O}{A}.$$

$$\begin{aligned}\tan B &= \frac{30}{40} \\ &= 0.75 \\ B &= \tan^{-1}(0.75) \\ &= 37^\circ\end{aligned}$$

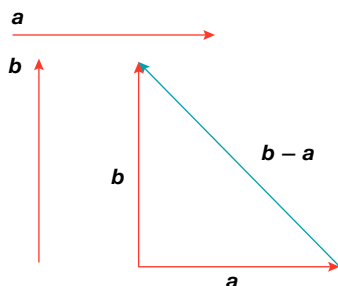
The vector sum, and net force, is 50 N at an angle of N53°E (53° clockwise from north as $A + B = 90^\circ$).

It is important to know the various trigonometric ratios in order to assist finding unknown angles (when at least 2 side lengths are known) or unknown sides (when at least 1 angle and 1 side length is known). Sometimes using sine or cosine may be more appropriate.

Subtracting vectors

One vector can be subtracted from another simply by adding its negative. It works because subtracting a vector is the same as adding the negative vector (just as subtracting a positive number is the same as adding the negative of that number). Another way to *subtract* vectors is to place them tail to tail, as shown in figure 6.4. The difference between the vectors a and b ($b - a$) is given by the vector that begins at the head of vector a and ends at the head of vector b .

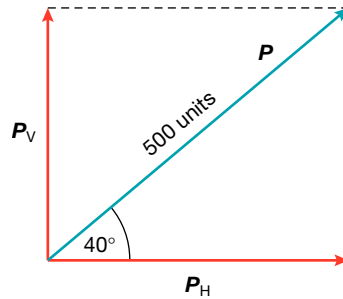
FIGURE 6.4 Subtracting vectors can be done either by placing them tail to tail, or through adding the negative vector.



Finding vector components

The magnitude of vector components can be determined using trigonometric ratios. The vector P in figure 6.5 can be resolved into vertical and horizontal components.

FIGURE 6.5 A vector can be split into vertical and horizontal components.



The magnitude of the horizontal component, labelled P_H , is given by:

$$\begin{aligned}P_H &= P \cos 40^\circ \left(\text{since } \cos 40^\circ = \frac{P_H}{P} \right) \\ \Rightarrow P_H &= 500 \text{ units} \times 0.7660 \\ &= 383 \text{ units.}\end{aligned}$$

The magnitude of the vertical component, labelled as P_V , is given by:

$$\begin{aligned}P_V &= P \sin 40^\circ \left(\text{since } \sin 40^\circ = \frac{P_V}{P} \right) \\ \Rightarrow P_V &= 500 \text{ units} \times 0.6428 \\ &= 321 \text{ units.}\end{aligned}$$

SAMPLE PROBLEM 1

Determine the average acceleration of each of the following objects.

- A car starting from rest reaches a velocity of 60 km h^{-1} due north in 5.0 s.
- A car travelling due west at a speed of 15 m s^{-1} turns due north at a speed of 20 m s^{-1} . The change occurs in a time interval of 2.5 s.
- A cyclist riding due north at 8.0 m s^{-1} turns right to ride due east without changing speed in a time interval of 4.0 s.

THINK

- The change in velocity of the car is 60 km h^{-1} north. To determine the acceleration in SI units, the velocity should be expressed in m s^{-1} (divide by 3.6 to convert from km h^{-1} to m s^{-1}).
- Use the formula $a_{\text{av}} = \frac{\Delta v}{\Delta t}$ to calculate the average acceleration.

WRITE

a. $60 \text{ km h}^{-1} = 16.7 \text{ m s}^{-1}$

$$\begin{aligned}a_{\text{av}} &= \frac{\Delta v}{\Delta t} = \frac{16.7}{5.0} \\ &= 3.3 \text{ m s}^{-2} \text{ north}\end{aligned}$$

- b. 1. The change in velocity must first be found by subtracting vectors because $\Delta \mathbf{v} = \mathbf{v} - \mathbf{u}$. The final velocity ($\mathbf{v}$) is 20 m s^{-1} north and the initial velocity ($\mathbf{u}$) is 15 m s^{-1} west.

The magnitude of the change in velocity can be found by using Pythagoras's theorem or by trigonometry. Remember, subtracting $\mathbf{u}$ is the same as adding the negative vector for $\mathbf{u}$ (which is shown in the diagram as going east rather than west).

2. The direction can be found by calculating the value of the angle θ .

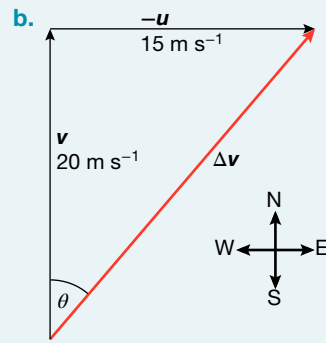
3. Use the formula $a_{av} = \frac{\Delta \mathbf{v}}{\Delta t}$ to calculate the average acceleration, where $\Delta \mathbf{v} = 25 \text{ m s}^{-1}$ N37°E and $t = 2.5 \text{ s}$.

- c. 1. The change in velocity must first be found by subtracting vectors because $\Delta \mathbf{v} = \mathbf{v} - \mathbf{u}$. The final velocity ($\mathbf{v}$) is 8 m s^{-1} east and the initial velocity ($\mathbf{u}$) is 8 m s^{-1} north.

The magnitude of the change in velocity can be found by using Pythagoras's theorem or by trigonometry. Remember, subtracting $\mathbf{u}$ is the same as adding the negative vector for $\mathbf{u}$ (which is shown in the diagram as going south rather than north).

2. The direction can be found by calculating the value of the angle θ .

3. Use the formula $a_{av} = \frac{\Delta \mathbf{v}}{\Delta t}$ to calculate the average acceleration, where $\Delta \mathbf{v} = 11.3 \text{ m s}^{-1}$ S45°E and $\Delta t = 4.0 \text{ s}$.



$$\Delta v = \sqrt{20^2 + 15^2}$$

$$= 25 \text{ m s}^{-1}$$

$$\tan \theta = \frac{15}{20}$$

$$= 0.75$$

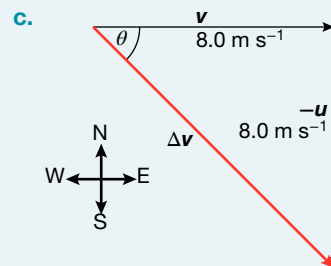
$$\Rightarrow \theta = 37^\circ$$

The direction of the change in velocity is therefore N37°E.

$$a_{av} = \frac{\Delta v}{\Delta t}$$

$$= \frac{25}{2.5}$$

$$= 10 \text{ m s}^{-2} \text{ N37}^\circ\text{E}$$



$$\Delta v = \sqrt{8.0^2 + 8.0^2}$$

$$= 11.3 \text{ m s}^{-1}$$

The triangle formed by the vector diagram shown is a right-angled isosceles triangle. The angle θ is therefore 45° and the direction of the change in velocity is south-east.

$$a_{av} = \frac{\Delta v}{\Delta t}$$

$$= \frac{11.3}{4.0}$$

$$= 2.8 \text{ m s}^{-2} \text{ south-east (or S45}^\circ\text{E)}$$

PRACTICE PROBLEM 1

Determine the average acceleration (in m s^{-2}) of:

- a rocket launched from rest that reaches a velocity of 15 m s^{-1} during the first 5.0 s after lift-off
- a roller-coaster cart travelling due north at 20 m s^{-1} that turns left during an interval of 4.0 s without changing speed
- a rally car travelling west at 100 km h^{-1} that turns left and slows to a speed of 80 km h^{-1} south. The turn takes 5.0 s to complete.

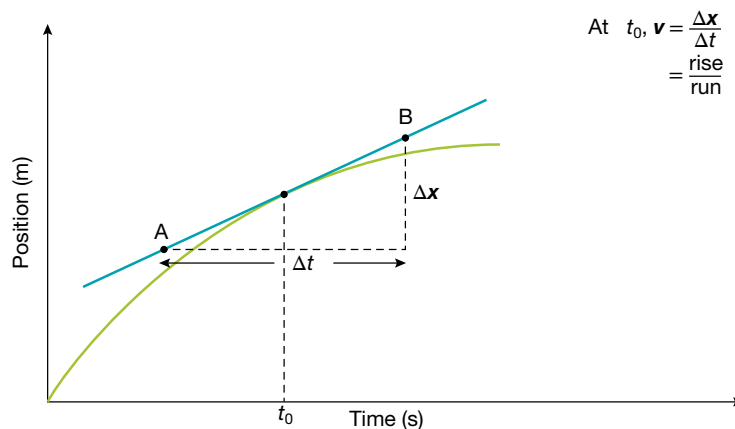
6.2.2 Graphical analysis of motion

A description of motion in terms of displacement, average velocity and average acceleration is not complete. These quantities provide a ‘summary’ of motion but do not provide detailed information. By describing the motion of an object in graphical form, it is possible to estimate its displacement, velocity or acceleration at any instant during a chosen time interval.

Position–time graphs

A graph of position versus time provides information about the displacement and velocity at any instant of time during the interval described by the graph. If the graph is a straight line or smooth curve, it is also possible to estimate the displacement and velocity outside the time interval described by the graph.

FIGURE 6.6 The instantaneous velocity $\mathbf{v}$ of an object is equal to the gradient of the position–time graph. If the graph is a smooth curve, the gradient of the tangent must be determined.



The velocity of an object at an instant of time can be obtained from a position–time graph by determining the gradient of the line or curve at the point representing that instant. This method is a direct consequence of the fact that velocity is a measure of the rate of change in position. If the graph is a smooth curve, the gradient at an instant of time is the same as the gradient of the tangent to the curve at that instant.

Similarly, the speed of an object at an instant of time can be obtained by determining the gradient of a graph of the object’s distance from a reference point versus time.

Velocity–time graphs

A graph of velocity versus time provides information about the velocity and acceleration at any instant of time during the interval described by the graph. It also provides information about the displacement between any two instants.

The instantaneous acceleration of an object at an instant of time can be obtained from a velocity–time graph, by determining the gradient of the line or curve at the point representing that instant. This method is a direct consequence of the fact that acceleration is defined as the rate of change of velocity. If the graph is a smooth curve, the gradient at an instant of time is the same as the gradient of the tangent to the curve at that instant.

The displacement of an object during a time interval can be obtained by determining the area under the velocity–time graph representing that time interval. The actual position of an object at any instant during the time interval can be found only if the starting position is known.

Similarly, the distance travelled by an object during a time interval can be obtained by determining the corresponding area under the speed-versus-time graph for the object.

Acceleration–time graphs

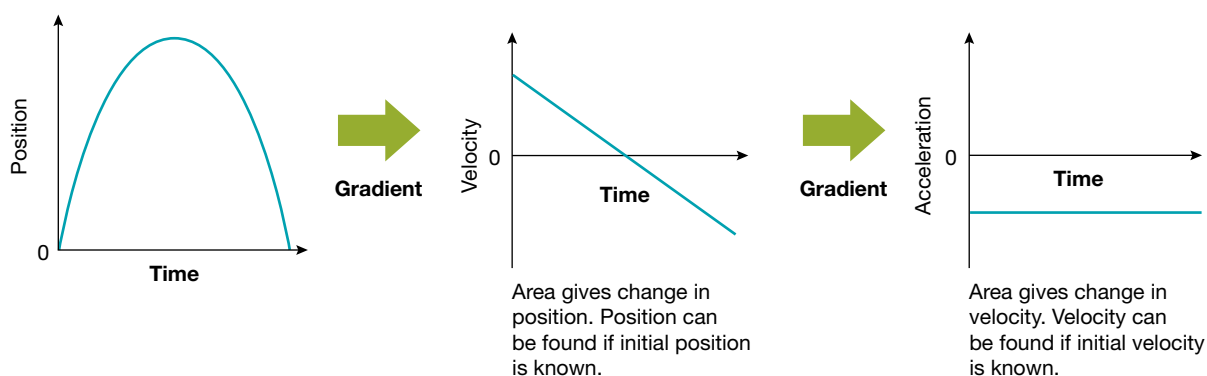
A graph of acceleration versus time provides information about the acceleration at any instant of time during the time interval described by the graph. It also provides information about the change in velocity between any two instants.

The change in velocity of an object during a time interval can be obtained by determining the area under the acceleration–time graph representing that time interval. The actual velocity of the object can be found at any instant during the time interval only if the initial velocity is known.

The relationship between position, velocity and acceleration–time graphs

Position–time, velocity–time and acceleration–time graphs are all related. As velocity is the change of position over time, it is equivalent to the gradient of the position–time graph. Acceleration is the change of velocity over time, and is the gradient of the velocity–time graph, as seen in figure 6.7.

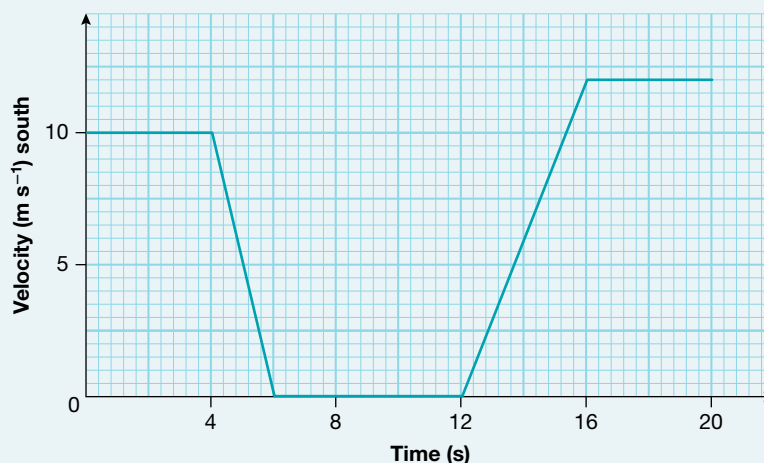
FIGURE 6.7 The position–time, velocity–time and acceleration–time graphs for an object thrown vertically into the air (air resistance is assumed to be negligible). As long as one graph is given, the other two can be deduced. However, some extra information is needed in some cases.



SAMPLE PROBLEM 2

The following velocity–time graph describes the motion of a car as it travels due south through an intersection. The car was stationary for 6.0 s while the traffic lights were red.

- What was the displacement of the car during the interval in which it was slowing down?
- What was the acceleration of the car during the first 4.0 s after the lights turned green?
- Determine the average velocity of the car during the interval described by the graph.



THINK

- The displacement of the car while it was slowing down is given by the area under the graph describing the time interval between 4.0 s and 6.0 s.

Note that the units need to be considered when calculating the area. In this case, the area has a direction as well.

- The acceleration is given by the gradient of the graph describing the first 4.0 s after the lights turned green, that is, the time interval between 12 and 16 s. During this time, the velocity increases from 0 m s⁻¹ south to 12 m s⁻¹. Therefore the 'rise' is 12 m s⁻¹ south and the 'run' is 4.0 s.

1. The displacement during the whole time interval described by the graph is given by the total area under the graph. In this case, the area is split into 4 shapes (2 rectangles and 2 triangles).

2. The average velocity is determined by the formula:

$$v_{\text{av}} = \frac{\Delta s}{\Delta t}, \text{ where } \Delta s = 122 \text{ m south and } \Delta t = 20 \text{ s}$$

WRITE

$$\begin{aligned} \text{a. area} &= \frac{1}{2} \times 2.0 \text{ s} \times 10 \text{ m s}^{-1} \text{ south} \\ &= 10 \text{ m south} \end{aligned}$$

$$\begin{aligned} \text{b. } a &= \frac{\text{rise}}{\text{run}} \\ &= \frac{12}{4.0} \\ &= 3.0 \text{ m s}^{-2} \text{ south} \end{aligned}$$

$$\begin{aligned} \text{c. area} &= (4.0 \times 10) \\ &\quad + \left(\frac{1}{2} \times 2.0 \times 10 \right) \\ &\quad + \left(\frac{1}{2} \times 4.0 \times 12 \right) \\ &\quad + (4.0 \times 12) \\ &= 40 + 10 + 24 + 48 \\ &= 122 \text{ m south} \\ v_{\text{av}} &= \frac{\Delta s}{\Delta t} \\ &= \frac{122}{20} \\ &= 6.1 \text{ m s}^{-1} \text{ south} \end{aligned}$$

PRACTICE PROBLEM 2

Use the velocity–time graph in sample problem 2 to answer the following questions.

- What was the acceleration of the car while it had a positive southerly acceleration?
- What was the acceleration of the car during the 2.0 s before it came to a stop at the traffic lights?
- What was the average velocity of the car during the 6.0 s before it stopped at the traffic lights?



Resources



Video eLesson Motion with constant acceleration (eles-0030)

6.2.3 Algebraic analysis of motion

The motion of an object moving in a straight line with a constant acceleration can be described by a number of formulae. Each of these four formulae allows you to determine an unknown characteristic of straight-line motion with a constant acceleration, as long as you know three other characteristics.

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

where: $\vec{u}$ is the initial velocity

$\vec{v}$ is the final velocity

$\vec{s}$ is the displacement

$\vec{a}$ is the acceleration

t is the time interval

The first two formulae above can be derived from the definitions of velocity and acceleration. The other three can be derived by combining the first two. Because the formulae describe motion along a straight line, vector notation is not necessary. The displacement, velocity and acceleration can be expressed as positive or negative quantities.

SAMPLE PROBLEM 3

Amy rides a toboggan down a steep snow-covered slope. Starting from rest, she reaches a speed of 12 m s^{-1} as she passes her brother, who is standing 19 m further down the slope from her starting position. Assume that Amy's acceleration is constant.

- Determine Amy's acceleration.
- How long did she take to reach her brother?
- How far had Amy travelled when she reached an instantaneous velocity equal to her average velocity?
- At what instant was Amy travelling at an instantaneous velocity equal to her average velocity?

Teacher-led video: SP3 (tlvd-0145)

THINK

- List the known information.
- The appropriate formula here is:
 $v^2 = u^2 + 2as$, because it includes the three known quantities and the unknown quantity a .

WRITE

a. $u = 0$, $v = 12 \text{ m s}^{-1}$, $s = 19 \text{ m}$

$$v^2 = u^2 + 2as$$
$$\Rightarrow 12^2 = 0 + 2a \times 19$$
$$144 = 38 \times a$$
$$\Rightarrow a = 3.8 \text{ m s}^{-2} \text{ down the slope}$$

- b. 1.** List the known information.

(Note that it is better to use the data given rather than data calculated in the previous part of the question. That way, rounding or errors in an earlier part of the question will not affect the answer.)

- 2.** The appropriate formula here is

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

- c. 1.** The magnitude of the average velocity during a period of constant acceleration is given by: $v_{av} = \frac{u + v}{2}$

- 2.** The distance travelled when Amy reaches an instantaneous velocity of this magnitude can now be calculated. List the known information.

- 3.** The appropriate formula here is $v^2 = u^2 + 2as$.

- d. 1.** List the known information.

- 2.** The appropriate formula here is $v = u + at$.

b. $u = 0, v = 12 \text{ m s}^{-1}, s = 19 \text{ m}$

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

$$\Rightarrow 19 = \frac{1}{2}(0 + 12)t$$

$$19 = 6.0 \times t$$

$$\Rightarrow t = \frac{19}{6.0}$$

$$= 3.2 \text{ s}$$

c. $v_{av} = \frac{u + v}{2}$

$$= \frac{0 + 12}{2}$$

$$= 6.0 \text{ m s}^{-1}$$

$u = 0, v = 6.0 \text{ m s}^{-1}, a = 3.8 \text{ m s}^{-2}$

$$v^2 = u^2 + 2as$$

$$\Rightarrow (6.0)^2 = 0 + 2 \times 3.8 \times s$$

$$36 = 7.6 \times s$$

$$\Rightarrow s = \frac{36}{7.6}$$

$$= 4.7 \text{ m}$$

Note that this is well short of the halfway mark in terms of distance.

d. $u = 0, v = 6.0 \text{ m s}^{-1}, a = 3.8 \text{ m s}^{-2}$

$$v = u + at$$

$$\Rightarrow 6.0 = 0 + 3.8 \times t$$

$$6.0 = 3.8 \times t$$

$$\Rightarrow t = \frac{6.0}{3.8}$$

$$= 1.6 \text{ s}$$

This is the midpoint of the entire time interval. In fact, during any motion in which the acceleration is constant, the instantaneous velocity halfway (in time) through the interval is equal to the average velocity during the interval.

PRACTICE PROBLEM 3

A car initially travelling at a speed of 20 m s^{-1} on a straight road accelerates at a constant rate for 16 s over a distance of 400 m.

- Calculate the final speed of the car.
- Determine the car's acceleration without using your answer to part (a).
- What is the average speed of the car?
- What is the instantaneous speed of the car after:
 - 2.0 s
 - 8.0 s?

6.2.4 Momentum

When explaining changes in motion, it is necessary to consider another property of the object: its mass. It is clear, for example, that stopping a truck moving at 20 m s^{-1} is more difficult than stopping a tennis ball moving at the same speed. The physical quantity **momentum** is useful in explaining changes in motion, because it takes into account the mass as well as the velocity of a moving object.

The momentum $\vec{p}$ of an object is defined as the product of its mass m and its velocity $\vec{v}$.

$$\vec{p} = m\vec{v}$$

where: $\vec{p}$ is the momentum
 m is the mass
 $\vec{v}$ is the velocity

Momentum is a vector quantity that has the same direction as that of the velocity. The SI unit of momentum is kg m s^{-1} .



Resources



Weblink Forces and motion

6.2 EXERCISE

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

- Two physics students are trying to determine the instantaneous speed of a bicycle 5.0 m from the start of a 1000 m sprint. They use a stopwatch to measure the time taken for the bicycle to cover the first 10 m. If the acceleration was constant, and the measured time was 4.0 s, what was the instantaneous speed of the bicycle at the 5.0 m mark?
- A car travelling north at a speed of 40 km h^{-1} turns right to head due east at a speed of 30 km h^{-1} . This change in direction and speed takes 2.0 s. Calculate the average acceleration of the car in:
 - $\text{km h}^{-1} \text{ s}^{-1}$
 - m s^{-2} .
- An aeroplane approaches Melbourne Airport and touches down on the runway while travelling at 70 m s^{-1} . This speed is maintained for 8 seconds. Following this, the brakes are engaged, and the aeroplane comes to a stop with a uniform deceleration of 4 m s^{-2} .
 - Calculate how long it takes the aeroplane to stop after landing.
 - Draw a velocity–time graph to describe the motion of the aeroplane from landing to the moment it comes to a stop. Ensure your graph is fully labelled.
 - Use your graph to determine the length of runway used in the landing process.
- A student whose mass is 65 kg runs at a velocity of 35 km h^{-1} . Determine the student's momentum.

6.3 Newton's laws of motion and their application

KEY CONCEPT

- Investigate and apply theoretically and practically Newton's three laws of motion in situations where two or more coplanar forces act along a straight line and in two dimensions.

6.3.1 Newton's three laws of motion

Sir Isaac Newton's three laws of motion, first published in 1687, explain changes in the motion of objects in terms of the forces acting on them. However, Einstein and others have since shown that Newton's laws have limitations. Newton's laws fail, for example, to explain successfully the motion of objects travelling at speeds close to the speed of light. They do not explain the bending of light by the gravitational forces exerted by stars, planets and other large bodies in the universe. However, they do successfully explain the motion of most objects at Earth's surface, the motion of satellites and the orbits of the planets that make up the solar system. In fact, it was Newton's laws that enabled NASA to plan the trajectories of artificial satellites.

Newton's First Law of Motion

Every object continues in its state of rest or uniform motion unless made to change by a non-zero net force.

Newton's First Law of Motion explains many things, for example, why you need to strike a golf ball with the club before it soars through the air. Without a **net force** acting on it, the golf ball will remain in its state of rest on the tee or grass. (Recall that the vector sum of the forces acting on an object is called the net force.) It explains why seatbelts must be worn in a moving car and why you should never leave loose objects (like books, luggage or pets) in the back of a moving car. When a car stops suddenly, it does so because there is a large net force acting on it — as a result of braking or a collision. However, the large force does not act on you or the loose objects in the car. The loose objects continue their motion until stopped by a non-zero net force. Without a properly fitted seatbelt, you would move forward until stopped by the steering wheel, the windscreen or even the road. The loose objects in the car will also continue moving forward, posing a danger to anyone in the car.

Newton's First Law of Motion can also be expressed in terms of momentum by stating that the momentum of an object does not change unless the object is acted upon by a non-zero net force.

Newton's Second Law of Motion

The rate of change in momentum is directly proportional to the magnitude of the net force and is in the direction of the net force.

$$\vec{F}_{net} = \frac{\Delta \vec{p}}{\Delta t} = \frac{m \Delta \vec{v}}{\Delta t} = m \vec{a}$$

(provided the mass is constant)

where: $\Delta \vec{p}$ is the change in momentum

$\Delta \vec{v}$ is the change in velocity

Δt is the time interval

m is the mass

$\vec{a}$ is the acceleration

This expression of Newton's Second Law of Motion is especially useful because it relates the net force to a description of the motion of objects. An acceleration of 1 m s^{-2} results when a net force of 1 N acts on an object of mass 1 kg .

Newton's third law

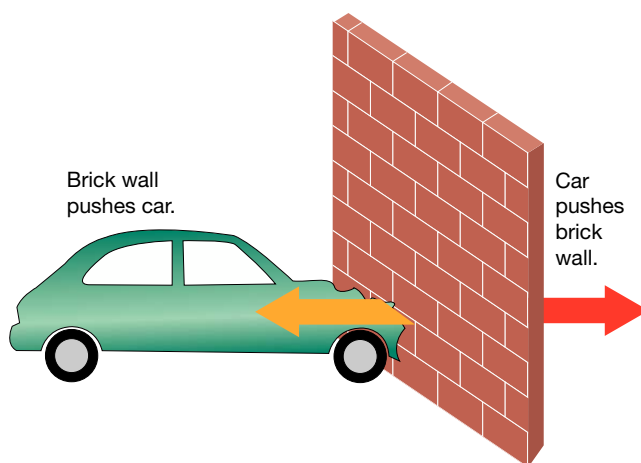
Newton's Third Law of Motion

If object B applies a force to object A, then object A applies an equal and opposite force on object B:

$$\vec{F}_{\text{on A by B}} = -\vec{F}_{\text{on B by A}}$$

It is important to remember that the forces that make up the force pair act on different objects. The subsequent motion of each object is determined by the net force acting on it. For example, in figure 6.8, the net force on the brick wall at the left is the sum of the force applied to it by the car (shown by the red arrow) and all the other forces acting on it. The force shown by the blue arrow is not applied to the brick wall and does not affect its motion. The net force on the car is the sum of the force applied by the brick wall (shown by the blue arrow) and all the other forces acting on it.

FIGURE 6.8 Newton's Third Law of Motion in action



Applying Newton's laws of motion

Newton's laws of motion can be used to explain the motion of objects. It is important to determine the specific laws that should be applied to a particular problem. Since Newton's first law refers only to objects at rest or in uniform motion, this law can be applied in instances when an object is not accelerating. Newton's second law applies to a single object (or a system of more than one body where the bodies are connected to each other) being acted upon by one or more forces, while Newton's third law applies when two objects interact with one another and exert equal but opposite forces on each other. Often, more than one of Newton's laws will be required to solve a problem.

on Resources

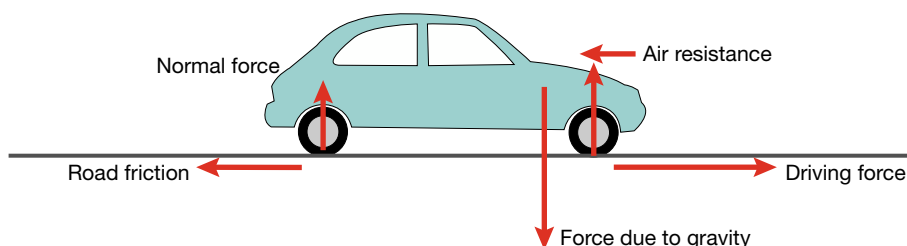
 **Video eLesson** Newton's second law (eles-0033)

6.3.2 On level ground

Whether you are walking on level ground, driving a car, riding in a roller-coaster or flying in a space shuttle, your motion is controlled by the net force acting on you.

Figure 6.9 shows the forces acting on a car moving at a constant velocity on a level surface.

FIGURE 6.9 Forces acting on a car moving on a level surface. The car's engine is making the front wheels turn.



The forces acting on the car are described as follows.

- *The force due to gravity.* The weight of an object is equal to the pull of gravity on it and is usually given the symbol F_g . The force due to gravity of an object is given by:

$$F_g = mg$$

where m is mass and g is the gravitational field strength.

Throughout this text, the magnitude of g at the Earth's surface will be taken as 9.8 N kg^{-1} . The force due to gravity, or weight, of a medium-sized sedan carrying a driver and passenger is about 15 000 N.

- *Normal force.* The normal force is the upward push of the surface on the car. A normal force acts on all four wheels of the car. It is described as a *normal* force because it acts at right angles to the surface. It is also described as a *reaction* force because it acts in response to the force that the object applies to the surface. Unless the surface itself is accelerating up or down, the force applied to the surface by the object is the same as the force due to gravity acting on the object. The total normal force is therefore equal and opposite in direction to the force due to gravity.
- *Driving force.* The force that pushes the car forward is provided at the driving wheels — the wheels that are turned by the motor. In most cars, either the front wheels or the rear wheels are the driving wheels. The motor of a four-wheel drive pushes all four wheels. As the tyres push back on the road, the road pushes forward on the tyres, propelling the car forward. The forward push of the road on the tyres is a frictional force, as it is the resistance to movement of one surface across another. In this case, it is the force that prevents the tyres from sliding across the road. If the road or tyres is too smooth, the driving force is reduced, the tyres slide backwards and the wheels spin.
- *Resistance forces.* As the car moves, it applies a force to the air in front of it. The air applies an equal force opposite to its direction of motion. This force is called **air resistance**. The air resistance on an object increases as its speed increases. The other resistance force acting on the car is **road friction**. It opposes the forward motion of the non-driving wheels, rotating them in the same direction as the driving wheels. In the car in figure 6.9, the front wheels are the driving wheels. Road friction opposes the motion of the rear wheels along the road and, therefore, the forward motion of the car. This road friction is an example of rolling friction, which is considerably smaller than both the sliding friction that acts when the brakes are applied and the friction that acts on the driving wheels.

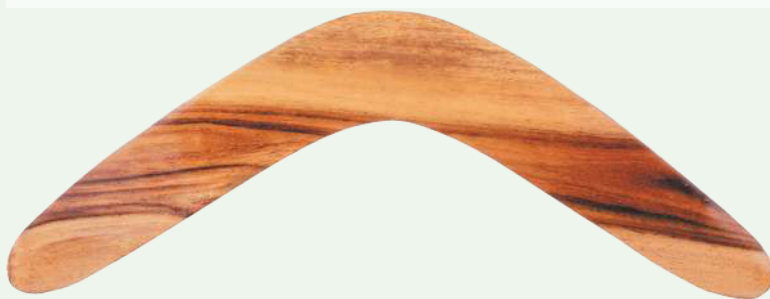
The centre of mass

The forces on a moving car do not all act at the same point on the car. When analysing the translational motion of an object (its movement across space without considering rotational motion), all of the forces applied to an object can be considered to be acting at one particular point. That point is the **centre of mass**. The centre of mass of a symmetrical object with uniform mass distribution is at the centre of the object. For example, the centre of mass of a ruler, a solid ball or an ice cube is at the centre. However, the centre of mass of a person or a car is not.

AS A MATTER OF FACT

If you hold an object such as a ruler at its centre of mass, it will balance. However, the centre of mass does not have to be within the object. For example, the centre of mass of a donut is in its centre. A high jumper can improve her performance by manoeuvring her body over the bar so that her centre of mass is below the bar. The centre of gravity of an object is a point through which the gravitational force can be considered to act. For most objects near the Earth's surface, it is reasonable to assume that the centre of mass is at the same point as the centre of gravity. This is because the gravitational field strength is approximately constant at the Earth's surface.

FIGURE 6.10 Where is the centre of mass of a boomerang? Try balancing a boomerang in a horizontal plane on one finger.



6.3.3 Applying Newton's Second Law of Motion

Sample problem 4 shows how Newton's Second Law of Motion can be applied to single objects or to a system of two objects.

Remember that when the problem involves connected bodies, the whole system, as well as each individual part of the system, will have the same acceleration.

Some tips for using Newton's Second Law of Motion:

1. Draw a diagram of the system.
2. Use clearly labelled diagrams to represent the forces acting on each object in the system. The diagram can be simplified, if necessary, by drawing all the forces as though they were acting through the centre of mass.
3. Apply Newton's second law to the system and/or each individual object until you have the information you need.

SAMPLE PROBLEM 4

A large car of mass 1600 kg starts from rest on a horizontal road with a forward thrust of 5400 N due east. The sum of the forces resisting the motion of the car is 600 N.

- a. Determine the acceleration of the car.
- b. The same car is used to tow a 400 kg trailer with the same forward thrust as before. The sum of the forces resisting the motion of the trailer is 200 N.
 - i. Determine the acceleration of the system of the car and the trailer.
 - ii. What is the magnitude of the force exerted by the trailer on the car? (The force is labelled F_{tc} in the following figure.)

 Teacher-led video: SP4 (tlvd-0146)

THINK

- a. 1. Determine the net force acting on the car. The forward thrust is 5400 N and the sum of the forces acting in the negative direction is 600 N.
2. Apply Newton's second law to determine the acceleration of the car, where the net force is 4800 N and the mass is 1600 kg.

- b. i. 1. A diagram must be drawn to show the forces acting on the car and trailer. The vertical forces can be omitted in this case because it is clear that the sum of the vertical forces is zero. (Otherwise, there would be a vertical component of acceleration.) The vertical forces have been omitted in the figure at right. Assign due east as positive.

2. Determine the net force acting on the entire system.
3. Apply Newton's second law to determine the acceleration of the system, where the net force is 4600 N and the mass of the system is 2000 kg.

- ii. Newton's second law can be applied to either the car or the trailer to answer this question.

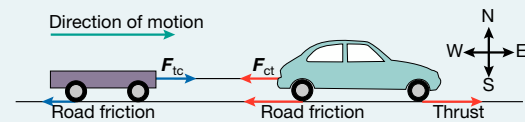
1. *Method 1: Applying Newton's second law to the car*
2. Write an expression for the net force acting on the car, and use it to determine the magnitude of the force exerted by the trailer on the car.

3. *Method 2: Applying Newton's second law to the trailer*

WRITE

$$\begin{aligned} \text{a. } F_{\text{net}} &= 5400 - 600 \\ &= 4800 \text{ N} \end{aligned}$$

$$\begin{aligned} F_{\text{net}} &= ma \\ a &= \frac{F_{\text{net}}}{m} \\ &= \frac{4800}{1600} \\ &= 3.0 \text{ m s}^{-2} \text{ east} \end{aligned}$$



$$\begin{aligned} \text{b. i. } F_{\text{net}} &= 5400 - 600 - 200 \\ &= 4600 \text{ N} \end{aligned}$$

$$\begin{aligned} F_{\text{net}} &= ma \\ a &= \frac{F_{\text{net}}}{m} \\ &= \frac{4600}{2000} \\ &= 2.3 \text{ m s}^{-2} \text{ east} \end{aligned}$$

$$\begin{aligned} \text{ii. } F_{\text{net}} &= ma \\ &= 1600 \times 2.3 \\ &= 3680 \text{ N} \end{aligned}$$

$F_{\text{net}} = 5400 - 600 - F_{\text{tc}}$ where F_{tc} is the magnitude of the force exerted by the trailer on the car.

$$\begin{aligned} 3680 &= 5400 - 600 - F_{\text{tc}} \\ \Rightarrow F_{\text{tc}} &= 5400 - 600 - 3680 \\ &= 1120 \text{ N} \end{aligned}$$

$$\begin{aligned} F_{\text{net}} &= ma \\ &= 400 \times 2.3 \\ &= 920 \text{ N} \end{aligned}$$

4. Write an expression for the net force acting on the trailer, and use it to determine the magnitude of the force exerted by the car on the trailer.

$$F_{\text{net}} = F_{\text{ct}} - 200$$

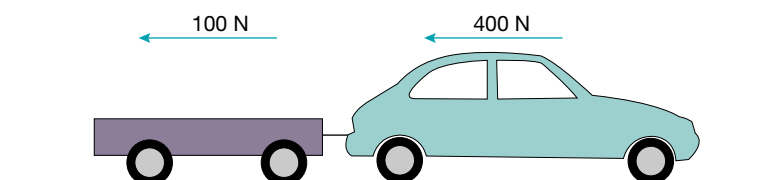
where F_{ct} is the magnitude of the force exerted by the car on the trailer.

$$920 = F_{\text{ct}} - 200$$

$$\Rightarrow F_{\text{ct}} = 920 + 200 \\ = 1120 \text{ N}$$

PRACTICE PROBLEM 4

- a. A car of mass 1400 kg tows a trailer of mass 600 kg due north along a level road at constant speed. The forces resisting the motion of the car and trailer are 400 N and 100 N respectively.



- i. Determine the forward thrust applied to the car.
 - ii. What is the magnitude of the tension in the bar between the car and the trailer?
- b. If the car and trailer in part (a), with the same resistance forces, have a northerly acceleration of 2.0 m s^{-2} , what is:
- i. the net force applied to the trailer
 - ii. the magnitude of the tension in the bar between the car and the trailer
 - iii. the forward thrust applied to the car?

6.3.4 Feeling lighter — feeling heavier

As you sit reading this, the force due to gravity on you by the Earth ($F_g = mg$), is pulling you down towards the centre of the Earth, but the chair is in the way. The material in the chair is being compressed and pushes up on you. This force is called the normal force (F_N) because it is perpendicular or normal to the surface. If these two forces, the force due to gravity and the normal force, balance, the net force on you is zero.

The normal force is responsible for the feeling of ‘heaviness’.
The greater the normal force, the heavier you will feel.

You ‘feel’ the Earth’s pull on you because of Newton’s third law. The upward compressive force on you by the chair is paired with the downward force on the chair by you. You sense this upward force through the compression in the bones in your pelvis.

What happens to these forces when you are in a lift? A lift going up initially accelerates upwards, then travels at a constant speed (no acceleration) and finally slows down (the direction of acceleration is downwards). You experience each of these stages differently.

Accelerating upwards

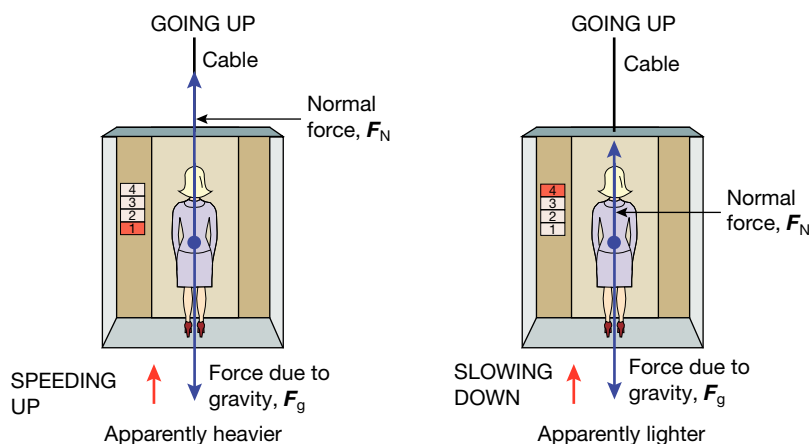
When you are accelerating upwards, the net force on you is upwards. The only forces acting on you are the force due to gravity downwards and the normal force by the floor acting upwards. The force due to gravity is not going to change. So, if the net force on you is up, then the normal force on you must be greater than the force due to gravity: $F_N > mg$.

If the normal force applied to you by the floor of the lift is greater than the force applied to you due to gravity, then, by Newton's third law, the force on the floor of the lift by you is also greater than the force due to gravity. You 'feel heavier'.

Accelerating downwards

When you are accelerating downwards, the net force on you is downwards. So, the normal force on you must be less than the force on you due to gravity: $F_N < mg$. You 'feel lighter'.

FIGURE 6.11 You sense your weight only because the floor pushes up on you. The magnitude of the normal force determines how 'heavy' you feel.



on Resources

Interactivity Going up? (int-6606)

6.3.5 Motion on an incline

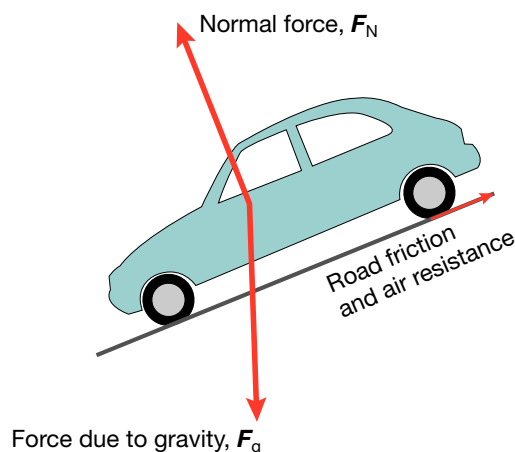
The forces acting on objects on an inclined plane are similar to those acting on the same objects on a level surface. However, the direction of some of the forces is different. As a result, the direction of net force may also be different.

The forces acting on a car rolling down an inclined plane are shown in figure 6.12. The car is considered to behave like a single particle and the rotational motion of the wheels is ignored.

Resolving forces into components

The net force on a car can be found by finding the vector sum of the forces acting on it. It is also helpful in analysing the forces and subsequent motion of the car to 'break up', or resolve, the forces into components. Figure 6.13 shows how the force due to gravity can be resolved into two components — one parallel to the surface and one perpendicular to the surface.

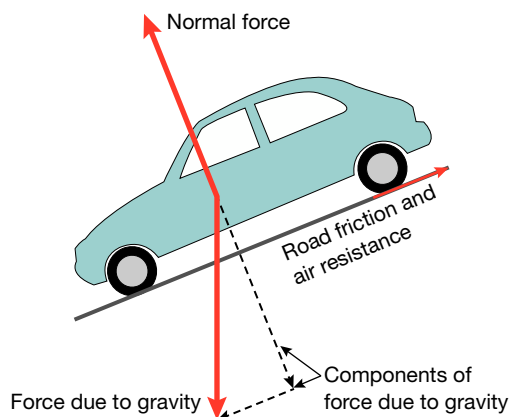
FIGURE 6.12 The forces acting on a car rolling down an inclined plane



By resolving the force due to gravity into these components, the analysis of the forces and subsequent motion of the car is made simpler. Consider the forces perpendicular to the inclined plane. Figure 6.13 shows that the magnitude of the normal force is equal to the component of the force due to gravity that is perpendicular to the surface. Thus, the net force has no component perpendicular to the surface. (Imagine what would happen if this wasn't the case!)

Now consider the forces parallel to the inclined plane. The horizontal component of the force due to gravity is greater than the sum of road friction and air resistance. The net force is therefore parallel to the surface. The car will accelerate down the slope.

FIGURE 6.13 Forces can be resolved into components. In this case, the force due to gravity has been resolved into two components.



SAMPLE PROBLEM 5

A downhill snow skier of mass 70 kg is moving down a slope inclined at 15° to the horizontal with a constant velocity.

Determine the magnitude and direction of:

- the normal force (F_N)
- the sum of the resistance forces (F_R) acting on the skier.

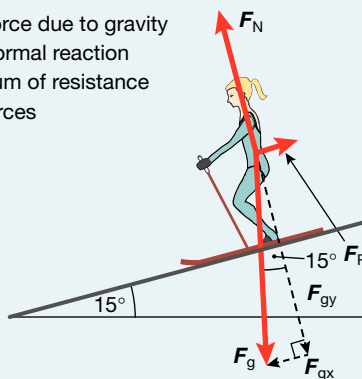
Teacher-led video: SP5 (tlvd-0147)

THINK

1. A diagram must be drawn to show the forces acting on the skier.

WRITE

- F_g = Force due to gravity
 F_N = Normal reaction
 F_R = Sum of resistance forces



2. The net force on the skier has no component perpendicular to the surface of the snow, thus,
 $F_N = F_{gy}$.
 Use $F_g = mg$, where
 $m = 70 \text{ kg}$ and $g = 9.8 \text{ N kg}^{-1}$.

$$\begin{aligned}
 F_N &= F_{gy} \\
 &= F_g \cos 15^\circ \left(\text{since } \cos 15^\circ = \frac{F_{gy}}{F_g} \Rightarrow F_{gy} = F_g \cos 15^\circ \right) \\
 &= mg \cos 15^\circ \\
 &= 70 \times 9.8 \times \cos 15^\circ \\
 &= 663 \text{ N, rounded to } 660 \text{ N}
 \end{aligned}$$

The normal force is therefore 660 N in the direction perpendicular to the surface as shown (as we are specifying the direction, we do not need to use a negative sign).

- b. The net force on the skier in the direction parallel to the surface is zero. This is known because the skier has a constant velocity. The magnitude of the sum of resistance forces therefore must be equal to the component of the force due to gravity that is parallel to the surface, $F_R = F_{gx}$.

$$\begin{aligned}
 \text{b. } F_R &= F_{gx} \\
 &= F_g \sin 15^\circ \left(\text{since } \sin 15^\circ = \frac{F_{gx}}{F_g} \Rightarrow F_{gx} = F_g \sin 15^\circ \right) \\
 &= mg \sin 15^\circ \\
 &= 70 \times 9.8 \times \sin 15^\circ \\
 &= 178 \text{ N, rounded to } 180 \text{ N}
 \end{aligned}$$

The sum of the resistance forces (air resistance and friction) acting on the skier is 180 N opposite to the direction of motion.

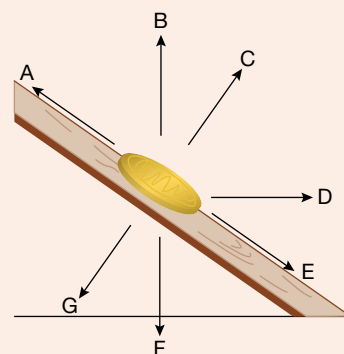
PRACTICE PROBLEM 5

- a. A cyclist rides at constant velocity up a hill that is inclined at 15° to the horizontal. The total mass of the cyclist and bicycle is 90 kg. The sum of the resistive forces on the cyclist and bicycle is 20 N. Determine:
- the forward driving force provided by the road on the bicycle
 - the normal force.
- b. If the cyclist in part (a) coasts down the same hill with a constant total resistance of 50 N, what is the cyclist's acceleration?

EXERCISE 6.3

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

- Draw a sketch (the length of the arrows should give a rough indication of relative size of the force) showing all the forces acting on a tennis ball while it is:
 - falling to the ground
 - in contact with the ground just before rebounding upwards
 - on its upward path after bouncing on the ground.
- A coin is allowed to slide with a constant velocity down an inclined plane as shown in the following diagram. Which of the arrows A to G on the diagram represents the direction of each of the following? If none of the directions is correct, write X.
 - The force due to gravity on the coin
 - The normal force
 - The net force
- A child pulls a 4.0 kg toy cart along a horizontal path with a rope so that the rope makes an angle of 30° with the horizontal. The tension in the rope is 12 N.
 - What is the force due to gravity acting on the toy cart?
 - What is the component of tension in the direction of motion?
 - What is the magnitude of the normal force?



4. A dodgem car of mass 200 kg is driven due south into a rigid barrier at an initial speed of 5.0 m s^{-1} . The dodgem rebounds at a speed of 2.0 m s^{-1} . It is in contact with the barrier for 0.20 s. Calculate:
 - (a) the average acceleration of the car during its interaction with the barrier
 - (b) the average net force applied to the car during its interaction with the barrier.
5. A 1500 kg car is resting on a slope inclined at 20° to the horizontal. It has been left out of gear, so the only reason it doesn't roll down the hill is that the handbrake is on.
 - (a) Draw a labelled diagram showing the forces acting on the car.
 - (b) Calculate the magnitude of the normal force.
 - (c) What is the net force acting on the car?
 - (d) What is the magnitude of the frictional force acting on the car?
6. An experienced downhill skier with a mass of 60 kg (including skis) moves in a straight line down a slope inclined at 30° to the horizontal with a constant speed of 15 m s^{-1} .
 - (a) What is the direction of the net force acting on the skier?
 - (b) What is the magnitude of the resistive forces opposing the skier's motion?
7. A waterskier of mass 70 kg is towed in a northerly direction by a speedboat with a mass of 350 kg. The frictional forces opposing the forward motion of the waterskier total 240 N.
 - (a) If the waterskier has an acceleration of 2.0 m s^{-2} due north, what is the tension in the rope towing the waterskier?
 - (b) If the frictional forces opposing the forward motion of the speedboat are increased to total 600 N, what is the thrust force applied to the boat due to the action of the motor?
8. A 4.0 kg magpie flies towards a very tight plastic wire on a clothes line. The wire is perfectly horizontal and is stretched between poles 4.0 m apart. The magpie lands on the centre of the wire, depressing it by a vertical distance of 4.0 cm. What is the magnitude of the tension in the wire?
9. An old light globe hangs by a wire from the roof of a train. What angle does the globe make with the vertical when the train is accelerating at 1.5 m s^{-2} ?

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6.4 Projectile motion

KEY CONCEPT

- Investigate and analyse theoretically and practically the motion of projectiles near Earth's surface, including a qualitative description of the effects of air resistance.

Any object that is launched into the air is a projectile. A basketball thrown towards a goal, a trapeze artist soaring through the air, and a package dropped from a helicopter are all examples of projectiles.

Except for those projectiles whose motion is initially straight up or down, or those that have their own power source (such as a guided missile), projectiles generally follow a parabolic path. Deviations from this path can be caused either by air resistance, by the spinning of the object or by wind. These effects are often small and can be ignored in many cases. A major exception, however, is the use of spin in many ball sports, but this effect will not be dealt with in this book.

6.4.1 Falling down

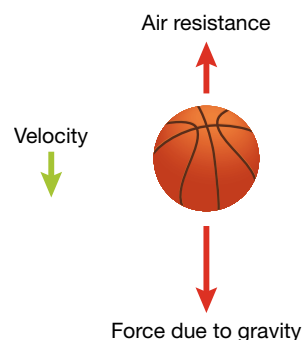
Imagine a ball that has been released some distance above the ground. Once the ball is set in motion, the only forces acting on it are the force due to gravity (straight down) and air resistance (straight up).

After the ball is released, the projection device (hand, gun, slingshot or whatever) stops exerting a downward force.

The net force on the ball in figure 6.14 is downwards. As a result, the ball accelerates downwards. If the size of the forces and the mass of the ball are known, the acceleration can be calculated using Newton's Second Law of Motion.

Often the force exerted on the ball by air resistance is very small in comparison to the force of gravity, and so can be ignored. This makes it possible to model projectile motion by assuming that the acceleration of the ball is due only to gravity and is a constant 9.8 m s^{-2} downwards.

FIGURE 6.14 The forces acting on a ball falling downwards



SAMPLE PROBLEM 6

A helicopter delivering supplies to a flood-stricken farm hovers 100 m above the ground. A package of supplies is dropped from rest, just outside the door of the helicopter. Air resistance can be ignored.

- Calculate how long it takes the package to reach the ground.
- Calculate how far from its original position the package has fallen after 0.50 s, 1.0 s, 1.5 s, 2.0 s, etc. until the package has hit the ground. (You may like to use a spreadsheet here.) Draw a scale diagram of the package's position at half-second intervals.

Teacher-led video: SP6 (tlvd-0148)

THINK

- List the known information.
- Use the rule $s = ut + \frac{1}{2}at^2$ to determine the time taken for the package to reach the ground. (Note: The negative square root can be ignored as time will be positive).
- Look at the position of the package after 0.50 s. List the known information.

WRITE

a. $u = 0 \text{ m s}^{-1}$, $s = 100 \text{ m}$, $a = 9.8 \text{ m s}^{-2}$

$$s = ut + \frac{1}{2}at^2$$

$$100 = 0 \times t + \frac{1}{2}(9.8)t^2$$

$$\frac{100}{4.9} = t^2$$

$$t = \sqrt{\frac{100}{4.9}}$$

$$t = 4.5 \text{ s}$$

b. $t = 0.50 \text{ s}$, $u = 0 \text{ m s}^{-1}$, $a = 9.8 \text{ m s}^{-2}$

2. Use the rule $s = ut + \frac{1}{2}at^2$ to determine the distance the package has travelled between $t = 0.00$ s and $t = 0.50$ s.

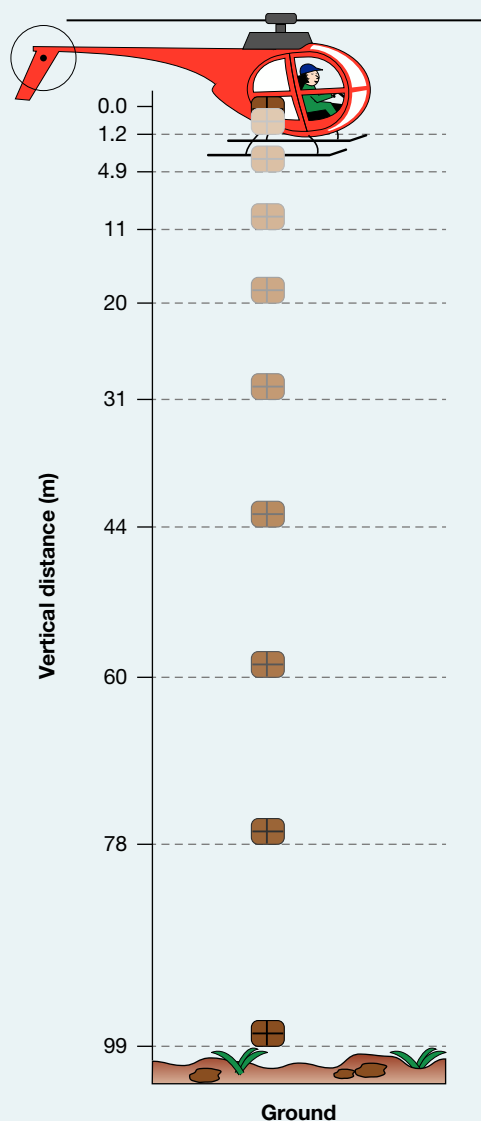
$$\begin{aligned}s &= ut + \frac{1}{2}at^2 \\ &= 0 \times 0.5 + \frac{1}{2}(9.8)(0.5)^2 \\ &= 1.2 \text{ m}\end{aligned}$$

3. Repeat this for $t = 1$ s, 1.5 s, 2 s, etc. until the package hits the ground, and list the results in a table.

Time (s)	0.50	1.0	1.5	2.0
Vertical distance (m)	1.2	4.9	11	20

Time (s)	2.5	3.0	3.5	4.0	4.5
Vertical distance (m)	31	44	60	78	99

4. Draw a scale diagram of the package's position at half-second intervals.



PRACTICE PROBLEM 6

A camera is dropped by a tourist from a lookout and falls vertically to the ground. The thud of the camera hitting the hard ground below is heard by the tourist 3.0 seconds later. Air resistance and the time taken for the sound to reach the tourist can be ignored.

- How far did the camera fall?
- What was the velocity of the camera when it hit the ground below?

Terminal velocity

The air resistance on a falling object increases as its velocity increases. An object falling from rest initially experiences no air resistance. As the object accelerates due to gravity, the air resistance increases. Eventually, if the object doesn't hit a surface first, the air resistance will become as large as the force due to gravity acting on the object. The net force on it becomes zero and the object continues to fall with a constant velocity, referred to as its **terminal velocity**.



Resources



Video eLessons Ball toss (eles-0031)

Air resistance (eles-0035)

6.4.2 Moving and falling

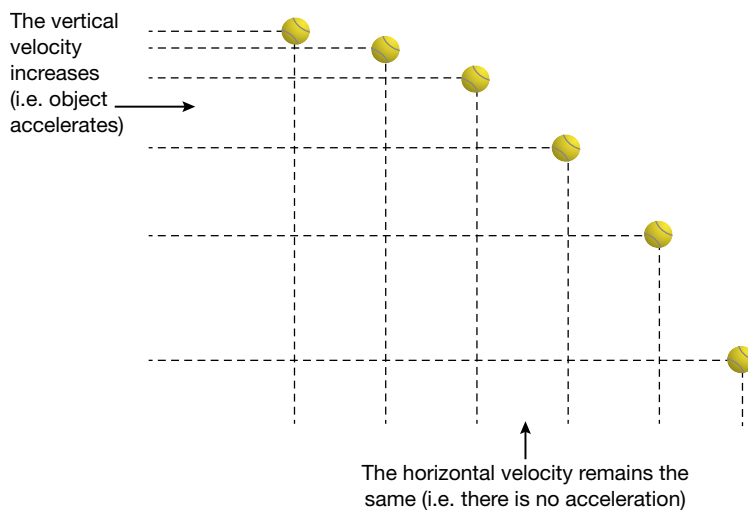
Moving and falling

If a ball is thrown horizontally, the only force acting on the ball once it has been released is the force due to gravity (ignoring air resistance). As the force of gravity is the same regardless of the motion of the ball, the ball will still accelerate downwards at the same rate as if it were dropped. There will not be any horizontal acceleration as there is no net force acting horizontally. This means that, while the ball's vertical velocity will change, its horizontal velocity remains the same throughout its motion.

It is the constant horizontal velocity and changing vertical velocity that give projectiles their characteristic parabolic motion.

Notice that the vertical distance travelled by the ball in each time period increases, but that the horizontal distance is constant.

FIGURE 6.15 Position of a ball at constant time intervals



In modelling projectile motion, the vertical and horizontal components of the motion are treated separately.

1. The total time taken for the projectile motion is determined by the vertical part of the motion as the projectile cannot continue to move horizontally once it has hit the ground, the target or whatever else it might collide with.
2. This total time can then be used to calculate the horizontal distance, or range, over which the projectile travels.

SAMPLE PROBLEM 7

Imagine that the helicopter described in sample problem 6 is not stationary but is flying at a slow and steady speed of 20 m s^{-1} and is 100 m above the ground when the package is dropped.

- a. Calculate how long it takes the package to hit the ground.
- b. What is the range of the package?
- c. Calculate the vertical distance the package has fallen after 0.50 s , 1.0 s , 1.5 s , 2.0 s , etc. until the package has reached the ground. (You may like to use a spreadsheet here.) Then calculate the corresponding horizontal distance, and hence draw a scale diagram of the package's position at half-second intervals.

 Teacher-led video: SP7 (tlvd-0149)

THINK

- a. 1. Remember, the horizontal and vertical components of the package's motion must be considered separately. In this part of the question, the vertical component is important.

2. Use the rule $s = ut + \frac{1}{2}at^2$ to determine the time taken for the package to reach the ground.

WRITE

- a. $u = 0 \text{ m s}^{-1}$, $s = 100 \text{ m}$, $a = 9.8 \text{ m s}^{-2}$

$$s = ut + \frac{1}{2}at^2$$
$$100 = 0 \times t + \frac{1}{2}(9.8)t^2$$

$$\frac{100}{4.9} = t^2$$

$$t = \sqrt{\frac{100}{4.9}}$$

$$t = 4.5 \text{ s}$$

(Note: The positive square root is taken, as the concern is only with what happens after $t = 0$.)

- b. 1. The range of the package is the horizontal distance over which it travels. It is the horizontal component of velocity that must be used here.

List the known information in relation to the horizontal motion of the helicopter.

- b. $u = 20 \text{ m s}^{-1}$ (The initial velocity of the package is the same as the velocity of the helicopter in which it has been travelling.)

$a = 0 \text{ m s}^{-2}$ $a = 0 \text{ m s}^{-2}$ (No forces act horizontally so there is no horizontal acceleration.)

$t = 4.5 \text{ s}$ (from part (a) of this example)

2. Use the rule $s = ut + \frac{1}{2}at^2$ to determine the horizontal distance over which the package travels.

- c. 1. For $t = 0.50$ s, list the known information regarding the vertical and horizontal motions separately.

Use the rule $s = ut + \frac{1}{2}at^2$ to determine the vertical and horizontal distance over which the package travels.

$$\begin{aligned}s &= ut + \frac{1}{2}at^2 \\ &= 20 \times 4.5 + 0 \\ &= 90 \text{ m}\end{aligned}$$

c. Vertical component

$$u = 0 \text{ m s}^{-1}, t = 0.50 \text{ s}, a = 9.8 \text{ m s}^{-2}$$

$$\begin{aligned}s &= ut + \frac{1}{2}at^2 \\ &= 0 \times 0.5 + \frac{1}{2}(9.8)(0.50)^2 \\ &= 1.2 \text{ m}\end{aligned}$$

Horizontal component

$$u = 20 \text{ m s}^{-1}, t = 0.50 \text{ s}, a = 0 \text{ m s}^{-2}$$

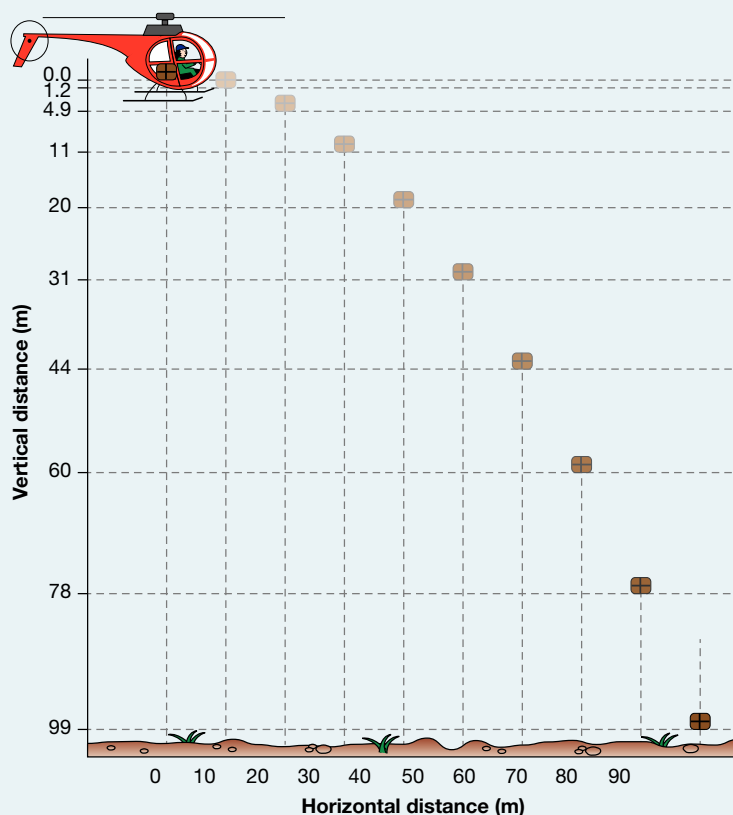
$$\begin{aligned}s &= ut + \frac{1}{2}at^2 \\ &= 20 \times 0.50 + 0 \\ &= 10 \text{ m}\end{aligned}$$

2. Repeat the calculations for $t = 1.0$ s, 1.5 s, 2.0 s, etc. until the package reaches the ground.

Time (s)	Vertical distance (m)	Horizontal distance (m)
0.5	1.2	10
1.0	4.9	20
1.5	11.0	30
2.0	20.0	40
2.5	31.0	50
3.0	44.0	60
3.5	60.0	70
4.0	78.0	80
4.5	99.0	90



3. Draw a scale diagram of the package's position at half-second intervals.



PRACTICE PROBLEM 7

A ball is thrown horizontally at a speed of 40 m s^{-1} from the top of a cliff into the ocean below and takes 4.0 seconds to land in the water. Air resistance can be ignored.

- What is the height of the cliff above sea level if the thrower's hand releases the ball from a height of 2.0 metres above the ground?
- What horizontal distance did the ball cover?
- Calculate the vertical component of the velocity at which the ball hits the water.
- At what angle to the horizontal does the ball strike the water?



Resources



Digital documents Investigation 6.1 Modelling projectile motion (doc-31599)
Investigation 6.2 The drop zone (doc-31600)
eModelling: Falling from a helicopter (doc-0033)

6.4.3 What goes up must come down

Most projectiles are set in motion with velocity. The simplest case is that of a ball thrown directly upwards. The only force acting on the ball is the force due to gravity (ignoring air resistance). The ball accelerates downwards. Initially, this results in the ball slowing down. Eventually, it comes to a halt, then begins to move downwards, speeding up as it goes.

Notice that, when air resistance is ignored, the motion of the ball is identical whether it is going up or coming down. The speed will be the same when the ball is at the same height, regardless of whether it is going up or coming down. Therefore, if a ball is thrown upwards and lands at the exact same height, the ball will return with the same speed with which it was projected. Throughout the motion illustrated in figure 6.16 (graphs are shown in figure 6.17), the acceleration of the ball is a constant 9.8 m s^{-2} downwards. A common error made by physics students is to suggest that the acceleration of the ball is zero at the top of its flight. If this were true, would the ball ever come down?

FIGURE 6.16 The motion of a ball projected vertically upwards

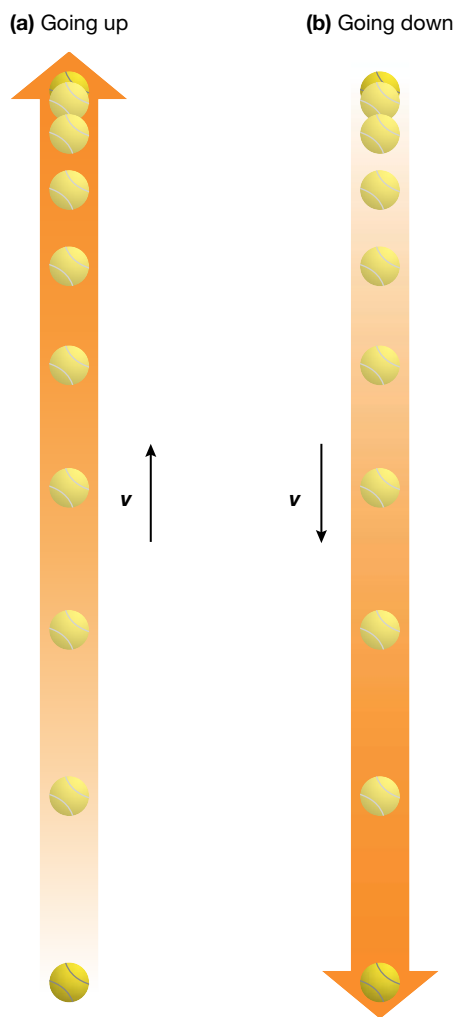
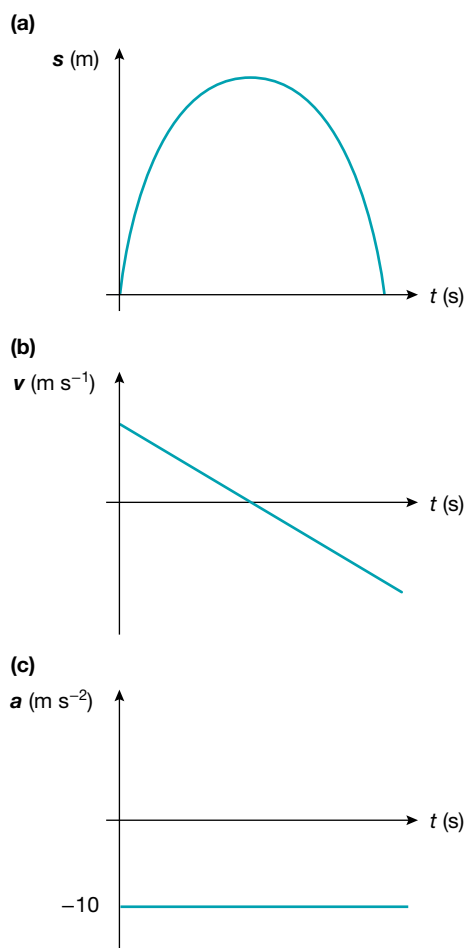


FIGURE 6.17 Graphs of motion for a ball thrown straight upwards



AS A MATTER OF FACT

The axiom 'what goes up must come down' applies equally so to bullets as it does to balls. Unfortunately, this means that people sometimes get killed when they shoot guns straight up into the air. If the bullet left the gun at a speed of 60 m s^{-1} , it will return to Earth at roughly the same speed. This speed is well and truly fast enough to kill a person who is hit by the returning bullet.

SAMPLE PROBLEM 8

A dancer jumps vertically upwards with an initial velocity of 4.0 m s^{-1} . Assume the dancer's centre of mass was initially 1.0 m above the ground, and ignore air resistance.

- How long did the dancer take to reach her maximum height?
- What was the maximum displacement of the dancer's centre of mass?
- What is the acceleration of the dancer at the top of her jump?
- Calculate the velocity of the dancer's centre of mass when it returns to its original height above the ground.

THINK

- List the known information regarding the dancer's upward motion. Assign up as positive and down as negative.
 - Use the rule $v = u + at$ to determine the time taken for the dancer to reach her maximum height.
- List the known information regarding the dancer's upward motion.
 - Use the rule $v^2 = u^2 + 2as$ to determine the displacement over the upward part of the dancer's motion.
- At the top of the jump, the only force acting on the dancer is the force of gravity (but gravity acts at all other points of the jump too). Therefore, the acceleration of the dancer is acceleration due to gravity.
- For this calculation, only the downward motion needs to be investigated. List the known information regarding the dancer's downward motion. (Alternatively, you could look at the whole motion rather than using previously calculated values.)

WRITE

- $u = 4.0 \text{ m s}^{-1}$, $a = -9.8 \text{ m s}^{-2}$, $v = 0 \text{ m s}^{-1}$
(as the dancer comes to a halt at the highest point of the jump)

$$v = u + at$$

$$0 = 4.0 + (-9.8) \times t$$

$$\Rightarrow t = \frac{4.0}{9.8}$$

$$= 0.41 \text{ s}$$

The dancer takes 0.41 s to reach her highest point.

- $u = 4.0 \text{ m s}^{-1}$, $a = -9.8 \text{ m s}^{-2}$, $v = 0 \text{ m s}^{-1}$
(as the dancer comes to a halt at the highest point of the jump)

$$v^2 = u^2 + 2as$$

$$(0)^2 = (4.0)^2 + 2(-9.8)s$$

$$16 = 19.6s$$

$$\Rightarrow s = 0.82 \text{ m}$$

The maximum displacement of the dancer's centre of mass is 0.82 m .

- 9.8 m s^{-2} downwards

- $u = 0 \text{ m s}^{-1}$, $a = -9.8 \text{ m s}^{-2}$, $s = -0.82 \text{ m}$
(as the motion is downwards)

2. Use the rule $v^2 = u^2 + 2as$ to determine the dancer's velocity when she returns to the ground.

(Note: Here, the negative square root is used, as the dancer is moving downwards.

Remember, the positive and negative signs show direction only.)

$$v^2 = u^2 + 2as$$

$$v^2 = (0)^2 + 2(-9.8)(-0.82)$$

$$v^2 = 16.072$$

$$\Rightarrow v = -4.0 \text{ m s}^{-1}$$

The velocity of the dancer's centre of mass when it returns to its original height is 4.0 m s^{-1} downwards.

PRACTICE PROBLEM 8

A basketball player jumps directly upwards so that his centre of mass reaches a maximum displacement of 50 cm.

- What is the velocity of the basketballer's centre of mass when it returns to its original height above the ground?
- For how long was the basketballer's centre of mass above its original height?

HANGING IN MID AIR

Sometimes dancers, basketballers and high jumpers seem to hang in mid air. It is as though the force of gravity had temporarily stopped acting on them. Of course this is not so! It is only the person's centre of mass that moves in a parabolic path. The arrangement of the person's body can change the position of the centre of mass, causing the body to appear to be hanging in mid air even though the centre of mass is still following its original path.

High jumpers can use this effect to increase the height of their jumps. By bending her body as she passes over the bar, a high jumper can cause her centre of mass to be outside her body! This allows her body to pass over the bar, while her centre of mass passes under it. The amount of energy available to raise the high jumper's centre of mass is limited, so she can raise her centre of mass only by a certain amount. This technique allows her to clear a higher bar than other techniques for the same amount of energy.

FIGURE 6.18 Croatian high jumper Ana Simic's centre of mass passes under the bar, while her body passes over the bar!



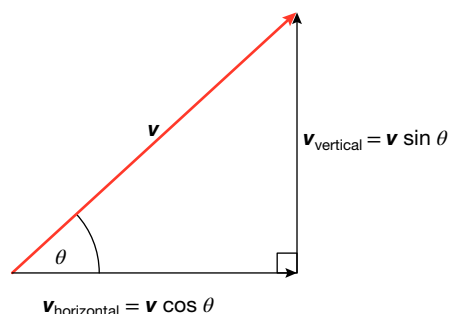
6.4.4 Shooting at an angle

Generally, projectiles are shot, thrown or driven at some angle to the horizontal. In these cases, the initial velocity may be resolved into its horizontal and vertical components to help simplify the analysis of the motion.

If the velocity and the angle to the horizontal are known, the size of the components can be calculated using trigonometry.

The motion of projectiles with an initial velocity at an angle to the horizontal can be dealt with in exactly the same manner as those with a velocity straight up or straight across. However, the initial velocity must be separated into its vertical and horizontal components.

FIGURE 6.19 The velocity can be resolved into a vertical and a horizontal component.



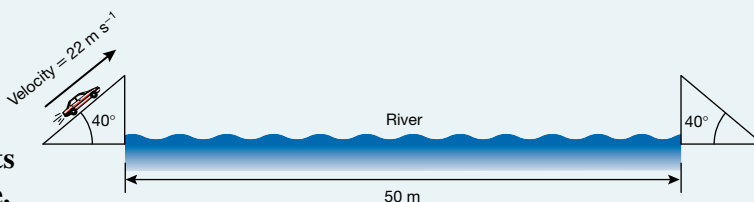
Projectile motion calculations

Some tips for projectile motion calculations:

- It helps to draw a diagram.
- Always separate the motion into vertical and horizontal components.
- Remember to resolve the initial velocity into its components if necessary.
- The time in flight is the link between the separate vertical and horizontal components of the motion.
- At the end of any calculation, check to see if the quantities you have calculated are reasonable.

SAMPLE PROBLEM 9

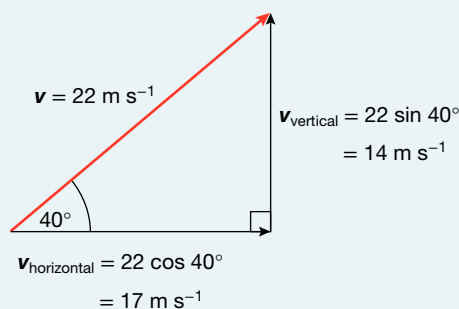
A stunt driver is trying to drive a car over a small river. The car will travel up a ramp (at an angle of 40°) and leave the ramp at 22 m s^{-1} before landing back at its initial height. The river is 50 m wide. Will the car make it?



THINK

1. Before either part of the motion can be examined, it is important to calculate the vertical and horizontal components of the initial velocity. Assign up as positive and down as negative.

WRITE



Therefore, the initial vertical velocity is 14 m s^{-1} and the initial horizontal velocity is 17 m s^{-1} .

2. The vertical motion is used to calculate the time in the air. Use the first half of the motion — from take-off until the car has reached its highest point.

(It is possible to double the time in this situation because air resistance has been ignored. The two parts of the motion are symmetrical.)

3. The horizontal component is used to calculate the range.

Vertical component

$u = 14 \text{ m s}^{-1}$, $a = -9.8 \text{ m s}^{-2}$,
 $v = 0 \text{ m s}^{-1}$ (as the car comes to a vertical halt at its highest point):

$$v = u + at$$

$$0 = 14 + (-9.8) \times t$$

$$\Rightarrow t = \frac{14}{-9.8}$$

$$= 1.4 \text{ s}$$

As this is only half the motion, the total time in the air is 2.8 s.

Horizontal component

$u = 17 \text{ m s}^{-1}$, $t = 2.8 \text{ s}$, $a = 0 \text{ m s}^{-2}$:

$$s = ut$$

$$= 17 \times 2.8$$

$$= 48 \text{ m}$$

Therefore, the unlucky stunt driver will fall short of the second ramp and will land in the river. Perhaps the study of physics should be a prerequisite for all stunt drivers!

PRACTICE PROBLEM 9

A hockey ball is hit towards the goal at an angle of 25° to the ground with an initial speed of 32 km h^{-1} .

- What are the horizontal and vertical components of the initial velocity of the ball?
- How long does the ball spend in flight?
- What is the range of the hockey ball?



Resources



Digital documents eModelling: Free throw shooter (doc-0034)

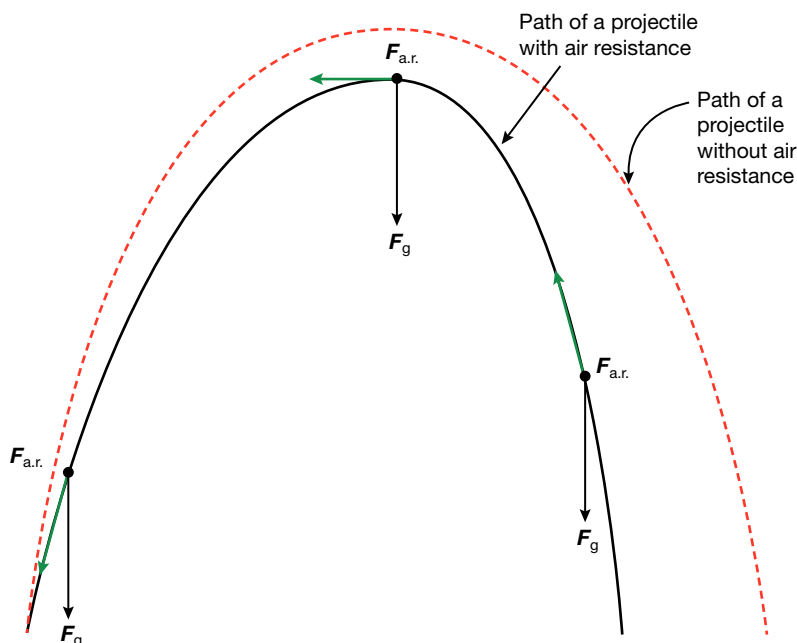
eModelling: Modelling a stunt driver (doc-0035)

6.4.5 The real world — including air resistance

So far in this topic, the effects of air resistance have been ignored so that projectile motion can easily be modelled. The reason the force of air resistance complicates matters so much is that it is not constant throughout the motion. It depends on a number of factors related to the object being thrown and the conditions in which it is being thrown. Consider what differences you might expect when you throw a crumpled-up piece of paper versus when you throw a cricket ball. Or, the difference when you throw a cricket ball in humid air conditions or dry air conditions.

The impact of air resistance can be influenced by the velocity (v) of the object — the faster an object moves, the greater the air resistance. The size of the object in cross-section to the direction it is being thrown also has an impact — the greater the area, the greater the air resistance. Related to the size of the object is the shape of the object — objects that are more streamlined will experience less air resistance. Finally, the density of the air can impact air resistance — the more dense the air, the greater the air resistance.

FIGURE 6.20 While the magnitude of air resistance changes throughout the motion, it always opposes the direction of the motion.



on Resources

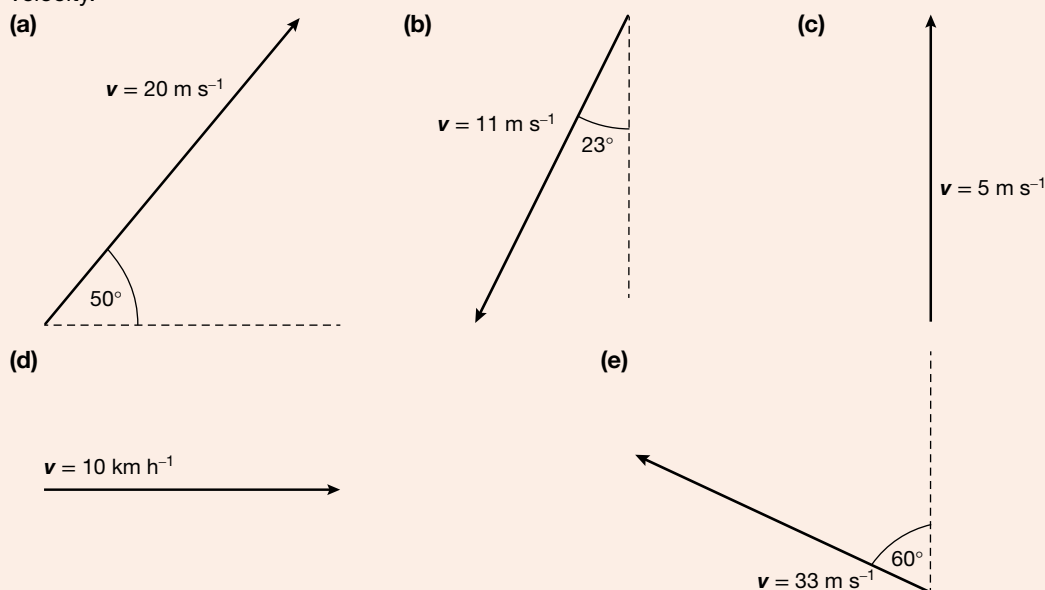
 **Weblink** Projectile motion applet

6.4 EXERCISE

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

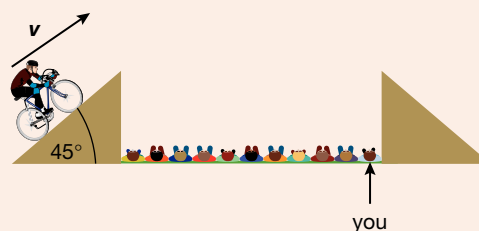
1. A ball has been thrown directly upwards. Draw the ball at three points during its flight (going up, at the top and going down) and mark on the diagrams all the forces acting on the ball at each time.
2. Ignoring air resistance, the acceleration of a projectile in flight is always the same, whether it is going up or down. Use graphs of motion to show why this is the case.

3. In each of the following cases, calculate the magnitude of the vertical and horizontal components of the velocity.



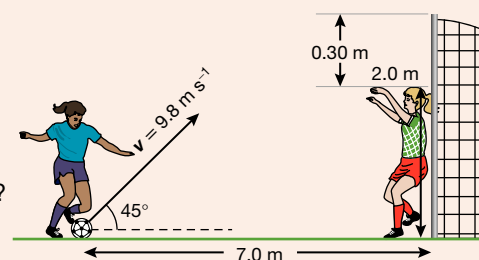
4. After taking a catch, a cricketer throws the cricket ball up into the air in jubilation.
- The vertical velocity of the ball as it leaves her hands is 18 m s^{-1} . How long will the ball take to return to its original position?
 - What was the ball's maximum vertical displacement?
 - Draw vectors to indicate the net force on the ball (ignoring air resistance),
 - the instant it left her hands
 - at the top of its flight
 - as it returns to its original position.

5. A friend wants to get into the *Guinness Book of Records* by jumping over 11 people on his pushbike and landing on the other side at the same height he jumped from. He has set up two ramps as shown in the following figure, and has allowed a space of 0.5 m within which each person can lie down. In practice attempts, he has averaged a speed of 7.0 m s^{-1} at the end of the ramp. Will you lie down as the eleventh person between the ramps?



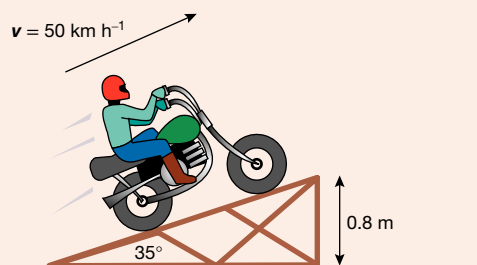
6. A skateboarder jumps a horizontal distance of 2 m (starting from the ground), taking off at a speed of 5 m s^{-1} . The jump takes 0.42 s to complete.
- What was the skateboarder's initial horizontal velocity?
 - What was the angle of take-off?
 - What was the maximum height above the ground reached during the jump?

7. During practice, a young soccer player shoots for goal. The short goalkeeper is able to stop the ball only if it is more than 30 cm beneath the crossbar. The ball is kicked at an angle of 45° with a speed of 9.8 m s^{-1} . The arrangement of the players is shown in the following diagram.



- How long does it take the ball to reach the top of its flight?
- How far vertically and horizontally has the ball travelled at this time?
- How long does it take the ball to reach the soccer net from the top of its flight?
- Will the ball go into the soccer net, over it, or will the goalkeeper stop it?

8. A motocross rider rides over the jump shown in the following diagram at a speed of 50 km h^{-1} .
- How long does it take the bike to reach the top of its flight?
 - How far vertically and horizontally has the bike travelled at this time?
 - How long does it take the bike to reach the ground from the top of its flight?
 - What is the total range of the jump?



9. A water skier at the Moomba Masters competition in Melbourne leaves a ramp at a speed of 50 km h^{-1} and at an angle of 30° . The edge of the ramp is 1.7 m above the water. Calculate:
- the range of the jump
 - the velocity at which the jumper hits the water.
- (Hint: Split the waterskier's motion into two sections, before the highest point and after the highest point, to avoid solving a quadratic equation.)
10. A gymnast wants to jump a horizontal distance of 2.5 m , leaving the ground at an angle of 28° . With what speed must the gymnast take off?
11. A horse rider wants to jump a 3.0-metre -wide stream. The horse can approach the stream with a speed of 7 m s^{-1} . At what angle must the horse take off? (This question is a challenge. Hint: You will need to use trigonometric ratios from mathematics, or model the situation using a spreadsheet to solve this problem.)

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6.5 Uniform circular motion

KEY CONCEPTS

- Investigate and analyse theoretically and practically the uniform circular motion of an object moving in a horizontal plane $\left(F_{\text{net}} = \frac{mv^2}{r} \right)$ including:
 - a vehicle moving around a circular road
 - a vehicle moving around a banked track
 - an object on the end of a string.
- Model natural and artificial satellite motion as uniform circular motion.

Uniform circular motion is the motion of an object in a circle at constant speed. Humans seem to spend a lot of time going around in circles. Traffic at roundabouts, children on merry-go-rounds, cyclists in velodromes. If you stop to think about it, you are always going around in circles as a result of Earth's rotation.

The satellites orbiting Earth, including the Moon, travel in ellipses. However, their orbits can be modelled as circular motion. This motion was covered in subtopic 2.2, when gravitational forces were closely explored.

This section will investigate and analyse the uniform circular motion of objects moving in a horizontal plane. In doing so, the way that the variables of motion are calculated will need to account for the fact that the motion is circular, rather than in a straight line. Examples will include a vehicle moving around a circular road, a vehicle moving around a banked track and an object at the end of a string.

6.5.1 Period and frequency

The time taken for an object, moving in a circular path and at a constant speed, to complete one revolution is called the **period**, T . The number of revolutions the object completes each second is called the **frequency**, f .

FIGURE 6.21 The motion of satellites around Earth can be modelled as circular motion with a constant speed.



$$f = \frac{1}{T} \quad \text{and} \quad T = \frac{1}{f}$$

where: f is the frequency
 T is the period

6.5.2 Instantaneous velocity

Imagine this scenario: Ralph the dog is chained to pole in the backyard while his owner does the gardening (don't worry — the chain is long enough so that he can still move around). A neighbourhood cat likes to tease him and makes Ralph run around in circles at a constant speed. Ralph's owner, Julie, is a physics teacher. She knows that no matter how great Ralph's average speed is, he always ends up in the same place, so his average velocity is always zero.

Although Ralph's average velocity for a single lap is zero, his instantaneous velocity is continually changing. Velocity is a vector and has a magnitude and direction. While the magnitude of Ralph's velocity may be constant, the direction is continually changing. At one point, Ralph is travelling east, so his instantaneous velocity is in an easterly direction. A short time later, he will be travelling south, so his instantaneous velocity is in a southerly direction.

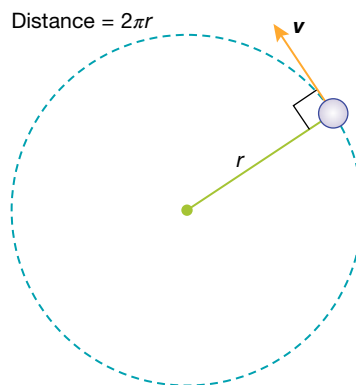
If Ralph could maintain a constant speed, the magnitude of his velocity would not change, but the direction would be continually changing.

FIGURE 6.22 A dog running in circles at a constant speed will have a constantly changing instantaneous velocity but an average velocity of zero.



The speed is therefore constant and can be calculated using the formula $\text{speed} = \frac{d}{t}$, where d is the distance travelled, and t is the time interval. It is most convenient to use the period of the object travelling in a circle. Thus:

FIGURE 6.23 An object moving in circular motion



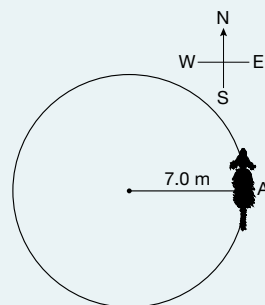
$$\begin{aligned}\text{speed} &= \frac{d}{t} \\ &= \frac{\text{circumference}}{\text{period}} \\ &= \frac{2\pi r}{T}\end{aligned}$$

where: r = radius of the circle
 T = period

SAMPLE PROBLEM 10

Ralph's chain is 7.0 m long and attached to a small post in the middle of the garden. It takes an average of 9 s to complete one lap.

- What is Ralph's average speed?
- What is Ralph's average velocity after three laps?
- What is Ralph's instantaneous velocity at point A?
 (Assume he travels at a constant speed around the circle.)



THINK

- To calculate Ralph's speed, the distance he has travelled is required. Use the formula for the circumference of a circle: $\text{distance} = 2\pi r$.
- Now the average speed can be calculated.

WRITE

$$\begin{aligned}\text{a. distance} &= 2\pi r \\ &= 2\pi \times 7.0 \text{ m} \\ &= 44 \text{ m} \\ \text{speed} &= \frac{d}{t} \\ &= \frac{44}{9} \\ &= 5 \text{ m s}^{-1}\end{aligned}$$

The average speed is 5 m s^{-1} .

b. After three laps, Ralph is in exactly the same place as he started, so his displacement is zero. No matter how long he took to run these laps, his average velocity would still be zero, as $v_{av} = \frac{\Delta x}{\Delta t}$.

c. Ralph's speed is a constant 5 m s^{-1} as he travels around the circle. At point A, the magnitude of his instantaneous velocity is also 5 m s^{-1} .

$$\begin{aligned} \text{b. } v_{av} &= \frac{\Delta x}{\Delta t} \\ &= \frac{0}{3 \times 9} \\ &= 0 \end{aligned}$$

c. At point A, Ralph's velocity is 5 m s^{-1} north.

PRACTICE PROBLEM 10

A battery-operated toy car completes a single lap of a circular track in 15 s with an average speed of 1.3 m s^{-1} . Assume that the speed of the toy car is constant.

- What is the radius of the track?
- What is the magnitude of the toy car's instantaneous velocity halfway through the lap?
- What is the average velocity of the toy car after half of the lap has been completed?
- What is the average velocity of the toy car over the entire lap?

6.5.3 Changing velocities and accelerations

Any object moving in a circle has a continually changing velocity. Remember that, although the magnitude of the velocity is constant, the direction is changing. As all objects with changing velocities are experiencing an acceleration, this means all objects that are moving in a circle are accelerating.

An acceleration can be caused only by an unbalanced force, so non-zero net force is needed to move an object in a circle. For example, a hammer thrower must apply a force to the hammer to keep it moving in a circle. When the hammer is released, it moves off with the velocity it had at the instant of release. The net force on the hammer is the gravitational force on it (neglecting the small amount of air resistance), and the hammer will experience projectile motion.

FIGURE 6.24 The hammer is always accelerating while it moves in a circle.



In which direction is the force?

Figure 6.26 shows diagrammatically the head of the hammer moving in a circle at two different times. It takes t seconds to move from A to B. (This movement is also covered in subtopic 2.2, in which the motion of satellites is explored.) This formula provides a way of calculating To determine the acceleration, the change in velocity between these two points must be determined. Vector addition must be used to do this:

$$\Delta v = v_2 - v_1$$

$$\Delta v = v_2 + (-v_1)$$

FIGURE 6.25 The hammer moves in a circle while the thrower turns. When the hammer is released, it moves in a straight line.

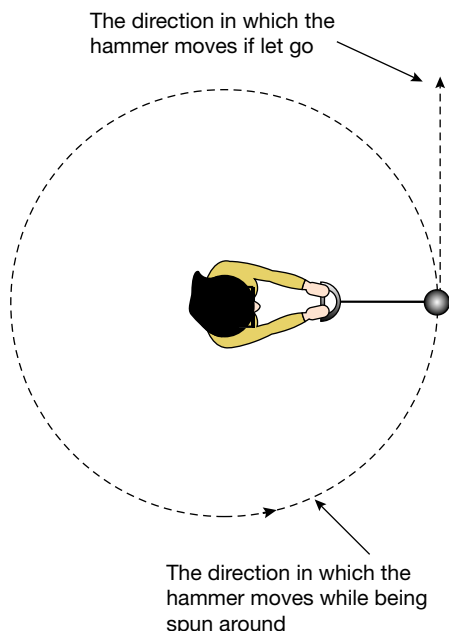
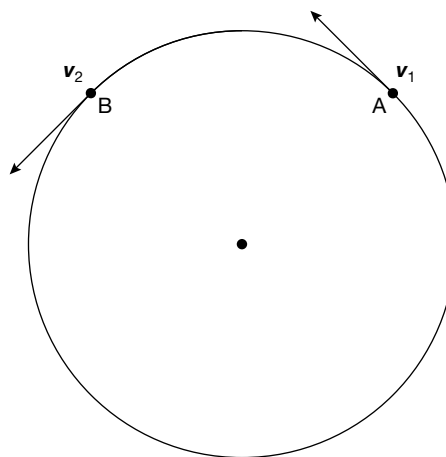
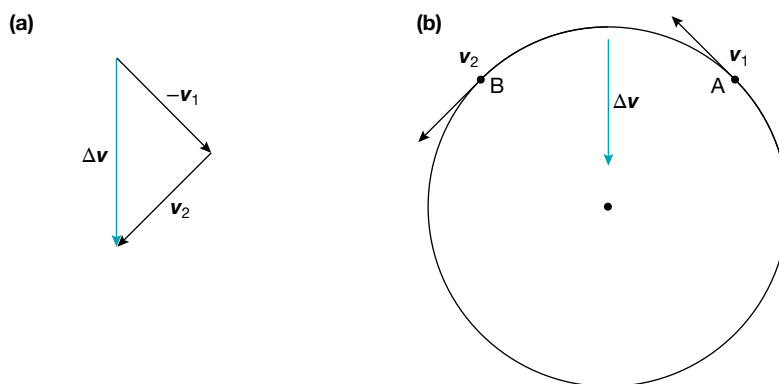


FIGURE 6.26 Velocity vectors for a hammer moving in an anticlockwise circle



Notice that when the $\Delta \mathbf{v}$ vector is transferred back to the original circle halfway between the two points in time, it is pointing towards the centre of the circle. (See figure 6.27b. Such calculations become more accurate when very small time intervals are used; however, a large time interval has been used here to make the diagram clear.)

FIGURE 6.27 (a) Vector addition (b) The change in velocity is towards the centre of the circle.



As $\mathbf{a} = \frac{\Delta \mathbf{v}}{t}$, the acceleration vector is in the same direction as $\Delta \mathbf{v}$, but has a different magnitude and different units.

No matter which time interval is chosen, the acceleration vector always points towards the centre of the circle. So, for an object to have uniform circular motion, the acceleration of the object *must be towards the centre* of the circle. Such an acceleration is called **centripetal acceleration**. The word *centripetal* literally means ‘centre-seeking’. As stated in Newton’s Second Law of Motion, the net force on an object is in the same direction as the acceleration ($\mathbf{F}_{\text{net}} = m\mathbf{a}$). Therefore, the net force on an object moving with uniform circular motion is towards the centre of the circle.

Remember that while the hammer thrower is exerting a force on the hammer head towards the centre of the circle, the hammer head must be exerting an equal and opposite force on the thrower away from the centre of the circle (according to Newton's Third Law of Motion).

6.5.4 Calculating accelerations and forces

Using vector diagrams and the formulae $a = \frac{\Delta v}{t}$ and $F_{\text{net}} = ma$, it is possible to calculate the accelerations and forces involved in circular motion. However, doing calculations this way is tedious, and results can be inaccurate if the vector diagrams are not drawn carefully. It is much simpler to have a formula that will avoid these difficulties. The derivation of such a formula is a little challenging, but it is worth the effort!

By re-examining the two previous figures, it is possible to see that they both 'contain' isosceles triangles. These are shown in figure 6.29.

In figure 6.29, diagram (a) shows distances. It has the radius of the circle marked in twice. These radii form two sides of an isosceles triangle. The third side is formed by a line, or chord, joining point A with point B. It is the distance between the two points. When the angle θ is very small, the length of the chord is virtually the same as the length of the arc that also joins these two points. As this is a distance, its length can be calculated using $s = vt$.

In figure 6.29, diagram (b) shows velocities. As the object was moving with *uniform* circular motion, the length of the vectors v_2 and $-v_1$ are identical and form two sides of an isosceles triangle. As both diagrams (a) and (b) are derived from figure 6.27, both of the angles marked as θ are the same size. Therefore, the triangles are both isosceles triangles, containing the same angle, θ . This means they are similar triangles — they can be thought of as the same triangle drawn on two different scales. Figure 6.29 shows these triangles redrawn to make this more obvious.

As the triangles are similar, the ratio of their sides must be constant, so:

$$\frac{\Delta v}{vt} = \frac{v}{r}$$

Multiplying both sides by v :

$$\frac{\Delta v}{t} = \frac{v^2}{r}$$

As $a = \frac{\Delta v}{t}$:

$$a = \frac{v^2}{r}$$

FIGURE 6.28 The triangles shown in parts (a) and (b) are both isosceles triangles.

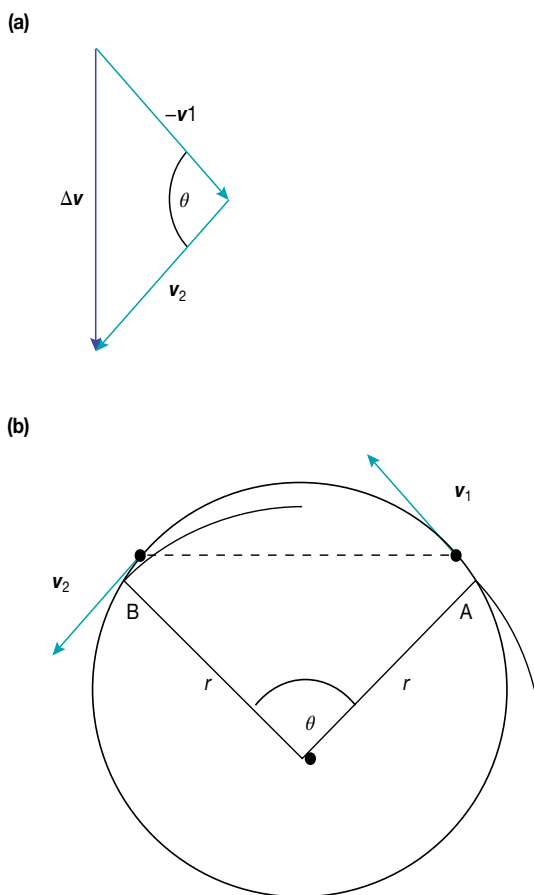
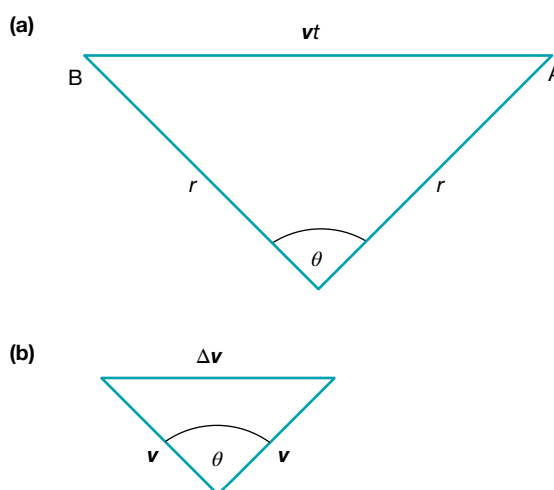


FIGURE 6.29 The two triangles are *similar* triangles.



Sometimes it is not easy to measure the velocity of the object undergoing circular motion. However, this can be calculated from the radius of the circle and the time taken to complete one circuit using the equations

$$v = \frac{2\pi r}{T} \text{ and } a = \frac{v^2}{r}:$$

$$\vec{a} = \frac{\vec{v}^2}{r} = \frac{4\pi^2 r}{T^2}$$

where: $\vec{a}$ is the centripetal acceleration directed towards the centre of the circle

$\vec{v}$ is the speed

r is the radius of the circle

T is the period of motion

This formula provides a way of calculating the centripetal acceleration of a mass moving with uniform circular motion having speed v and radius r .

If the acceleration of a known mass moving in a circle with constant speed has been calculated, the net force can be determined by applying $F_{\text{net}} = ma$.

The magnitude of the net force can also be calculated using:

$$\vec{F}_{\text{net}} = m\vec{a} = \frac{m\vec{v}^2}{r} = \frac{4\pi^2 rm}{T^2}$$

where: $\vec{F}_{\text{net}}$ is the centripetal force on the object

$\vec{a}$ is the acceleration

$\vec{v}$ is the speed

r is the radius of the circle

T is the period of motion.

SAMPLE PROBLEM 11

A car is driven around a roundabout at a constant speed of 20 km h^{-1} (5.6 m s^{-1}). The roundabout has a radius of 3.5 m and the car has a mass of 1200 kg .

- What is the magnitude and direction of the acceleration of the car?
- What is the magnitude and direction of the force on the car?

 **Teacher-led video:** SP11 (tlvd-0153)

THINK

1. List the known information.

WRITE

- $v = 5.6 \text{ m s}^{-1}$, $r = 3.5 \text{ m}$

2. Calculate the acceleration.

$$\begin{aligned}a &= \frac{v^2}{r} \\&= \frac{(5.6)^2}{3.5} \\&= 9.0 \text{ s}^{-1}\end{aligned}$$

The car accelerates at 9.0 m s^{-2} towards the centre of the roundabout.

b. 1. There are two different formulae that can be used to calculate this answer.

i. Use the answer to (a) and substitute into

$$F_{\text{net}} = ma.$$

ii. Use the formula $F_{\text{net}} = \frac{mv^2}{r}$.

b. $a = 9.0 \text{ m s}^{-2}$, $m = 1200 \text{ kg}$

$$\begin{aligned}F_{\text{net}} &= ma \\&= 1200 \times 9.0 \\&= 1.1 \times 10^4 \text{ N}\end{aligned}$$

$v = 5.6 \text{ m s}^{-1}$, $r = 3.5 \text{ m}$, $m = 1200 \text{ kg}$

$$\begin{aligned}F_{\text{net}} &= \frac{mv^2}{r} \\&= \frac{1200 (5.6)^2}{3.5} \\&= 1.1 \times 10^4 \text{ N}\end{aligned}$$

Both methods give the force on the car as $1.1 \times 10^4 \text{ N}$ towards the centre of the roundabout.

PRACTICE PROBLEM 11

Kwong (mass 60 kg) rides the Gravitron at the amusement park. This ride moves Kwong in a circle of radius 3.5 m, at a rate of one rotation every 2.5 s.

a. What is Kwong's acceleration?

b. What is the net force acting on Kwong? (Include a magnitude and a direction in your answer.)

c. Draw a labelled diagram showing all the forces acting on Kwong.



Resources



Digital document Investigation 6.3 Exploring circular motion (doc-31601)



Teacher-led video Investigation 6.3 Exploring circular motion (tlvd-0238)

6.5.5 Forces that produce centripetal acceleration

Whenever an object is in uniform circular motion, the net force on that object must be towards the centre of the circle. Some examples of common situations involving forces producing centripetal acceleration follow.

Tension

In physics, *tension* is used to describe the force applied by an object that is being pulled or stretched.

FIGURE 6.30 (a) Tension contributes to the net force in many amusement park rides. (b) The net force acting on a compartment in the ride

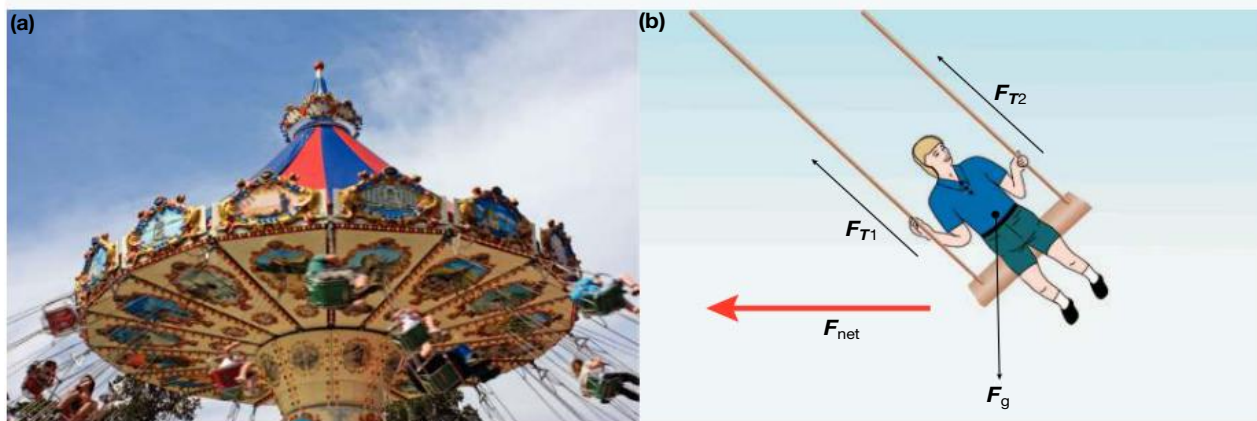
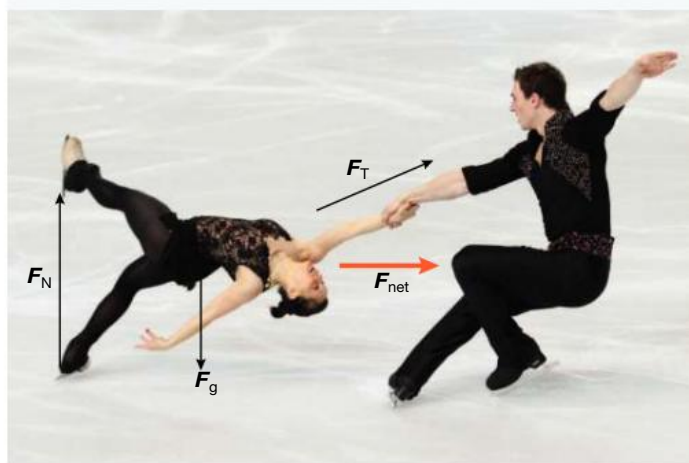


FIGURE 6.31 A component of the tension is the net force acting on the female skater when she is performing a 'death roll'.

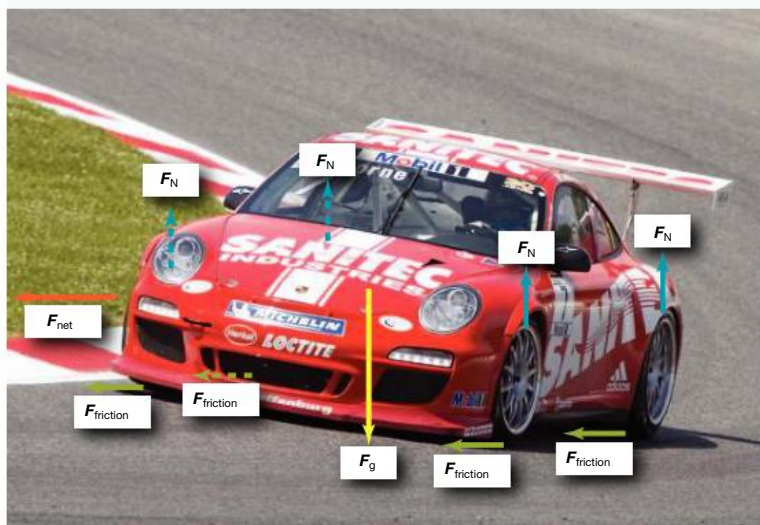


Friction

When a car rounds a corner, the sideways frictional forces contribute to the net force. The forward frictional forces by the ground on the tyres keep the car moving, but if the sideways frictional forces are not sufficient, the net force on the car will not be towards the centre of the curve. In this situation, the net force is less than the force required to keep the car moving in a circle at this radius, and the car will not make it around the corner!

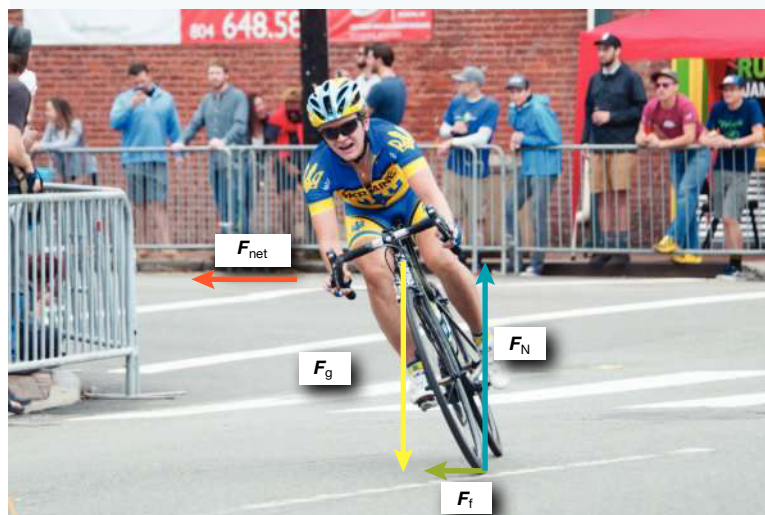
The formula $F_{\text{net}} = \frac{mv^2}{r}$ shows that as the velocity increases, the force needed to move in a circle greatly increases ($F_{\text{net}} \propto v^2$). This is why it is vital that cars do not attempt to corner while travelling too fast.

FIGURE 6.32 The sideways frictional forces of the ground on the tyres enable a car to move around a corner.



Track athletes, cyclists and motorcyclists also rely on sideways frictional forces to enable them to move around corners. To increase the size of the sideways frictional force, which will therefore allow them to corner more quickly, they often lean into the corner. The lean also means that they are pushing on the surface at an angle, so the reaction force is no longer normal to the ground. It has an upwards component, the normal force F_N , which balances the force due to gravity, F_g , and a horizontal component towards the centre of their circular motion due to the frictional force F_f .

FIGURE 6.33 Leaning into a corner increases the size of the net force, allowing a higher speed while cornering. Leaning sideways induces a sideways frictional force, resulting in the horizontal net force experienced by the bicycle.



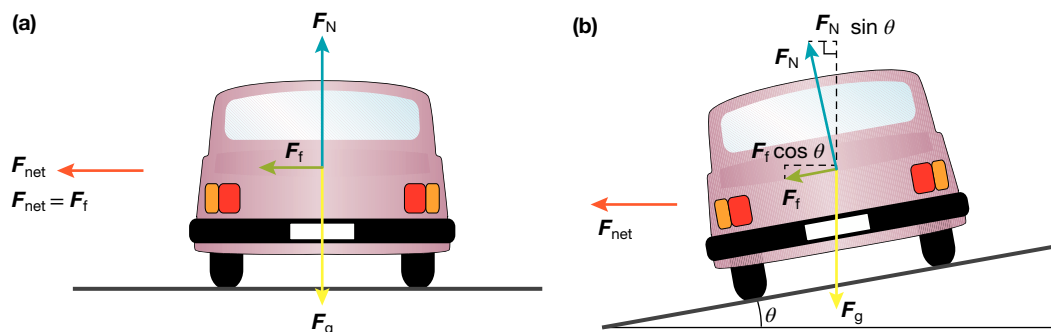
In velodromes, the track is banked so that a component of the normal force acts towards the centre of the velodrome, thus increasing the net force in this direction. As the centripetal force is larger, the cyclists can move around the corners faster than if they had to rely on friction alone.

Going around a bend

When a vehicle travels around a bend, or curve, at constant speed, its motion can be considered to be part of a circular motion. The curve makes up the arc of a circle. For a car to travel around a corner safely, the net force acting on it must be towards the centre of the circle.

Figure 6.34a shows the forces acting on a vehicle of mass m travelling around a curve with a radius r at a constant speed v . The forces acting on the car are the force due to gravity, F_g , friction, F_f , and the normal force, F_N .

FIGURE 6.34 (a) For the vehicle to take the corner safely, the net force must be towards the centre of the circle. (b) Banking the road allows a component of the normal force to contribute to the centripetal force.



On a level road, the only force with a component towards the centre of the circle is the ‘sideways’ friction. This sideways friction makes up the whole of the magnitude of the net force on the vehicle. That is:

$$\begin{aligned} F_{\text{net}} &= \text{sideways friction} \\ &= \frac{mv^2}{r} \end{aligned}$$

If you drive the vehicle around the curve with a speed so that $\frac{mv^2}{r}$ is greater than the sideways friction, the motion is no longer circular and the vehicle will skid off the road. If the road is wet, sideways friction is less and a lower speed is necessary to drive safely around the curve.

CALCULATING THE NET FORCE ON A BANKED ROAD

If the road is banked at an angle θ towards the centre of the circle, a component of the normal force $F_N \sin \theta$ can also contribute to the net force. This is shown in figure 6.34b.

$$F_{\text{net}} = F_f \cos \theta + F_N \sin \theta$$

The larger net force means that, for a given curve, banking the road makes a higher speed possible.

Loose gravel on bends in roads is dangerous because it reduces the sideways friction force. At low speeds this is not a problem, but a vehicle travelling at high speed is likely to lose control and run off the road in a straight line.

Cycling velodromes are steeply banked (often up to 40°), allowing cyclists to achieve very fast speeds. When engineers design velodromes (and other banked tracks, such as banked roadways) they need to consider the speed at which the force due to friction becomes zero. This is dependent on the angle at which the track is banked. The speed at which the force due to friction becomes zero is called the **design speed** and means that frictional force is not required to keep the vehicle on the track. As shown in figure 6.35, only the horizontal component of the normal force is contributing to the net force and there is no frictional force acting sideways.

The equation for net force can be simplified as follows:

$$\begin{aligned} F_{\text{net}} &= F_f \cos \theta + F_N \sin \theta \\ &= 0 + F_N \sin \theta \\ &= F_N \sin \theta \end{aligned}$$

From figure 6.35, it can also be shown that:

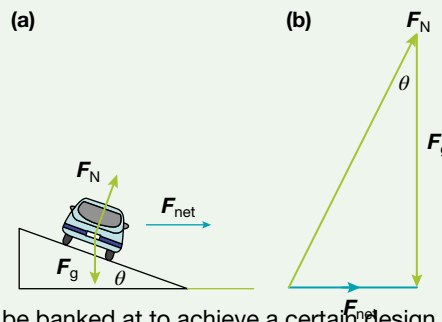
$$\begin{aligned} F_g &= F_N \cos \theta \\ F_{\text{net}} &= F_g \tan \theta \end{aligned}$$

These equations can be used to determine the angle a road needs to be banked at to achieve a certain design speed, or if the angle is known, the design speed can be determined.

Recall that $F_{\text{net}} = \frac{mv^2}{r}$ and $F_g = mg$. If the following is used in substitution, $\tan \theta = \frac{\frac{mv^2}{r}}{mg}$, then:

$$\begin{aligned} \tan \theta &= \frac{v^2}{rg} \\ \Rightarrow \theta &= \tan^{-1} \left(\frac{v^2}{rg} \right) \end{aligned}$$

FIGURE 6.35 (a) When travelling in circular motion at the design speed, the force due to friction is zero, so the only forces acting on the object are the force due to gravity and the normal force. (b) The vector addition of the force due to gravity and the normal force gives the net force as acting horizontally towards the centre of the circle.



When travelling at the design speed, the angle of the bank can be found by using:

$$\tan \theta = \frac{\vec{F}_{\text{net}}}{\vec{F}_g} = \frac{\vec{v}^2}{r\vec{g}}$$

$$\theta = \tan^{-1} \left(\frac{\vec{v}^2}{r\vec{g}} \right)$$

where: θ is the angle of the bank

$\vec{F}_{\text{net}}$ is the net force

$\vec{F}_g$ is the force due to gravity

$\vec{v}$ is the speed

r is the radius of the track

$\vec{g}$ is the acceleration due to gravity

The equation can be arranged so that the design speed can be determined if the bank angle is known.

The design speed can be found by using:

$$\vec{v}^2 = r\vec{g} \tan \theta$$

$$\vec{v} = \sqrt{r\vec{g} \tan \theta}$$

SAMPLE PROBLEM 12

A car of mass 1280 kg travels around a bend with a radius of 12.0 m. The total sideways friction on the wheels is 16 400 N. The road is not banked. Calculate the maximum constant speed at which the car can be driven around the bend without skidding off the road.

 Teacher-led video: SP12 (tlvd-0154)

THINK

The car will maintain the circular motion around the bend if: $F_{\text{net}} = \frac{mv^2}{r}$ where v = maximum speed, F_{net} is the sideways friction (16 400 N), $m = 1280$ kg and $r = 12.0$ m.

If v were to exceed this speed, $F_{\text{net}} < \frac{mv^2}{r}$, the circular motion would not be maintained and the vehicle would skid.

WRITE

$$F_{\text{net}} = 1280 \times \frac{v^2}{12.0}$$

$$v^2 = 16\,400 \times \frac{12.0}{1280}$$

$$= 153.75 \text{ m}^2 \text{ s}^{-2}$$

$$\Rightarrow v = 12.4 \text{ m s}^{-1}$$

The maximum constant speed at which the vehicle can be driven around the bend is 12.4 m s^{-1} .

PRACTICE PROBLEM 12

A motorcyclist is travelling around a circular track at a constant speed of 30 m s^{-1} . The surface is flat and horizontal. The radius of the track is 100 m. The mass of the cyclist with her motorbike is 200 kg. What is the net force experienced by the rider and her bike?

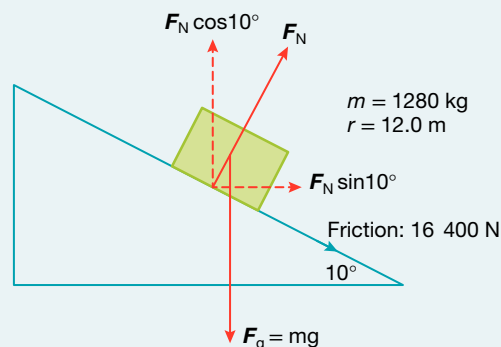
SAMPLE PROBLEM 13

Calculate the maximum constant speed of the car in sample problem 12 (without skidding off the road) if the road is banked at an angle of 10° to the horizontal.

THINK

1. Draw a diagram to represent the known information.
2. The vertical forces are balanced.
3. The net force is equal to the sum of the horizontal forces.

WRITE



$$F_N \cos 10^\circ = 16\,400 \sin 10^\circ + 1280 \times 9.8$$

$$F_N = \frac{15\,392}{\cos 10^\circ}$$

$$= 15\,629 \text{ N}$$

$$F_{\text{net}} = \frac{mv^2}{r}$$

$$F_N \sin 10^\circ + 16\,400 \cos 10^\circ = \frac{1280 \times v^2}{12}$$

$$15\,629 \sin 10^\circ + 16\,400 \cos 10^\circ = \frac{1280 \times v^2}{12}$$

$$\Rightarrow v = 13.3 \text{ m s}^{-1}$$

PRACTICE PROBLEM 13

A cyclist is training at her local velodrome. The velodrome has a radius of 25 m and she is travelling at 8 m s^{-1} . The total mass of the cyclist and her bike is 80 kg. The velodrome track is banked at an angle that results in there being no sideways frictional force on the bike's wheels by the track. Calculate the angle at which the track is banked for there to be no sideways frictional force.

6.5.6 Inside circular motion

What happens to people and objects inside larger objects that are travelling in circles? The answer to this question depends on several factors.

Let's think about passengers inside a bus. The sideways frictional forces by the road on the bus tyres act towards the centre of the circle, which increases the net force on the bus and keeps the bus moving around the circle. If the passengers are also to move in a circle (therefore keeping the same position in the bus) they need, too, to have a net force towards the centre of the circle. Without such a force, they would continue to move in a straight line and probably hit the side of the bus! Usually the friction between the seat and a passenger's legs is sufficient to prevent this happening.

However, if the bus is moving quickly, friction alone may not be adequate. In such cases, passengers may grab hold of the seat in front, thus adding a force of tension through their arms. Hopefully, the sum of the frictional force of the seat on a passenger's legs and the horizontal component of tensile force through the passenger's arms will provide a large enough centripetal force to keep that person moving in the same circle as the bus!

SAMPLE PROBLEM 14

When travelling around a roundabout, John notices that the fluffy dice suspended from his rear-vision mirror swing out. If John is travelling at 8.0 m s^{-1} and the roundabout has a radius of 5.0 m , what angle will the string connected to the fluffy dice (mass 100 g) make with the vertical?

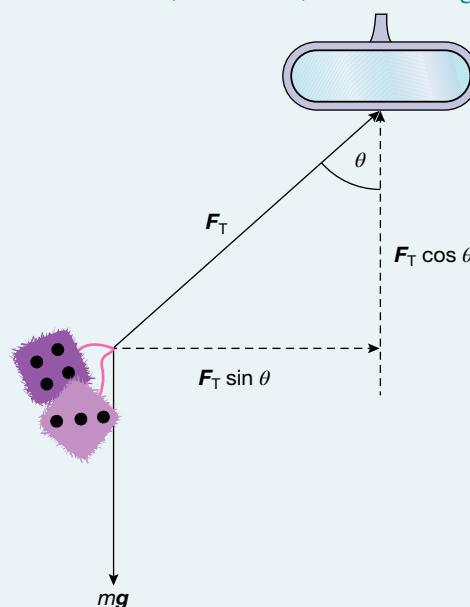
 Teacher-led video: SP14 (tlvd-0156)

THINK

1. When John enters the roundabout, the dice, which are hanging straight down, will begin to move outwards. As long as John maintains a constant speed, they will reach a point at which they become stationary at some angle to the vertical. At this point, the net force on the dice is the centripetal force. Because the dice appear stationary to John, they must be moving in the same circle, with the same speed, as John and his car.
2. Consider the vertical components of the forces. The acceleration has no vertical component.
3. Consider the horizontal components of the forces.
4. To solve the simultaneous equations, substitute for T (from equation (1)) into equation (2).

WRITE

$$v = 8.0 \text{ m s}^{-1}, r = 5.0 \text{ m}, m = 0.100 \text{ kg}$$



$$mg = F_T \cos \theta$$

$$\Rightarrow F_T = \frac{mg}{\cos \theta} \dots (1)$$

$$F_{\text{net}} = \frac{mv^2}{r} = F_T \sin \theta$$

$$\Rightarrow \frac{mv^2}{r} = F_T \sin \theta \dots (2)$$

$$\frac{mv^2}{r} = \frac{mg}{\cos \theta} \times \sin \theta$$

$$= mg \tan \theta$$

$$\Rightarrow \tan \theta = \frac{v^2}{rg}$$

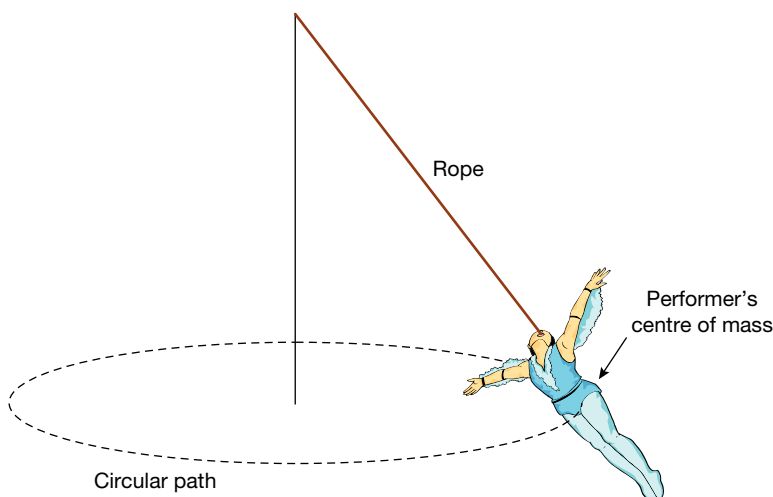
$$= \frac{(8.0)^2}{5.0 \times 9.8}$$

$$\Rightarrow \theta = 53^\circ$$

PRACTICE PROBLEM 14

A 50 kg circus performer grips a vertical rope with her teeth and sets herself moving in a circle with a radius of 5.0 m at a constant horizontal speed of 3.0 m s^{-1} .

- What angle does the rope make the vertical?
- What is the magnitude of the tension in the rope?



REVIEW OF NATURAL AND ARTIFICIAL SATELLITE MOTION

The motion of natural and artificial satellites is covered in section 2.2.2. In review, a satellite is an object that is orbiting the Earth (or other large body). Satellites can be natural, for example, the Moon, or they can be man-made, for example, communication or weather forecasting satellites. The motion of both types of satellites is governed by the same principle of physics — that of uniform circular motion.

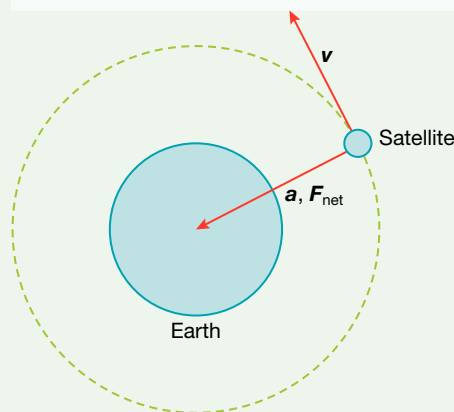
In a stable orbit, a communications satellite orbiting the Earth is subjected only to gravitational force between itself and the Earth. The gravitational force can be thought of like rope preventing the satellite from being flung into outer space. Similar to other examples of uniform circular motion, the direction of the force is towards the centre of the Earth.

Satellites need to be placed into orbit at just the right speed to prevent them from crashing back down to Earth or flying off into space. Once in place, the tendency for satellites to continue in a straight line (according to Newton's first law) is counteracted by the gravitational force accelerating the satellite towards the centre of the Earth (Newton's Universal Law of Gravitation). The gravitational force is described by:

$$F_{\text{gravity}} = \frac{GMm}{r^2}$$

where: M is the mass of the Earth, in kg
 m is the mass of the satellite, in kg
 r is the distance between the centres of the objects, in m
 G is the gravitational constant ($6.673 \times 10^{-11} \text{ N m}^2 \text{ kg}^{-2}$)

FIGURE 6.36 A satellite in circular motion



The net centripetal force acting on the satellite is:

$$F_{\text{net}} = \frac{mv^2}{r}$$

In a stable orbit, the centripetal force is equal to the gravitational force, thus:

$$\frac{mv^2}{r} = G \frac{M_1 M_2}{r^2}$$

As you have learned from Ralph the dog running in circles, acceleration towards the Earth can be related to the satellite's period:

$$a = \frac{v^2}{r} \text{ and } v = \frac{2\pi r}{T}$$
$$\Rightarrow a = \frac{4\pi^2 r}{T^2}$$

6.5 EXERCISE

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

1. A jogger of mass 65 kg runs around a circular track of radius 120 m with an average speed of 6.0 km h⁻¹.
 - (a) What is the centripetal acceleration of the jogger?
 - (b) What is the net force acting on the jogger?
2. At a children's amusement park, the miniature train ride completes a circuit of radius 350 m, maintaining a constant speed of 15 km h⁻¹.
 - (a) What is the centripetal acceleration of the train?
 - (b) What is the net force acting on a 35 kg child riding on the train?
 - (c) What is the net force acting on the 1500 kg train?
 - (d) Explain why the net forces acting on the child and the train are different and yet the train and the child are moving along the same path.
3. Explain why motorcyclists lean into bends.
4. A rubber stopper of mass 50.0 g is whirled in a horizontal circle on the end of a 1.50 m length of string. The time taken for ten complete revolutions of the stopper is 8.00 s. The string makes an angle of 6.03° with the horizontal. Calculate the following:
 - (a) the speed of the stopper
 - (b) the centripetal acceleration of the stopper
 - (c) the net force acting on the stopper
 - (d) the magnitude of the tension in the string.
5. Carl is riding around a corner on his bike at a constant speed of 15 km h⁻¹. The corner approximates part of a circle of radius 4.5 m. The combined mass of Carl and his bike is 90 kg. Carl keeps the bike in a vertical plane.
 - (a) What is the net force acting on Carl and his bike?
 - (b) What is the sideways frictional force acting on the tyres of the bike?
 - (c) Carl rides onto a patch of oil on the road; the sideways frictional forces are now 90% of their original amount. If Carl maintains a constant speed, what will happen to the radius of the circular path he is taking?
6. A road is to be banked so that any vehicle can take the bend at a speed of 30 m s⁻¹ without having to rely on sideways friction. The radius of curvature of the road is 12 m. At what angle should it be banked?

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6.6 Non-uniform circular motion

KEY CONCEPT

- Investigate and apply theoretically Newton's second law to circular motion in a vertical plane (forces at the highest and lowest positions only).

So far, you have considered only what happens when the circular motion is carried out at a constant speed. However, in many situations the speed is not constant. When the circle is vertical, the effects of gravity can cause the object to go slower at the top of the circle than at the bottom. Such situations can be examined either by analysing the energy transformations that take place or by applying Newton's laws of motion.

6.6.1 Energy review

Energy can be classified into many different types, including kinetic energy and gravitational potential energy. These concepts will help in the investigation of non-circular motion and will be explored further in topic 7.

Kinetic energy is the energy associated with the movement of an object. Gravitational potential energy is the energy an object has based on being in a position from which it could fall.

The Law of Conservation of Energy states that energy cannot be created or destroyed, only converted from one form to another. When motion is in a vertical circle you will need to consider that energy is converted from gravitational potential energy to kinetic energy.

$$E_g = m\vec{g}\Delta h$$

$$E_k = \frac{1}{2}m\vec{v}^2$$

where: E_g is the gravitational potential energy

E_k is the kinetic energy

m is the mass

$\vec{g}$ is the acceleration due to gravity

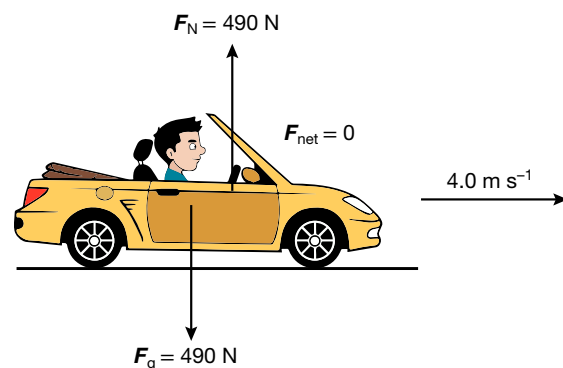
Δh is the change in height, or the height above a reference point

$\vec{v}$ is the velocity

6.6.2 Uniform horizontal motion

If a person is sitting in a roller-coaster cart moving in a straight line at a constant speed, the force due to gravity (a person's actual weight) balances the normal force from the seat. Because there is no unbalanced force acting on the person, the person feels the same as their actual weight.

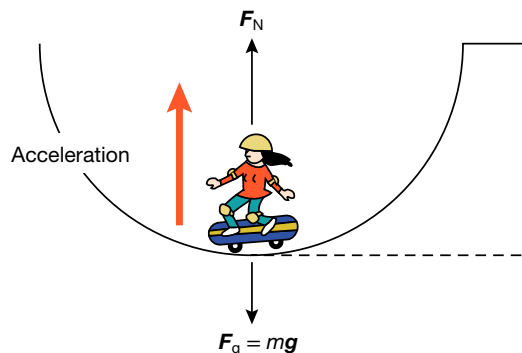
FIGURE 6.37 The forces acting on an object in uniform horizontal motion



6.6.3 Travelling through dips

When a skateboarder enters a half-pipe from the top, that person has a certain amount of potential energy, but a velocity, and hence kinetic energy, close to zero. At the bottom of the half-pipe, some of the gravitational potential energy of the skateboarder has been transformed into kinetic energy. As long as the person's change in height is known, it is possible to calculate the speed at that point. At the bottom of the half-pipe, the normal force acting on the skateboarder is greater than the force due to gravity, causing the skateboarder to feel heavier than usual. The net force acting on the skateboarder is given by $F_{\text{net}} = ma = F_N + F_g = F_N - mg$ (taking the upward direction as positive). In this case, because the normal force is greater than the force due to gravity, the net force and hence the acceleration will be directed upwards towards the centre of the circle.

FIGURE 6.38 Forces acting on the skateboarder at the bottom of a dip



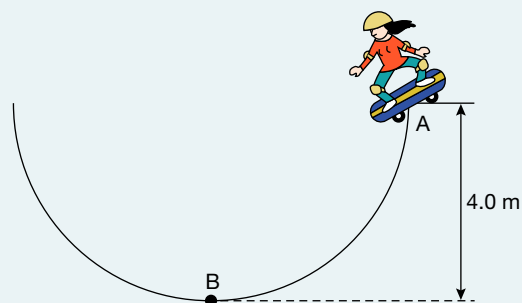
For circular motion, the acceleration is centripetal and is given by the expression $\frac{v^2}{r}$:

$$\frac{mv^2}{r} = F_N - mg$$

SAMPLE PROBLEM 15

A skateboarder, with an initial velocity of 0 m s^{-1} and a mass of 60 kg , enters the half-pipe at point A, as shown in the following figure. Assume the frictional forces are negligible.

- What is the skateboarder's speed at point B?
- What is the net force on the skateboarder at B?
- What is the normal force on the skateboarder at B?



Teacher-led video: SP15 (tlvd-0157)

THINK

- At point A, the skateboarder has potential energy but no kinetic energy. At point B, all the potential energy has been converted to kinetic energy. Once the kinetic energy is known, it is easy to calculate the velocity of the skateboarder.

WRITE

- $m = 60 \text{ kg}$, $h_A = 4.0 \text{ m}$, $h_B = 0.0 \text{ m}$,
 $g = 9.8 \text{ m s}^{-2}$

2. The decrease of potential energy from A to B is equal to the increase of kinetic energy from A to B.

$$-(PE_B - PE_A = KE_B - KE_A$$

$$-(mgh_B - mgh_A = \frac{1}{2}mv_B^2 - 0$$

$$-mg(h_B - h_A) = \frac{1}{2}mv^2$$

Cancelling m from both sides:

$$-g(h_B - h_A) = \frac{1}{2}v^2$$

$$-9.8(0 - 4.0) = \frac{1}{2}v^2$$

$$\Rightarrow v^2 = 78.4$$

$$\Rightarrow v = 8.9 \text{ m s}^{-1}$$

The skateboarder's speed at B is 8.9 m s^{-1} .

- b. The formula $F_{\text{net}} = \frac{mv^2}{r}$ can still be used for any point of the centripetal motion. It must be remembered, however, that the force will be different at each point as the velocity is constantly changing.

- b. $m = 60 \text{ kg}$, $r = 4.0 \text{ m}$, $v = 8.9 \text{ m s}^{-1}$

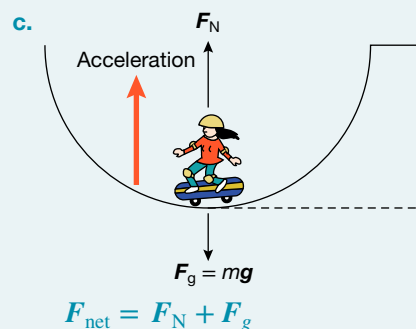
$$F_{\text{net}} = \frac{mv^2}{r}$$

$$= \frac{60 \times (8.9)^2}{4.0}$$

$$\approx 1200 \text{ N}$$

The net force acting on the skateboarder at point B is 1200 N upwards.

- c. 1. As there is more than one force acting on the skateboarder, it helps to draw a diagram.



2. The net force is determined by adding together all the forces acting on the skateboarder.
3. Taking the upward direction as positive.

$$F_{\text{net}} = F_N - mg$$

$$\Rightarrow F_N = F_{\text{net}} + mg$$

$$= 1200 + 60 \times 9.8$$

$$\approx 1800 \text{ N}$$

The normal force acting on the skateboarder at point B is 1800 N upwards. This is larger than the normal force if the skateboarder was stationary. This causes the skateboarder to experience a sensation of heaviness.

PRACTICE PROBLEM 15

A roller-coaster car travels through the bottom of a dip of radius 9.0 m at a speed of 13 m s^{-1} .

- What is the net force on a passenger of mass 60 kg?
- What is the normal force on the passenger by the seat?
- Compare the size of the normal force to the force due to gravity.

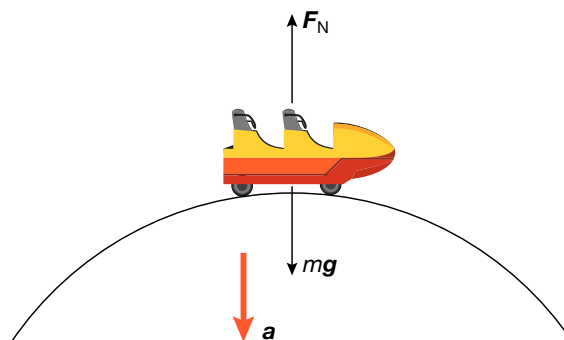
6.6.4 Travelling over humps

The experience of heaviness described in the previous section, when the normal force is greater than the force due to gravity, occurs on a roller-coaster when the roller-coaster car travels through a dip at the bottom of a vertical arc. When the car is at the top of a vertical arc, the passengers experience a feeling of being lighter. How can this be explained?

When the roller-coaster car is on the top of the track, the normal force is upwards, and the force due to gravity and the net force are downwards. So, $F_{\text{net}} = ma = F_N + F_g = F_N - mg$ (taking the upward direction as positive). In this case, since the force due to gravity is larger than the normal force, the net force and acceleration will be directed downwards towards the centre of the circle.

For circular motion, the acceleration is centripetal and is given by the expression $\frac{v^2}{r}$.

FIGURE 6.39 The forces acting on a roller-coaster car at the top of a hump



$$\vec{a} = m\vec{g} - F_N = \frac{m\vec{v}^2}{r}$$

SAMPLE PROBLEM 16

A passenger is in a roller-coaster car at the top of a circular arc of radius 9.0 m.

- At what speed would the normal force on the passenger equal half the force due to gravity?
- What happens to the normal force as the speed increases?
- What would the passenger experience?

 **Teacher-led video:** SP16 (tlvd-0158)

THINK

- Write the known information.
- Calculate the speed using $\frac{mv^2}{r} = mg - F_N$.

WRITE

$$\begin{aligned} \text{a. } F_N &= \frac{mg}{2}, r = 9.0 \text{ m} \\ \frac{mv^2}{r} &= mg - \frac{mg}{2} \\ \frac{v^2}{r} &= \frac{g}{2} \\ \Rightarrow v &= \sqrt{\frac{gr}{2}} \\ &= \sqrt{\frac{9.8 \times 9.0}{2}} \\ &= 6.6 \text{ m s}^{-1} \end{aligned}$$

b. 1. Rearrange $\frac{mv^2}{r} = mg - F_N$ to make F_N the subject of the equation.

2. Comment on the effect of increasing v on F_N .

c. The normal force determines the apparent weight of the passenger.

b. Rearranging $\frac{mv^2}{r} = mg - F_N$ gives

$$F_N = mg - \frac{mv^2}{r}.$$

The force due to gravity, mg , is constant, so as the speed, v , increases, the normal force, F_N , gets smaller.

c. The normal force is less than the force due to gravity, so the passenger will feel lighter.

PRACTICE PROBLEM 16

- a. A car of mass 800 kg slows down to a speed of 4.0 m s^{-1} to travel over a speed hump that forms the arc of a circle of radius 2.4 m. What normal force acts on the car at the top of the speed hump?
- b. At what minimum speed would a car of mass 1000 kg have to travel to momentarily leave the road at the top of the speed hump described in part (a)? (To leave the road, the normal force would have to decrease to zero.)

The normal force is a push by the track on the wheels of the roller-coaster car. The track can only push up on the wheels; it cannot pull down on the wheels to provide a downward force. So as the speed increases, there is a limit on how small the normal force can be. The smallest value is zero. What would the passenger feel? And what is happening to the roller-coaster car?

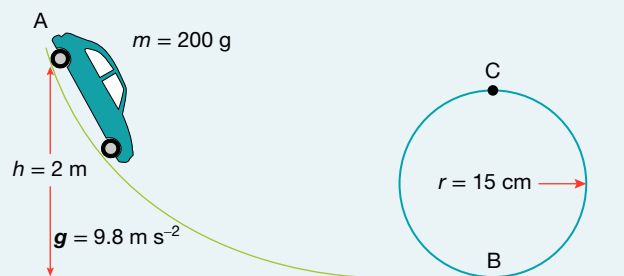
When the normal force is zero, the passenger will feel as if they are floating just above the seat. They will feel no compression in the bones of their backside. At this point the car has lost contact with the track. Any attempt to put on the brakes will not slow down the car, as the frictional contact with the track depends on the size of the normal force. No normal force means no friction.

Modern roller-coaster cars have two sets of wheels, one set above the track and one set below the track, so that if the car is moving too fast, the track can supply a downward normal force on the lower set of wheels.

The safety features of roller-coasters cannot be applied to cars on the road. If a car goes too fast over a hump on the road, the situation is potentially very dangerous. Loss of contact with the road means that turning the steering wheel to avoid an obstacle or an oncoming car will have no effect whatsoever. The car will continue on in the same direction.

SAMPLE PROBLEM 17

A toy car travels through a vertical loop of radius 15.0 cm on a racetrack. The toy car, of mass 200 g, is released from rest at point A, which is 2.00 m above the lowest point on the track. The car rolls down the track and travels inside the loop. Friction can be ignored.



- Calculate the speed of the car at point B, the bottom of the loop.
- What is the net force on the toy car at point B?
- What is the normal force on the car at point B?
- What is the speed of the car when it reaches point C?
- What is the normal force on the car at point C?

THINK

- List all known information at points A and B.
 - Calculate the total energy of the car at point A by adding the car's gravitational potential energy and kinetic energy.
 - The total energy of the car at point B is equal to the total energy of the car at point A.
- During circular motion, the net force is always directed towards the centre of the circle. So, at point B, the net force will be directed upwards.

WRITE

a. At point A,
 $m = 0.200 \text{ kg}$, $h = 2.00 \text{ m}$, $v = 0 \text{ m s}^{-1}$,
 $g = 9.8 \text{ m s}^{-2}$

At point B,
 $m = 0.2 \text{ kg}$, $h = 0.00 \text{ m}$, $g = 9.8 \text{ m s}^{-2}$

$$\begin{aligned}
 E_A &= E_k + E_g \\
 &= \frac{1}{2}mv^2 + mg\Delta h \\
 &= 0 + (0.200 \times 9.8 \times 2.00) \\
 &= 3.92 \text{ J}
 \end{aligned}$$

$$\begin{aligned}
 E_B &= E_k + E_g \\
 &= \frac{1}{2}mv^2 + mg\Delta h
 \end{aligned}$$

$$3.92 = \left(\frac{1}{2} \times 0.200 \times v^2 \right) + 0$$

$$3.92 = 0.100v^2$$

$$\begin{aligned}
 v^2 &= \frac{3.92}{0.100} \\
 \Rightarrow v &= \sqrt{39.2} \\
 &= 6.26 \text{ m s}^{-1}
 \end{aligned}$$

$$\begin{aligned}
 \text{b. } F_{\text{net}} &= \frac{mv^2}{r} \\
 &= \frac{0.200 \times 6.26^2}{0.15} \\
 &= 78.4 \text{ N up}
 \end{aligned}$$

- c. The net force is equal to the sum of the normal force and the force due to gravity. Take the upward direction to be positive.

- d. 1. List all known information at point C.
2. From part (a), it is known that the total energy of the car at all points is 3.92 J.

- e. 1. Determine the net force acting on the car at point C.
The net force on the car at point C will be directed downwards towards the centre of the circle.

2. The net force is equal to the sum of the normal force and the force due to gravity. Take the upward direction to be positive. *Note:* In this case, both the normal force and the force due to gravity act in the downward direction.

$$c. F_{\text{net}} = F_N + F_g$$

$$F_{\text{net}} = F_N - mg$$

$$78.4 = F_N - (0.200 \times 9.8)$$

$$78.4 = F_N - 1.96$$

$$F_N = 78.4 + 1.96$$

$$= 80.4 \text{ N up}$$

$$d. m = 0.200 \text{ kg}, h = 0.300 \text{ m}, g = 9.8 \text{ m s}^{-2}$$

At point C,

$$E_C = E_k + E_g$$

$$= \frac{1}{2}mv^2 + mg\Delta h$$

$$3.92 = \left(\frac{1}{2} \times 0.200 \times v^2 \right) + (0.200 \times 9.8 \times 0.300)$$

$$3.92 = 0.100v^2 + 0.588$$

$$0.100v^2 = 3.332$$

$$v^2 = \frac{3.332}{0.100}$$

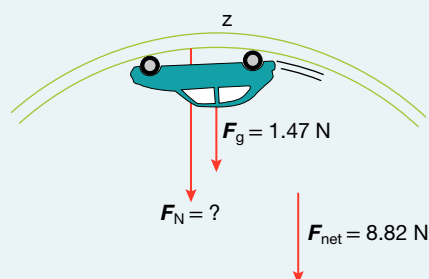
$$\Rightarrow v = \sqrt{33.32}$$

$$= 5.77 \text{ m s}^{-1}$$

$$e. F_{\text{net}} = \frac{mv^2}{r}$$

$$= \frac{0.200 \times 5.77^2}{0.15}$$

$$= 44.4 \text{ N down}$$



$$F_{\text{net}} = F_N + F_g$$

$$F_{\text{net}} = F_N - mg$$

$$-44.4 = F_N - (0.200 \times 9.8)$$

$$-44.4 = F_N - 1.96$$

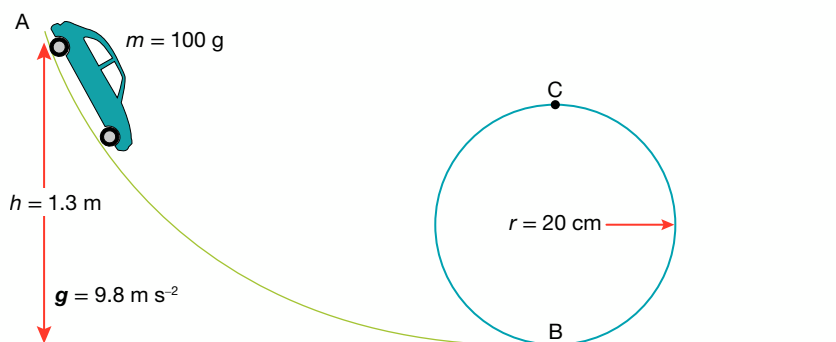
$$\Rightarrow F_N = -44.4 + 1.96$$

$$= -42.7$$

$$= 42.7 \text{ N down}$$

PRACTICE PROBLEM 17

A toy car travels through a vertical loop of radius 20.0 cm on a racetrack. The toy car, of mass 100 g, is released from rest at point A, which is 1.30 m above the lowest point on the track. The car rolls down the track and travels inside the loop. Friction can be ignored.

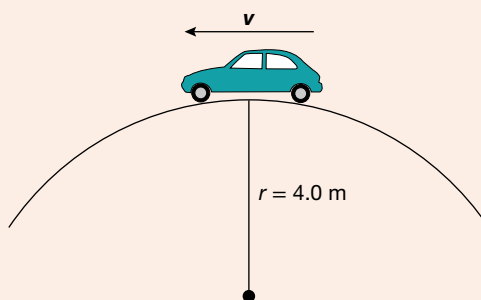


- Calculate the speed of the car at point B, the bottom of the loop.
- What is the net force on the toy car at point B?
- What is the normal force on the car at point B?
- What is the speed of the car when it reaches point C?
- What is the normal force on the car at point C?

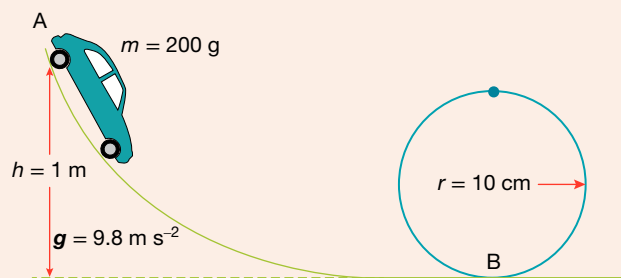
6.6 EXERCISE

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- A ball is swung in a vertical circle with a constant speed. At which point is the tension force:
 - at its maximum value
 - at its minimum value?
- A car of mass 800 kg travels over the crest of a hill that forms the arc of a circle, as shown in the following figure.
 - Draw a labelled diagram showing all the forces acting on the car.
 - The car travels just fast enough for it to leave the ground momentarily at the crest of the hill. This means the normal force is zero at this point.
 - What is the net force acting on the car at this point?
 - What is the speed of the car at this point?



- A toy car travels through a vertical loop on a racetrack. The loop has a radius of 10 cm and the mass of the toy car is 120 g. The car is released from the start of the track, which is at a height of 1 m (position A), and travels inside the loop. Assume g is 9.8 m s^{-2} and ignore friction.



- (a) Calculate the speed of the car at point B, the bottom of the loop.
- (b) What is the net force on the toy car at point B?
- (c) What is the normal force on the car at point B?
4. A passenger, who has a mass of 60 kg, is in a roller-coaster and travels down a small dip with a radius of 12 m. At the bottom of the dip, the passenger is travelling with a speed of 14 m s^{-1} and is feeling a larger than normal force. Use Newton's second law to calculate the normal force acting upon their body.
5. A BMX rider, with a mass of 75 kg, is riding in a half-pipe with a radius of 2.5 m. At the lowest point of the half-pipe, the rider attains a speed of 7 m s^{-1} . Assume there is no air resistance or friction.
 - (a) What is the acceleration of the rider at the lowest point of the half-pipe?
 - (b) Determine the magnitude of the normal force acting on the rider at the lowest point of the half-pipe.

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6.7 Review

6.7.1 Summary

- Motion can be described in terms of distance, displacement, speed, velocity, acceleration and time.
- Distance is a measure of the length of the path taken when an object changes position.
- Displacement is a measure of the change in position of an object.
- Speed is a measure of the rate at which an object moves over a distance.

$$\text{average speed} = \frac{\text{distance travelled}}{\text{time interval}}$$

- Velocity is a measure of the rate of displacement, or the rate of changing position.

$$v_{\text{av}} = \frac{\Delta x}{\Delta t}$$

- Acceleration is the rate of change of velocity.

$$a_{\text{av}} = \frac{\Delta v}{\Delta t}$$

- Displacement, velocity and acceleration are vector quantities.
- Instantaneous speed is the speed at a particular instant of time. Instantaneous velocity is the velocity at a particular instant of time.

- The velocity (or speed) of an object at an instant is equal to the gradient of the graph of position versus time (or distance versus time) for that instant.
- The acceleration of an object at an instant is equal to the gradient of the graph of velocity versus time for that instant.
- The displacement of an object during a time interval is equal to the area under the velocity–time graph representing the time interval.
- The change in velocity of an object during a time interval is equal to the area under the acceleration–time graph representing the time interval.
- The motion of an object moving in a straight line can be described algebraically using several formulae including:

$$\begin{aligned}
 v &= u + at \\
 s &= \frac{1}{2}(u + v)t \\
 s &= ut + \frac{1}{2}at^2 \\
 s &= vt - \frac{1}{2}at^2 \\
 v^2 &= u^2 + 2as
 \end{aligned}$$

- Newton’s three laws of motion can be applied to explain, predict or analyse situations in which one or more forces act on an object or system of objects.
 - Newton’s First Law of Motion states that every object continues in its state of rest or uniform motion unless made to change by a non-zero net force.
 - Newton’s Second Law of Motion can be expressed algebraically as:

$$F_{\text{net}} = ma \quad \text{or} \quad F_{\text{net}} = \frac{\Delta p}{\Delta t}$$

- Newton’s Third Law of Motion states that whenever an object applies a force to a second object, the second object applies an equal and opposite force to the first object:

$$F_{\text{on A by B}} = -F_{\text{on B by A}}$$

- The forces acting on a moving vehicle include the force due to gravity, normal force, driving force and resistive forces including air resistance and road friction. The motion of the car depends on the net force acting on the vehicle.
- For a vehicle on a slope, analysis of forces acting on, and motion of, the vehicle can be undertaken by resolving the forces into two components — one parallel to the slope and one perpendicular to the slope.
- Momentum is the product of the mass of an object and its velocity. Momentum is a vector quantity.
- There are two forces acting on a projectile in flight: the force due to gravity (gravitational force) acting downwards and air resistance acting in the opposite direction to that of the motion. In modelling projectile motion, it is helpful to ignore the air resistance.
- To analyse the motion of a projectile, the equations of motion with constant acceleration can be applied to the horizontal and vertical components of the motion separately.
- An object projected horizontally near Earth’s surface travels in a parabolic path if air resistance is negligible.

- The average speed and velocity of an object moving in a circle is quite different from its instantaneous speed and velocity. The speed of an object moving at constant speed in a circle of radius r is given by the equation $\text{speed} = \frac{2\pi r}{T}$ where T is the period of the circular motion.
- The acceleration of an object in uniform circular motion is always directed towards the centre of the circle. It is called centripetal acceleration.
- The magnitude of the acceleration a of an object in uniform circular motion can be calculated using the equations: $a = \frac{v^2}{r}$ or $a = \frac{4\pi^2 r}{T^2}$
- The net force on an object in uniform circular motion is always towards the centre of the circle.

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6.7.2 Key terms

Acceleration is the rate of change of velocity. It is a vector quantity.

Air resistance is the force applied to an object opposite to its direction of motion, by the air through which it is moving.

The **centre of mass** is the point at which all of the mass of an object can be considered to be positioned when modelling the external forces acting on the object.

Centripetal acceleration is the centre-directed acceleration of an object moving in a circle.

The **design speed** is the speed at which the force due to friction becomes zero, as seen on a banked track.

Displacement is a measure of the change in position of an object. It is a vector quantity.

Distance is a measure of the length of the path taken when an object changes position. It is a scalar quantity.

The **frequency** is the number of revolutions that an object completes each second.

Instantaneous speed is the speed at a particular instant of time.

Instantaneous velocity is the velocity at a particular instant of time.

Momentum is the product of the mass of an object and its velocity. Momentum is a vector quantity.

Net force is the vector sum of all the forces acting on an object.

The **period** is the time taken for an object, moving in a circular path and at a constant speed, to complete one revolution.

Road friction is the force applied by the road surface to the wheels of a vehicle in a direction opposite to the direction of motion of the vehicle.

A **scalar quantity** has magnitude (size) but not direction.

Speed is a measure of the time rate at which an object moves over a distance.

A falling object reaches its **terminal velocity** when the upward air resistance becomes equal to the downward force of gravity.

A **vector quantity** has direction as well as magnitude (size).

Velocity is a measure of the time rate of displacement, or the time rate of changing position. It is a vector quantity.

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 **Digital document** Key terms glossary (doc-32257)

6.7.3 Practical work and investigations

Investigation 6.1

Modelling projectile motion

Aim: To model projectile motion by studying the motion of a ball bearing projected onto an inclined plane

Digital document: doc-31599

Investigation 6.2

The drop zone

Aim: To explore the relationship between the initial speed of a horizontally launched object and its range

Digital document: doc-31600

Investigation 6.3

Exploring circular motion

Aim: To examine some of the factors affecting the motion of an object undergoing uniform circular motion, and then to determine the quantitative relationship between the variables of force, velocity and radius

Digital document: doc-31601

Teacher-led video: tlvd-0238



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Digital document Practical investigation logbook (doc-32258)

6.7 Exercises

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6.7 Exercise 1: Multiple choice questions

1. In which of the following situations would the net force on an object be zero?

- A. The object is moving at a constant speed on a circular track.
- B. The object is falling freely.
- C. The object moves at constant acceleration.
- D. The object covers equal displacements over equal time intervals.

Use the following information to answer Questions 2 to 4.

An 80 g yo-yo is swung in a horizontal circle from a 40 cm piece of string. The period of the ball's motion is 1.8 seconds.

2. What is the yo-yo's average speed?

- A. 2.8 m s^{-1}
- B. 0 m s^{-1}
- C. 1.4 m s^{-1}
- D. 0.22 m s^{-1}

3. What would the yo-yo's centripetal acceleration be?
 - A. 4.87 m s^{-2}
 - B. 0.78 m s^{-2}
 - C. 4.87 m s^{-1}
 - D. 9.8 m s^{-2}
4. What is the net force on the yo-yo?
 - A. 0.78 N
 - B. 0.06 N
 - C. 1.17 N
 - D. 0.39 N
5. Which of the following statements about the effects of air resistance on an object is false?
 - A. The faster an object is moving, the greater the air resistance.
 - B. The higher the density of an object, the less drag it experiences.
 - C. The more streamlined an object's shape, the less of an effect the air resistance has.
 - D. The larger the cross-sectional area of an object, the greater drag due to air resistance.
6. A netball player makes a horizontal pass to their teammate, who misses the ball. Ignoring air resistance, which of the following statements best describes the movement of the ball as it falls towards the ground.
 - A. The ball travels in a circular path.
 - B. The only force acting on the ball once it has been released is the force due to gravity (gravitational force).
 - C. The ball's vertical velocity will remain the same, while the horizontal velocity will increase.
 - D. The horizontal distance covered by the ball decreases as it falls, while the vertical distance remains the same.
7. Which one of the following objects has the greatest momentum?
 - A. A road train with four trailers at rest
 - B. A Year 12 student of average mass walking home from school
 - C. A sports car driving over the Westgate Bridge
 - D. A cricket ball bowled during a Test match
8. A ball with a mass m is attached to a string and swung in a vertical circle. What will the tension in the string be when the ball is at the highest point of the circle?
 - A. mg
 - B. $mg + ma$
 - C. $mg - ma$
 - D. $\frac{mg}{ma}$
9. A football player kicks a football with an initial velocity of 25 m s^{-1} at an angle of 53° above the horizontal. What is the vertical component of the initial velocity of the ball?
 - A. 25 m s^{-1}
 - B. 20 m s^{-1}
 - C. 15 m s^{-1}
 - D. 10 m s^{-1}
10. A projectile is launched at 45° above the horizon. What are the projectile's horizontal and vertical accelerations when it reaches its highest point? Ignore air resistance.
 - A. The horizontal and vertical accelerations are both zero.
 - B. The horizontal acceleration is zero and the vertical acceleration is 9.8 m s^{-2} .
 - C. The horizontal acceleration is 9.8 m s^{-2} and the vertical acceleration is zero.
 - D. Both the horizontal and vertical accelerations are 9.8 m s^{-2} .

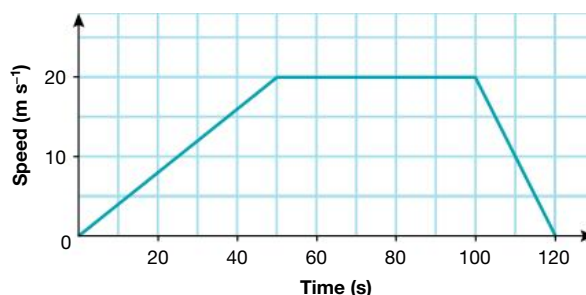
6.7 Exercise 2: Short answer questions

1. When a stationary car is hit from behind by another vehicle at moderate speed, headrests behind the occupants reduce the likelihood of injury. Explain in terms of Newton's laws how they do this.
2. It is often said that seatbelts prevent a passenger from being thrown forward in a car collision. What is wrong with such a statement?
3. What is the matching 'reaction' to the gravitational pull of Earth on you?
4. Explain why the horizontal component of velocity remains the same when a projectile's motion is modelled.
5. While many pieces of information relating to the vertical and horizontal parts of a particular projectile's motion are different, the time is always the same. Explain why this is so.
6. Describe the effects of air resistance on the motion of a basketball falling vertically from a height.
7. When a mass moves in a circle, it is subject to a net force. This force acts at right angles to the direction of motion of the mass at any point in time. Use Newton's laws to explain why the mass does not need a propelling force to act in the direction of its motion.

6.7 Exercise 3: Exam practice questions

Question 1 (9 marks)

The following graph describes the motion of a 40 t (4.0×10^4 kg) train as it travels between two neighbouring railway stations. The total friction force resisting the motion of the train while the brakes are not applied is 8000 N. The brakes are not applied until the final 20 s of the journey.



- a. What is the braking distance of the train? **1 mark**
- b. A cyclist travels between the stations at a constant speed, leaving the first station and arriving at the second station at the same time as the train. What is the constant speed of the cyclist? **2 marks**
- c. What forward force is applied to the train by the tracks while it is accelerating? **3 marks**
- d. What additional frictional force is applied to the train while it is braking? **3 marks**

Question 2 (6 marks)

At a children's amusement park, the miniature train ride completes a circuit of radius 350 m, maintaining a constant speed of 15 km h^{-1} .

- a. What is the centripetal acceleration of the train? **2 marks**
- b. What is the net force acting on a 35 kg child riding on the train? **1 mark**
- c. What is the net force acting on the 1500 kg train? **1 mark**
- d. Explain why the net forces acting on the child and the train are different and yet the train and the child are moving along the same path. **2 marks**

Question 3 (7 marks)

During a game of tottem tennis, the ball, of mass 100 g, is whirled in a horizontal circle on the end of a 1.30 m length of string. The time taken for ten complete revolutions of the ball is 12.0 s. The string makes an angle of 30.0° with the horizontal. Calculate:

- a. the speed of the ball 2 marks
- b. the centripetal acceleration of the ball 2 marks
- c. the net force acting on the ball 1 mark
- d. the magnitude of the tension in the string 2 marks

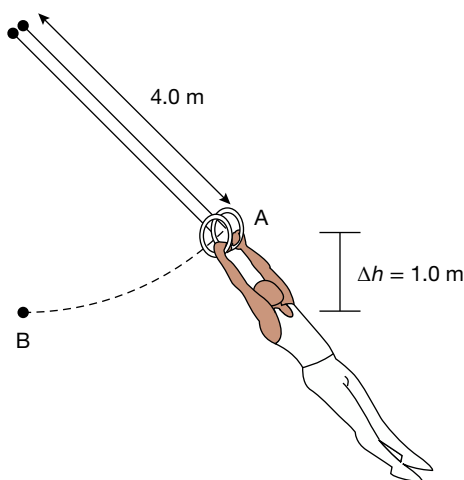
Question 4 (4 marks)

A road is to be banked so that any vehicle can take the bend at a speed of 40.0 m s^{-1} without having to rely on sideways friction. The radius of curvature of the road is 15.0 m. At what angle should it be banked?

Question 5 (6 marks)

A gymnast of mass 65 kg, who is swinging on the rings, follows the path shown in the following figure.

- a. What is the speed of the gymnast at point B, if he is at rest at point A? 3 marks
- b. What is the centripetal force acting on the gymnast at point B? 1 mark
- c. Draw a labelled diagram of the forces acting on the gymnast at point B. Include the magnitude of all forces. 2 marks



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7 Force, energy and mass in collisions and other interactions

7.1 Overview

Numerous **videos** and **interactivities** are available just where you need them, at the point of learning, in your digital formats, learnON and eBookPLUS at www.jacplus.com.au.

7.1.1 Introduction

Have you been in a collision today? It is possible that you have, without even realising it. Collisions feature more often than you might expect in your day-to-day life. Perhaps you were knocked into a fellow student as you walked down the corridor, or you had a boxing match and took a hit to the head, or maybe you are a basketball star and you hit the floor after being fouled. Whatever happened in your day, it is likely that you were involved in some sort of collision. How significant that collision was depends on the forces involved, the energy of the interaction and the mass of the objects colliding.

FIGURE 7.1 Collisions occur often in sports such as boxing.



7.1.2 What you will learn

KEY KNOWLEDGE

After completing this topic, you will be able to:

- investigate and apply theoretically and practically the laws of energy and momentum conservation in isolated systems in one dimension
- investigate and analyse theoretically and practically impulse in an isolated system for collisions between objects moving in a straight line: $F\Delta t = m\Delta v$
- investigate and apply theoretically and practically the concept of work done by a constant force using:
 - work done = constant force $\times$ distance moved in direction of net force
 - work done = area under force–distance graph.
- analyse transformations of energy between kinetic energy, strain potential energy, gravitational potential energy and energy dissipated to the environment (considered as a combination of heat, sound and deformation of material):
 - kinetic energy at low speeds: $E_k = \frac{1}{2}mv^2$; elastic and inelastic collisions with reference to conservation of kinetic energy
 - strain potential energy: area under force–distance graph including ideal springs obeying Hooke's Law: $E_s = \frac{1}{2}k\Delta x^2$
 - gravitational potential energy: $E_g = mg\Delta h$.

Source: VCE Physics Study Design (2017–2021) extracts © VCAA; reproduced by permission.

PRACTICAL WORK AND INVESTIGATIONS

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

Resources

 **Digital documents** Key science skills — VCE Units 1–4 (doc-32112)

Key terms glossary (doc-32263)

Practical investigation logbook (doc-32294)

To access key concept summaries and past VCAA exam questions download and print the **studyON: Revision and past VCAA exam question booklet** (sonr-0056).

7.2 Momentum and impulse

KEY CONCEPTS

- Investigate and apply theoretically and practically the laws of energy and momentum conservation in isolated systems in one dimension.
- Investigate and analyse theoretically and practically impulse in an isolated system for collisions between objects moving in a straight line: $F\Delta t = m\Delta v$.

7.2.1 Momentum and impulse in a collision

Calculating momentum and impulse algebraically

Momentum was introduced in sections 6.2.4 and 6.3.1 as one way to describe the motion of an object.

Momentum is useful in explaining changes in motion, because it takes into account the mass as well as the velocity of a moving object. Momentum is a vector quantity with the same direction as the velocity, but is expressed in the units kg m s^{-1} . Newton's First Law of Motion can be expressed in terms of momentum, as the rate of change in momentum is directly proportional to the magnitude of the net force. Momentum and impulse are particularly useful for understanding what happens in a collision.

The momentum of an object is the product of the mass and velocity of the object:

$$\text{momentum} = \text{mass} \times \text{velocity}$$

$$\vec{p} = m \times \vec{v}$$

where: $\vec{p}$ is the momentum, in kg m s^{-1}

m is the mass, in kg

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

Newton's Second Law of Motion describes how the effect of the average net force on an object depends on its mass ($F = ma$). In previous topics, it was useful to express Newton's second law in terms of acceleration. However, it is sometimes useful to express it in terms of the change in momentum of an object. That is:

$$\begin{aligned} F_{\text{av}} &= \frac{\Delta p}{\Delta t} \\ \Rightarrow F_{\text{av}} \Delta t &= \Delta p \\ &= m \Delta v \end{aligned}$$

If the force is constant, this may be instead written as F_{net} .

The product $F_{\text{av}} \times \Delta t$ is called the **impulse** of the average net force. Impulse is a vector quantity that has SI units of N s. Calculations can be carried out to show that:

$$1 \text{ N s} = 1 \text{ kg m s}^{-1}$$

Thus, the effect of an average net force on the motion of an object can be summarised by the statement:

$$\text{impulse } (\vec{I}) = \text{change in momentum } (\Delta \vec{p})$$

When two or more objects collide, the change in the motion of each object can be described by Newton's Second Law of Motion. By expressing Newton's second law in the form $F_{av} = \frac{\Delta p}{\Delta t}$, it is possible to examine the effect of collisions on the human body.

When a car collides with an 'immovable' object such as a large tree, its change in momentum is fixed. It is determined by the mass of the car and its initial velocity at the instant of impact. The final momentum is zero. Since the impulse is equal to the change in momentum, the impulse $F_{av} \times \Delta t$ is also fixed. By designing the car so that Δt is as large as possible, the magnitude of the average net force on the car (and hence its deceleration) can be reduced. The decrease in the deceleration of the car makes it safer for the occupants.

Airbags, collapsible steering wheels and padded dashboards are all designed to increase the time interval during which the momentum of a human body changes during a collision.

The polystyrene liner of bicycle helmets is designed to crush during a collision. This increases the time interval during which the skull accelerates (or decelerates) during a collision, decreasing the average net force applied to the skull.

FIGURE 7.2 Cars are designed to crumple in collisions. This increases the time interval over which the momentum changes, decreasing the average net force on the car.



FIGURE 7.3 Bicycle helmets: Newton's second law provides an explanation for their life-saving function.



SAMPLE PROBLEM 1

A 1200 kg car collides with a concrete wall at a speed of 15 m s^{-1} and takes 0.060 s to come to rest.

- What is the change in momentum of the car?
- What is the impulse on the car?
- What is the average magnitude of the force exerted by the wall on the car?
- What would be the average magnitude of the force exerted by the wall on the car if the car bounced back from the wall with a speed of 3.0 m s^{-1} after being in contact for 0.06 s?

 Teacher-led video: SP1 (tlvd-0160)

THINK

- Assign the initial direction of the car as positive. Calculate the change in momentum.
- State the change in momentum of the car; this should be a positive number.

WRITE

$$\begin{aligned}
 \text{a. } m &= 1200 \text{ kg}; u = 15 \text{ m s}^{-1}; v = 0 \text{ m s}^{-1}; \Delta t = 0.060 \text{ s} \\
 \Delta p &= mv - mu \\
 &= m(v - u) \\
 &= 1200 \times (0 - 15) \\
 &= 1200 \times (-15) \\
 &= -1.8 \times 10^4 \text{ kg m s}^{-1}
 \end{aligned}$$

The change in momentum is $1.8 \times 10^4 \text{ kg m s}^{-1}$ in a direction opposite to the original direction of the car.

- b. 1.** Determine the impulse of the car using the change in momentum.
- 2.** State the impulse on the car.
- c.** Determine the magnitude of force using $\Delta p = F\Delta t$.
- d. 1.** Determine the impulse of the car.
In this case, the final momentum $p = -3.0 \text{ m s}^{-1}$ and the initial velocity, $u = 15 \text{ m s}^{-1}$ (remember the change in velocity or Δv is equal to the initial velocity subtracted from the final velocity).
- 2.** Determine the magnitude of force using $\Delta p = F\Delta t$, where $\Delta p = 2.16 \times 10^4 \text{ N s}$ and $\Delta t = 0.060 \text{ s}$.
- b. Impulse on car = change in momentum of car**

$$= -1.8 \times 10^4 \text{ kg m s}^{-1}$$
The impulse on the car is $1.8 \times 10^4 \text{ N s}$ in a direction opposite to the original direction of the car.
- c.** $\Delta p = F\Delta t$

$$1.8 \times 10^4 = F \times 0.06$$

$$\Rightarrow F = \frac{1.8 \times 10^4}{0.06}$$

$$= 3.0 \times 10^5$$
- d. Impulse = $m\Delta v$**

$$= 1200(-3 - 15)$$

$$= 1200 \times (-18)$$

$$= -2.16 \times 10^4 \text{ N s or kg m s}^{-1}$$
- $$\Delta p = F\Delta t$$

$$2.16 \times 10^4 = F \times 0.06$$

$$\Rightarrow F = \frac{2.16 \times 10^4}{0.06}$$

$$= 3.6 \times 10^5 \text{ N}$$

PRACTICE PROBLEM 1

A dodgem car of mass 200 kg strikes a barrier head-on at a speed of 8.0 m s^{-1} due west and rebounds in the opposite direction with a speed of 2.0 m s^{-1} .

- What is the impulse delivered to the dodgem car?
- If the dodgem car is in contact with the barrier for 0.8 s , what average force does the barrier apply to the car?
- What average force does the car apply to the barrier?

Calculating impulse from a force–time graph

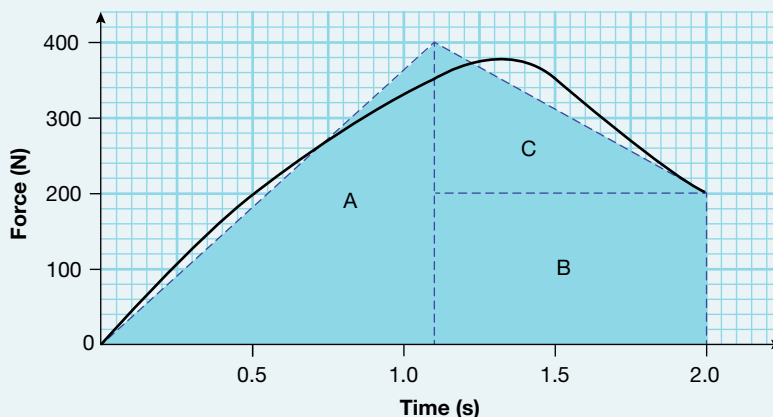
The impulse delivered by a changing force is given by $F_{\text{av}}\Delta t$.

If a graph of force versus time is plotted, the impulse can be determined from the area under the graph. The area under the graph can be calculated using a variety of methods:

- If a grid is provided, the area can be determined by finding the area of each ‘square’ and multiplying it by the number of squares (found by counting the ‘squares’ between the graph and the horizontal axis). The more grid squares there are, the more accurate the calculated area will be. You can also add sections of partial squares together to make full squares (for example, two half squares make up one full square).
- Another way to calculate areas is by drawing a regular shape (or shapes) that have approximately the same area as the area under the graph. For example, the graph shown in sample problem 2 may be divided into triangles and rectangles, and the areas may be calculated and added together. (This is much easier for graphs with straight-line sections as opposed to curved sections.)

SAMPLE PROBLEM 2

The following graph describes the changing horizontal force on a 40 kg rollerskater as she begins to move from rest. Estimate her speed after 2.0 seconds.



Teacher-led video: SP2 (tlvd-0161)

THINK

1. The magnitude of the impulse on the skater can be determined by calculating the area under the graph. This can be determined by either counting squares or by determining the shaded area. In this example, the areas have been provided.
2. Determine the magnitude of impulse using the change in momentum using $\Delta p = m\Delta v$, where $\Delta p = 490 \text{ N s}$, and $m = 40 \text{ kg}$.
3. Determine the speed.

WRITE

Magnitude of impulse = area A + area B + area C

$$\begin{aligned}
 &= \left(\frac{1}{2} \times 1.1 \times 400 + 0.9 \times 200 \right. \\
 &\quad \left. + \frac{1}{2} \times 0.9 \times 200 \right) \\
 &= (220 + 180 + 90) \\
 &= 490 \text{ N s}
 \end{aligned}$$

Magnitude of impulse = magnitude of change in momentum

$$\begin{aligned}
 &= m\Delta v \\
 490 \text{ N s} &= 40 \text{ kg} \times \Delta v \\
 \Rightarrow \Delta v &= \frac{490}{40} \\
 &= 12 \text{ m s}^{-1}
 \end{aligned}$$

As her initial speed is zero (she started from rest), her speed after 2.0 seconds is 12 m s^{-1} .

PRACTICE PROBLEM 2

Estimate the speed of the rollerskater in sample problem 2 after 1.0 s.

7.2.2 Conservation of momentum

Newton's Second Law of Motion can be applied to the system of two objects just as it can be applied to each object. By applying the formula $F_{\text{av}} = \frac{\Delta p}{\Delta t}$ to a system of one or more objects, another expression of Newton's second law can be written: if the net force acting on a system is zero, the total momentum of the system does not change.

This statement is an expression of the Law of Conservation of Momentum. It is also expressed as follows: if there are no external forces acting on a system, the total momentum of the system remains constant.

The Law of Conservation of Momentum can also be written as:

$$\vec{p}_{\text{before}} = \vec{p}_{\text{after}}$$

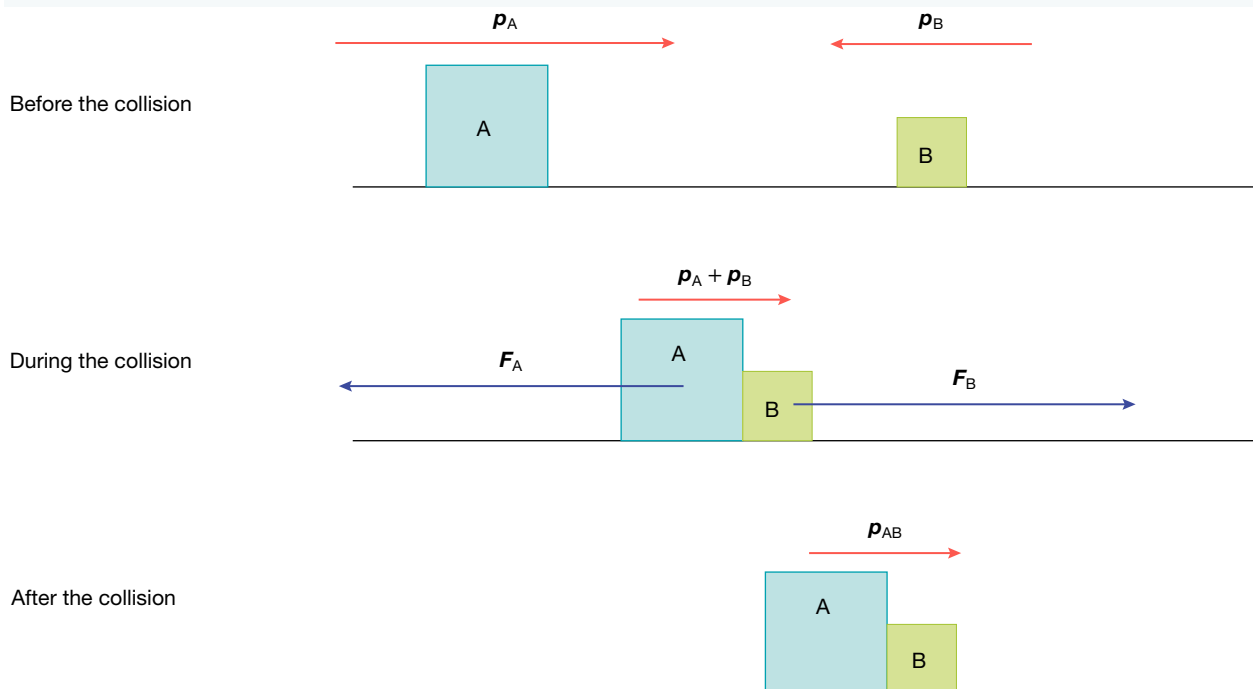
A system on which no external forces act is called an **isolated system**. The only forces acting on objects in the system are those applied by other objects in the system. In practice, collisions at the surface of the Earth do not take place within isolated systems. For example, a system comprising two cars that collide is not isolated because forces are applied to the cars by objects outside the system. Road friction and the gravitational pull of Earth are two examples of external forces on the system.

However, if the cars collide on an icy horizontal road, the collision can be considered to take place in an isolated system. The sum of external forces (including the force of gravity and the normal force) acting on the system of the cars would be negligible compared with the forces that each car applies to the other. A system comprising a car and a tree struck by the car could not be considered to be an isolated system because the Earth exerts a large external force on the tree in the opposite direction to that applied to the tree by the car.

7.2.3 Modelling a collision

Consider the system of the two blocks labelled A and B in figure 7.4. The blocks are on a smooth horizontal surface. The system can be treated as isolated because the gravitational force and normal force on each of the blocks have no effect on their horizontal motion. Because the surface is described as smooth, the frictional force can be assumed to be negligible. The net force on the *system* is zero. Therefore, the total momentum of the system remains constant. The momentum of the centre of mass of the system also remains constant. However, the momentum of each of the blocks changes during the collision because each block has a non-zero net force acting on it.

FIGURE 7.4 The net force on this system of two blocks is zero. Its total momentum therefore remains constant.



The force exerted on block A by block B ($F_{\text{on A by B}}$) during the collision is equal in magnitude and opposite in direction to the force exerted on block B by block A ($F_{\text{on B by A}}$). Therefore, the change in momentum of block A (Δp_A) is equal and opposite to the change in momentum of block B (Δp_B). That is:

$$F_{\text{on A by B}} = F_{\text{on B by A}}$$

$$\Rightarrow F_{\text{on A by B}} \Delta t = -F_{\text{on B by A}} \Delta t$$

where: Δt = time duration of interaction

$$\Rightarrow \Delta p_A = -\Delta p_B$$

$$\Rightarrow \Delta p_A + \Delta p_B = 0$$

This result should be no surprise as, in order for the total momentum of the system consisting of the two blocks to be constant, the total change in momentum must be zero.

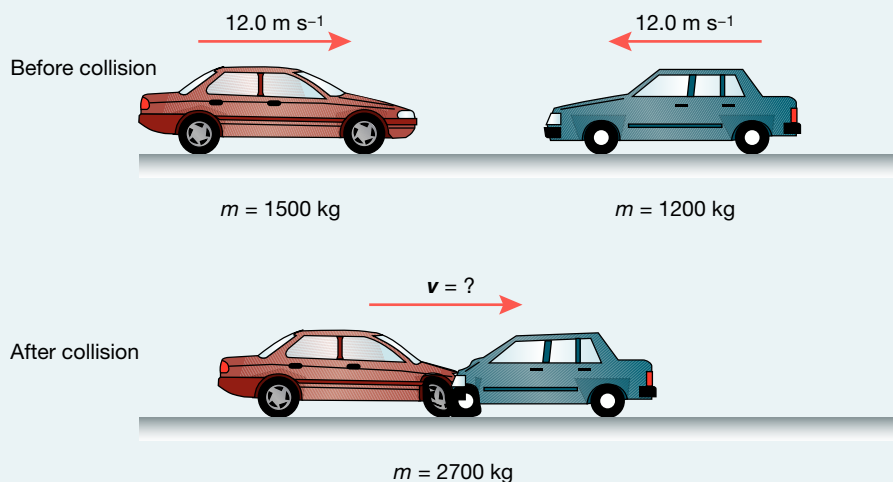
The interaction between blocks A and B can be summarised as follows:

- The total momentum of the system remains constant.
- The change in momentum of the system is zero.
- The momentum of the centre of mass of the system remains constant.
- The force that block A exerts on block B is equal and opposite to the force that block B exerts on block A.
- The change in momentum of block A is equal and opposite to the change in momentum of block B.

SAMPLE PROBLEM 3

A 1500 kg car travelling at 12.0 m s^{-1} on an icy road collides with a 1200 kg car travelling at the same speed, but in the opposite direction. The cars lock together after impact.

- What is the momentum of each car before the collision?
- What is the total momentum before the collision?
- What is the total momentum after the collision?
- With what speed is the tangled wreck moving *immediately* after the collision?
- What is the impulse on the 1200 kg car?
- What is the impulse on the 1500 kg car?



Teacher-led video: SP3 (tlvd-0162)

THINK

- a. 1. Assign the direction in which the first car is moving as positive.
2. Determine the momentum of the first car. (Remember, momentum is in the units kg m s^{-1} or N s .)
3. Determine the momentum of the second car.
- b. Determine the total momentum before the collision by adding the initial momentum of the 1500 kg car to the initial momentum of the 1200 kg car that was calculated in part a.
- c. The description of the road suggests that friction is insignificant. It can be assumed that there are no external forces acting on the system.
- d. The tangled wreck can be considered as a single mass of 2700 kg.
- e. The impulse on the 1200 kg car is equal to its change in momentum. The initial momentum was calculated in part a, and the final momentum can be calculated using $p = mv$, where the mass = 1200 kg, and the final velocity = 1.33 m s^{-1} (as calculated in part d).
- f. The impulse or change in momentum on the 1500 kg car is equal to the impulse on the 1200 kg car. This can be verified by calculating the change in momentum of the 1500 kg car. The initial momentum was calculated in part a, and the final momentum can be calculated using $p = mv$, where the mass = 1500 kg, and the final velocity = 1.33 m s^{-1} (as calculated in part d).

WRITE

- a. The 1500 kg car will have a positive velocity, and the 1200 kg car will have a negative velocity.
- $$m = 1500 \text{ kg}; v = 12.0 \text{ m s}^{-1}$$
- $$p = mv$$
- $$= 1500 \times 12.0$$
- $$= 18\,000 \text{ kg m s}^{-1}$$
- $$= 1.8 \times 10^4 \text{ kg m s}^{-1}$$
- $$m = 1200 \text{ kg}; v = -12.0 \text{ m s}^{-1}$$
- $$p = mv$$
- $$= 1200 \times (-12.0)$$
- $$= -14\,400 \text{ kg m s}^{-1}$$
- $$= -1.44 \times 10^4 \text{ kg m s}^{-1}$$
- b. $p_i = 18\,000 + (-14\,400)$
- $$= 3600 \text{ kg m s}^{-1}$$
- c. $p_f = p_i$
- $$= 3600 \text{ kg m s}^{-1}$$
- d. $p_f = mv$
- $$3600 = 2700 \times v$$
- $$v = \frac{3600}{2700}$$
- $$\Rightarrow v = 1.33 \text{ m s}^{-1}$$
- in the direction of the initial velocity of the first car
- e. $\Delta p = p_f - p_i$
- $$= (1200 \times 1.33) - (-14\,400)$$
- $$= 1600 + 14\,400$$
- $$= 16\,000 \text{ kg m s}^{-1} \text{ (or N s)}$$
- in the direction of motion of the tangled wreck
- f. $\Delta p = p_f - p_i$
- $$= (1500 \times 1.33) - (18\,000)$$
- $$= 2000 - 18\,000$$
- $$= -16\,000 \text{ kg m s}^{-1} \text{ (or N s)}$$
- in the direction opposite that of the 1200 kg car

PRACTICE PROBLEM 3

A 1000 kg car travelling north at 30 m s^{-1} (108 km h^{-1}) collides with a stationary delivery van of mass 2000 kg on an icy road. The two vehicles lock together after impact.

- What is the velocity of the tangled wreck immediately after the collision?
- What is the impulse on the delivery van?
- What is the impulse on the speeding car?
- After the collision, if — instead of locking together — the delivery van moved forward separately at a speed of 12 m s^{-1} , what velocity would the car have?

FEELING THE EARTH MOVE

Can you feel the Earth move when you bounce a basketball on the court? If the Earth and your basketball were an isolated system, the Earth *would* move! Its change in speed can be calculated by applying the Law of Conservation of Momentum.

The mass of the Earth is $6.0 \times 10^{24} \text{ kg}$. If the mass of a basketball is 600 g and it strikes the ground with a velocity of 12 m s^{-1} downwards in an isolated system, estimate the velocity of the Earth after impact.



Resources



Digital documents Investigation 7.1 Who's pulling whom? (doc-31602)

Investigation 7.2 The properties of a coil spring (doc-31603)



Teacher-led video Investigation 7.2 The properties of a coil spring (tlvd-0240)

7.2 EXERCISE

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

- Summarise the relationship between impulse and momentum in eight words or fewer.
- In a real collision between two cars on a bitumen road on a dry day, is it reasonable to assume that the total momentum of the two cars is conserved? Explain your answer.
- An empty railway cart of mass 500 kg is moving along a horizontal low-friction track at a velocity of 3.0 m s^{-1} due south when a 250 kg load of coal is dropped into it from a stationary container directly above it.
 - Calculate the velocity of the railway cart immediately after the load has been emptied into it.
 - What happens to the vertical momentum of the falling coal as it lands in the railway cart?
 - If the fully loaded railway cart is travelling along the track at the velocity calculated in part (a) and the entire load of coal falls out through a large hole in its floor, what is the final velocity of the cart?
- Are you generally safer in a big car or a small car in the event of an accident? If so, what is the reason? Considering the following questions, you might be able to work it out by making some estimates and applying Newton's laws to each car. You might also have to make some assumptions in predicting the outcomes of such a collision.
 - How do the forces on each car compare?
 - How do the masses of the cars compare with each other?
 - What is the subsequent change in velocity of each car as a result of the collision?
 - How does your body move during a collision and what does it collide with?
- A 400 g rubber ball hits a wall at 15 m s^{-1} and bounces back after being in contact with the wall for 0.1 seconds. The momentum of the ball changes by 10 kg m s^{-1} . (Air resistance and the gravitational force can be ignored.) Take the initial velocity as positive.
 - Calculate the magnitude and direction of the impulse that the wall exerts on the ball.
 - What is the magnitude of the average force that is exerted on the ball?
 - Calculate the velocity with which the ball bounces back.

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7.3 Work done

KEY CONCEPT

- Investigate and apply theoretically and practically the concept of work done by a constant force using:
 - work done = constant force $\times$ distance moved in direction of net force
 - work done = area under force–distance graph.

The amount of energy transferred to or from another object or transformed to or from another form by the action of a force is called **work**.

Work can be considered to be done if a force, F , acts on an object and the object is moved across a distance, Δx .

7.3.1 Calculating work done by a constant force

The work, W , done when a force, F , causes a movement of a distance, d , in the direction of the force is defined as:

work = magnitude of the force $\times$ distance moved in the direction of the force

$$W = F \times d$$

Work is a scalar quantity. The SI unit of work is the joule. One joule of work is done when a force of magnitude of 1 newton causes a change in distance of 1 metre in the same direction of the force.

The work done on an object of mass m by the net force acting on it is given by:

$$W = \vec{F}_{\text{net}} d$$

$$W = mad$$

where: W is the work done, in J

d is the magnitude of the object's displacement, in m

$\vec{F}$ is the force, in N

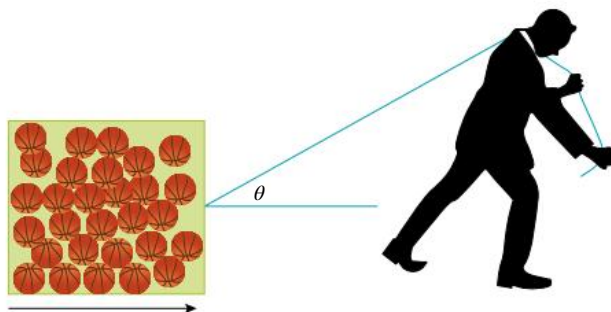
m is the mass, in kg

$\vec{a}$ is the acceleration of an object, in m s^{-2}

This formula is only accurate when the force applied is in the same direction as the direction of the distance moved. If the force is applied at an angle to the direction of the movement, then only the force in the same direction as the distance moved contributes to the work done on the object. In these situations, it is necessary to resolve the force into its different components to determine the part of the force that contributes to the work done.

Consider a student pulling a box along the ground using a piece of rope. The angle between the applied force and the direction of displacement is θ . It is this angle that allows the separation of the force in the direction of the displacement from the total force applied.

FIGURE 7.5 The angle between the applied force and direction changes the work done.



$$W = \vec{F}d\cos\theta$$

where: $\cos\theta$ is the cosine of angle of the force to the distance moved of the object

W is the work done, in J

d is the magnitude of the object's displacement, in m

$\vec{F}$ is the force, in N

When the force and the movement of the object are in the same direction, $\theta = 0^\circ$. Since $\cos 0^\circ = 1$, the formula for work done can be simplified to $W = Fd$.

When the force and the displacement of the object are in opposite directions, $\theta = 180^\circ$. Since $\cos 180^\circ = -1$, it can be concluded that the work leads to a loss of energy.

Since work is only considered to be done when a force (or a component of a force) is in the direction of the movement of the object, it can be seen that if an object is being carried at 90° to the direction of movement, no work is being done on the object. This is because $\cos 90^\circ = 0$. Sometimes, rather than d , you may see Δx used to describe the movement in the horizontal direction. If displacement is being used, the symbol s may instead be seen. However, as work is a scalar quantity, we often use distance (or the magnitude of displacement).

SAMPLE PROBLEM 4

Calculate the work done on a box when it is pulled by a rope that is at an angle of 30° to the direction of the movement. The box moves a distance of 585 m and the total force exerted on the box is 500 N.

 **Teacher-led video:** SP4 (tlvd-0163)

THINK

1. Use the formula for work when the direction of movement is angled.
2. Substitute in the values
 $F = 500 \text{ N}$; $d = 585 \text{ m}$; $\theta = 30^\circ$
3. Determine the work done on a box in joules.

WRITE

$$W = F\Delta x \cos\theta$$

$$W = 500 \times 585 \cos 30^\circ$$

$$W = 253\,312 \text{ J}$$

PRACTICE PROBLEM 4

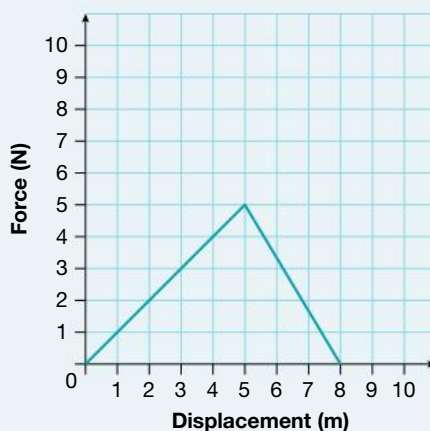
Calculate the work done on a container when it is pulled by a rope that is at an angle of 52° to the direction of the movement. The box moves a distance of 231 m and the total force exerted on the box is 440 N.

7.3.2 Calculating work done using a force–distance graph

The work done by a force can also be found by determining the area under a force–distance graph. This is particularly useful if the force is not constant. The techniques to calculate the area under a graph were outlined in section 7.2.1 under ‘Calculating impulse from a force–time graph’. As mentioned earlier, the area may be calculated by either counting squares or by calculating the area under the graph as a shape and calculating the area of this shape.

SAMPLE PROBLEM 5

Using the following graph, determine the amount of work done by the force when the object moves from 0 to 5 m.

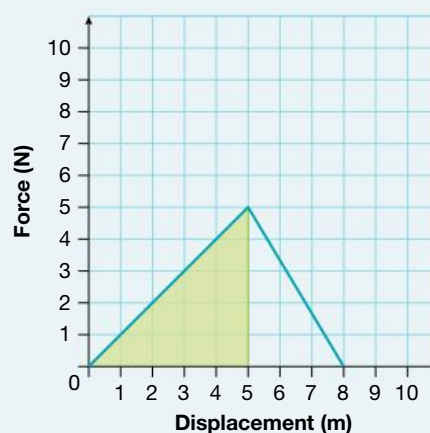


 Teacher-led video: SP5 (tlvd-0164)

THINK

1. The work done is the area under the line between 0 and 5 m.
Determine the dimensions of this area.

WRITE



The base of the triangle is 5 and the height is 5.

2. Calculate the area of the triangle to determine the amount of work done using the following formula:

$$A_{\text{triangle}} = \frac{1}{2} \times \text{base} \times \text{height}$$

$$\begin{aligned} A_{\text{triangle}} &= \frac{1}{2} \times 5 \times 5 \\ &= 12.5 \text{ J} \end{aligned}$$

PRACTICE PROBLEM 5

Determine the amount of work done by the force when the object moves from 5 to 8 m (using the graph from sample problem 5).

7.3 EXERCISE

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

1. A total of 10 000 J of energy is used to move a ute a distance of 50 m. What is the size of the force applied?
2. You use a rope, at 30° to the horizontal, to pull a box of your old physics textbooks along a brick-paved pathway. The box weighs 8 kg and you drag it for 5 m towards the shed. The tension in the rope, F_T , is 40 N, and the frictional force, F_R , is 20 N. Determine the total work done on the crate.
3. A weightlifter lifts a 125 kg barbell to a height of 1.1 m, at constant speed. Calculate the work done by the weightlifter.
4. An elastic band is stretched 40 cm and then released. Using the graph calculate the work done when the elastic band is released.



5. The science laboratory is on the second floor of the school building. Jo, a fellow science student, carries her 50 N backpack up the two flights of stairs. The two flights of stairs have a height of 7 m. How much work has Jo done on her backpack while carrying it up the stairs?

studyon

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studyON: Past VCAA exam questions 

Fully worked solutions and sample responses are available in your digital formats.

7.4 Kinetic and potential energy

KEY CONCEPT

- Analyse transformations of energy between kinetic energy, strain potential energy, gravitational potential energy and energy dissipated to the environment (considered as a combination of heat, sound and deformation of material):
 - kinetic energy at low speeds: $E_k = \frac{1}{2}mv^2$; elastic and inelastic collisions with reference to conservation of kinetic energy
 - strain potential energy: area under force–distance graph including ideal springs obeying Hooke's Law: $E_s = \frac{1}{2}k\Delta x^2$
 - gravitational potential energy: $E_g = mg\Delta h$.

Energy can be transferred from one object to another and is equal to the amount of work done. Energy can be transferred as a result of temperature difference (heating or cooling), by electromagnetic and nuclear radiation, or by the action of a force.

When you serve in a game of tennis, energy is transferred from the tennis racquet to the tennis ball. The energy is transferred to the tennis ball by the force applied to it by the tennis racquet. Energy can also be transformed from one form into another by the action of a force. For example, as a dropped tennis ball falls to the ground, gravitational potential energy is transformed into kinetic energy. The transformation of the energy possessed by the ball from one form into another is caused by the gravitational force acting on the tennis ball.

7.4.1 Law of Conservation of Energy

Energy cannot be created or destroyed. It can only be converted from one form into another. This is the Law of Conservation of Energy. During most energy transformations, some energy is degraded into less useful forms, heating the surroundings and causing noise. If air resistance and other types of friction are small, the amount of energy degraded can be considered negligible.

When two objects collide, the total energy of the system, which includes the two objects and the surroundings (the air and ground), is conserved. However, the total energy of the two objects is not conserved because, when they make contact, some of their energy is transferred to the surroundings.

7.4.2 Kinetic energy

Kinetic energy is the energy associated with the movement of an object. Like all forms of energy, kinetic energy is a scalar quantity.

Kinetic energy is the energy associated with the movement of an object. The kinetic energy, E_k , of an object of mass m and speed $\vec{v}$ is expressed as:

$$E_k = \frac{1}{2} m \vec{v}^2$$

The kinetic energy, E_k , of an object is equal to the work done on the object by the net force.

Recall from subtopic 7.3 that the work done on an object of mass, m , by the net force acting on it is given by:

$$\begin{aligned} W &= F_{\text{net}}d \\ &= mad \end{aligned}$$

where: d = the distance moved by an object.

If we use the constant acceleration formulas (where the displacement, s , can be equated to the distance, d), work can also be written as:

$$\begin{aligned} W &= \frac{ma(v^2 - u^2)}{2a} \\ &= \frac{1}{2}mv^2 - \frac{1}{2}mu^2 \\ &= \Delta E_k \end{aligned}$$

If the initial kinetic energy of the object is zero, the work done by the net force is equal to the final kinetic energy. If work is done to stop an object, the work done is equal to the initial kinetic energy.

SAMPLE PROBLEM 6

A car of mass 600 kg travelling at 12.0 m s^{-1} collides with a concrete wall and comes to a complete stop over a distance of 30.0 cm. Assume that the frictional forces acting on the car are negligible.

- How much work was done by the concrete wall to stop the car?
- What was the magnitude of net force acting on the car as it came to a halt?

 **Teacher-led video:** SP6 (tlvd-0165)

THINK

- As it is known that the car comes to a complete stop, the final kinetic energy is 0. As the change in kinetic energy is being calculated, you only need to focus on the initial kinetic energy.

- The magnitude is determined by:

$$W = F_{\text{net}} \times d$$

WRITE

- The net force on the car is equal to the force applied by the wall. The work done by the wall, W , is given by:

$$W = \Delta E_k$$

$$\Delta E_k = \frac{1}{2}mv^2, \text{ where } m = 600 \text{ kg and}$$

$$v = 12.0 \text{ m s}^{-1}.$$

$$W = \frac{1}{2}mv^2$$

$$= \frac{1}{2} \times 600 \times (12.0)^2$$

$$= 4.32 \times 10^4 \text{ J}$$

- $W = F_{\text{av}} \times d$

$$4.32 \times 10^4 = F_{\text{net}} \times 0.300$$

$$(F_{\text{av}} = F_{\text{net}} \text{ in this case})$$

$$\Rightarrow F_{\text{net}} = 1.44 \times 10^5 \text{ N}$$

PRACTICE PROBLEM 6

A car travelling at 15 m s^{-1} brakes heavily before colliding with another vehicle. The total mass of the car is 800 kg . The car skids for a distance of 20 m before making contact with the other vehicle at a speed of 5 m s^{-1} .

- How much work is done on the car by road friction during braking?
- Calculate the average road friction during braking.

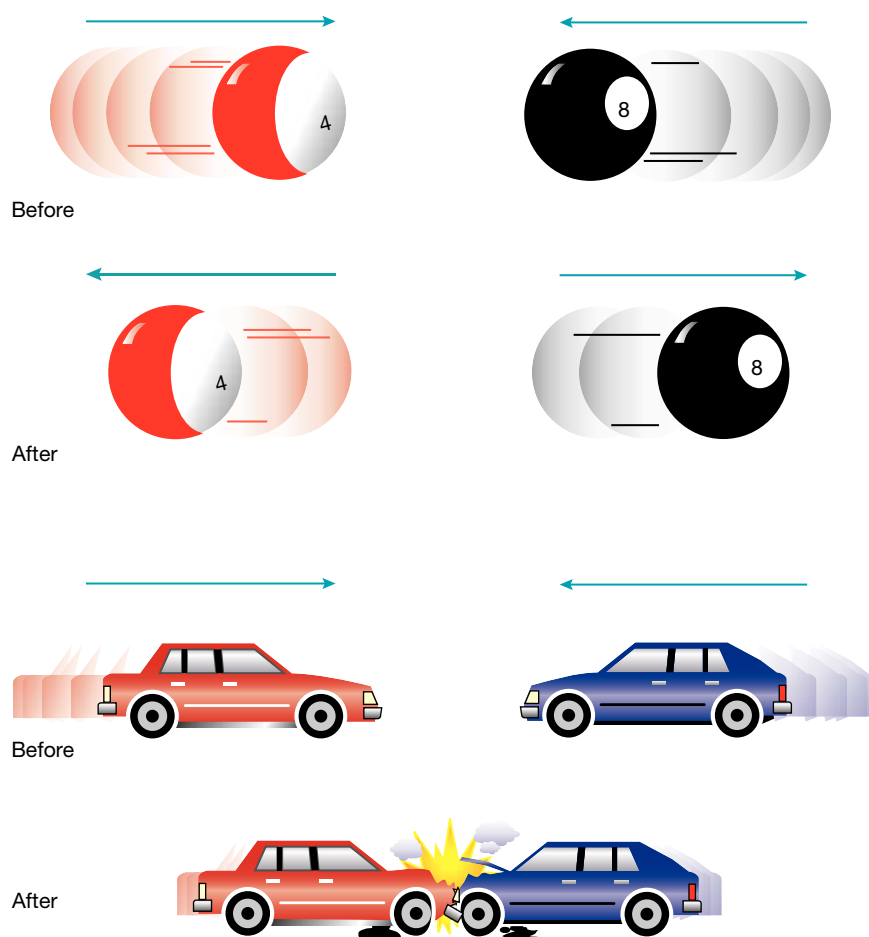
Elastic and inelastic collisions

The Law of Conservation of Momentum states the following: when a collision between two objects occurs, the total momentum of the two objects remains constant.

This statement is valid as long as the two objects comprise an isolated system — that is, as long as there are no external forces acting on each of the objects.

Consider the differences between the two collisions shown in figure 7.6: a collision between two billiard balls on a smooth, level billiard table, and a head-on collision between two cars travelling in opposite directions on a level, icy road.

FIGURE 7.6 Two collisions — momentum is conserved in both of them.



The two billiard balls can be considered to be an isolated system. The total momentum of the two billiard balls immediately after the collision is the same as it was immediately before the collision. (It is also the same during the collision. Momentum, unlike energy, cannot be stored.) The two cars can also be considered to be an isolated system, because the frictional forces on the cars are relatively small. Therefore, the total momentum of the cars immediately after the collision is the same as it was immediately before the collision.

What's the difference?

Apart from the difference between the masses of the objects involved in the collisions, there is one obvious difference:

- The collision between the two billiard balls is an almost perfect elastic collision. An **elastic collision** is one in which the total kinetic energy after the collision is the same as it was before the collision. The sound made when the balls collide provides evidence that the collision is not quite perfectly elastic. Some of the initial kinetic energy of the system is transferred to particles in the surrounding air (and within the balls themselves). However, when making predictions about the outcome of such a collision, it would be quite reasonable to treat the collision as a perfectly elastic one. In fact, a perfectly elastic 'collision' can only take place if the interacting objects do not actually make contact with each other. A perfectly elastic interaction can take place when two electrons move towards each other in a vacuum.
- The collision between the two cars is an **inelastic collision**. Even though momentum is conserved, the total kinetic energy of the cars after the collision is considerably less than it was before the collision. A significant proportion of the initial kinetic energy of the system is transferred to the bodies of both cars, changing their shapes and heating them. Some of the initial kinetic energy is also transformed to sound energy.

on Resources

 **Interactivity** Colliding dodgems (int-6610)

7.4.3 Strain potential energy

The energy stored in an object by changing its length or shape is usually called **strain potential energy** if the object can return naturally to its original shape. Work must be done on an object by a force in order to store energy as strain potential energy. However, when objects are compressed, stretched, bent or twisted, the force needed to change their shape is not constant. For example, the more you stretch a rubber band, the harder it is to stretch it further. The more you compress the sole of a running shoe, the harder it is to compress it further.

The strain potential energy of an object can be determined by calculating the amount of work done on it by the force. The work can also be determined by calculating the area under a graph of force versus compression (or the distance). In the case of a simple spring, rubber band or running shoe, the gain in strain potential energy can be calculated by determining the area under a graph of force versus extension or force versus compression.

When an object loses strain potential energy, it can do work on other objects. The amount of work done by the object (and hence the change in potential energy) is equal to the area under a graph of force versus compression.

When you close the lid of a jack-in-the-box, you do work on the spring to increase its strain potential energy, transferring energy from your body to the spring. The spring does work on the 'jack' when the lid is opened, transforming strain potential energy into kinetic energy.

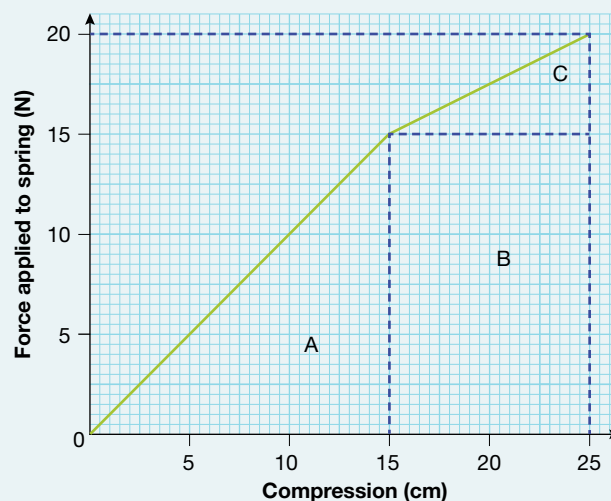
FIGURE 7.7 A jack-in-the-box. When the lid opens, the spring does work on the 'jack', transforming strain potential energy into kinetic energy.



SAMPLE PROBLEM 7

The following graph shows how the force required to compress a jack-in-the-box spring changes as the compression of the spring increases.

How much energy is stored in the spring when it is compressed by 25 cm?



Teacher-led video: SP7 (tlvd-0166)

THINK

1. The energy stored in the spring is equal to the amount of work done on it.
This is the area under the line in the graph.
2. Determine the sections under the graph to calculate the area. As work is in m, convert the horizontal units to m from cm.
3. Calculate the total area.
4. Determine the stored energy (remembering that J is the same as N m).

WRITE

$$W = \text{area under graph} \\ = \text{area A} + \text{area B} + \text{area C}$$

$$\text{Area A} = \frac{1}{2} \times 0.15 \times 15 = 1.125 \text{ N m}$$

$$\text{Area B} = 0.10 \times 15 = 1.5 \text{ N m}$$

$$\text{Area C} = \frac{1}{2} \times 0.10 \times 5.0 = 0.25 \text{ N m}$$

$$A + B + C = 1.125 + 1.5 + 0.25 \\ = 2.9 \text{ N m}$$

The stored energy is 2.9 J.

PRACTICE PROBLEM 7

The length of the spring represented by the graph in sample problem 7 is 35 cm.

- a. How much strain potential energy is stored in the spring when its length is 15 cm?
- b. What is the length of the spring when 0.50 J of strain potential energy is stored in it due to compression? (This question is a little harder.)

Hooke's Law springs to mind

Robert Hooke (1635–1703) investigated the behaviour of elastic springs and found that the **restoring force** exerted by the spring was directly proportional to its displacement. The force is called a restoring force because it acts in a direction that would restore the spring to its natural length.

In vector notation, Hooke's Law states:

$$\vec{F} = -k\Delta\vec{x}$$

where: $\vec{F}$ = restoring force, in N

$\Delta\vec{x}$ = displacement of the end of the spring from its natural position, in m

k = spring constant (also known as force constant), in N m^{-1}

The negative sign is necessary because the restoring force is always in the opposite direction to the displacement.

It is usually more convenient to express Hooke's Law in terms of magnitude so that the negative sign is not necessary. That is:

$$F = k\Delta x$$

where: F = magnitude of the restoring force

Δx = compression or extension of the spring

k = spring constant

Some important points to remember about Hooke's Law include:

- Hooke's Law applies to springs within certain limits. If a spring is compressed or extended so much that it is permanently deformed — unable to return to its original natural length — Hooke's Law no longer applies.
- The magnitude of the restoring force is equal to the force that is compressing or extending the spring (Newton's third law).
- The measure Δx is not the length of the spring. Rather, it is a measure of its compression or extension — the change in length of the spring.
- The spring constant has SI units of N m^{-1} .
- A graph of F versus Δx produces a straight line with a gradient of k .

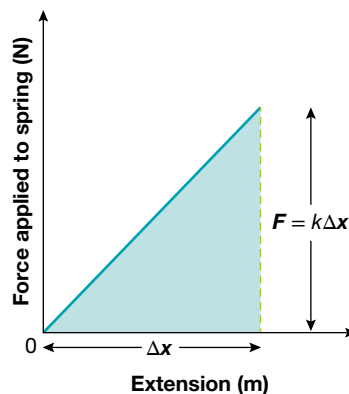
The strain potential energy of a spring that obeys Hooke's Law can be expressed as:

$$E_s = \frac{1}{2}k(\Delta x)^2$$

This can be verified by calculating the work done in extending the spring described in figure 7.8. This is done by calculating the area under the graph of force versus extension. If the spring obeys Hooke's Law, then:

$$\begin{aligned}\text{strain potential energy} &= \text{work done on spring} \\ &= \text{area under graph} \\ &= \frac{1}{2}\Delta x \times k\Delta x \\ &= \frac{1}{2}k(\Delta x)^2\end{aligned}$$

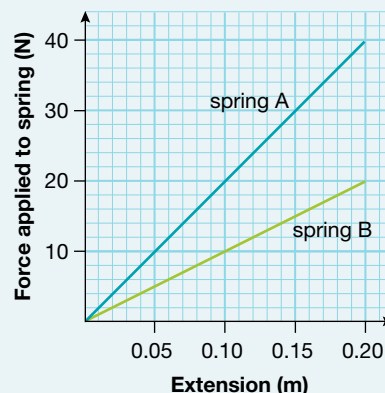
FIGURE 7.8 The strain potential energy of a spring is equal to the area under the graph.



SAMPLE PROBLEM 8

The following graph describes the behaviour of two springs that obey Hooke's Law. Both springs are extended by 20 cm.

- What is the spring constant of spring A?
- Which spring has the greatest spring constant?
- What is the strain potential energy of spring B?



Teacher-led video: SP8 (tlvd-0167)

THINK

- The spring constant k is equal to the gradient of the graph. Looking at spring A, the 'rise' of the graph is 40 N and the 'run' is 0.20 m.
- The gradient of the graph for spring A is greater than that for spring B.
- Since the spring obeys Hooke's Law, the strain potential energy of spring B can be calculated using the formula.
 - Determine k (the gradient). Looking at spring B, the 'rise' of the graph is 20 N and the 'run' is 0.20 m.
 - Use the formula to determine the strain potential energy.

WRITE

- $k = \frac{40}{0.20}$
 $= 200 \text{ N m}^{-1}$
- Therefore, spring A has a greater spring constant than spring B — in fact, it is twice the size.

$$\text{c. Strain potential energy} = \frac{1}{2}k(\Delta x)^2$$

$$k = \text{gradient}$$

$$= \frac{20}{0.20}$$

$$= 100 \text{ N m}^{-1}$$

$$\text{Strain potential energy}$$

$$= \frac{1}{2} \times 100 \times 0.20^2$$

$$= 2.0 \text{ J}$$

PRACTICE PROBLEM 8

- What is the spring constant of spring B, described in sample problem 8?
- How much strain potential energy is stored in spring A when it is extended by 20 cm?

SAMPLE PROBLEM 9

A toy car of mass 0.50 kg is pushed against a spring so that it is compressed by 0.10 m. The spring obeys Hooke's Law and has a spring constant of 50 N m^{-1} . When the toy car is released, what will its speed be at the instant that the spring returns to its natural length? Assume there is no friction within the spring and no frictional force resisting the motion of the toy car.

Teacher-led video: SP9 (tlvd-0168)

THINK

1. Determine the formula for strain potential energy.
2. Substitute in the provided values:
 $k = 50 \text{ N m}^{-1}$; $\Delta x = 0.10 \text{ m}$
3. Determine the speed when the spring returns to its natural length using:
 $\frac{1}{2}mv^2 = \text{energy}$
 where: $m = 0.50 \text{ kg}$ and the energy = 0.25 J
 (from step 2)
4. Respond to the question.

WRITE

$$\text{Strain potential energy} = \frac{1}{2}k(\Delta x)^2$$

$$\frac{1}{2}k(\Delta x)^2 = \frac{1}{2} \times 50 \times (0.10)^2$$

$$= 0.25 \text{ J}$$

$$\frac{1}{2}mv^2 = \text{energy}$$

$$\frac{1}{2} \times 0.50 \times v^2 = 0.25$$

$$\Rightarrow v^2 = \frac{0.25}{\frac{1}{2} \times 0.50}$$

$$\Rightarrow v = 1.0 \text{ m s}^{-1}$$

The speed of the toy car is 1.0 m s^{-1} .

PRACTICE PROBLEM 9

A model car of mass 0.40 kg travels along a frictionless horizontal surface at a speed of 0.80 m s^{-1} . It collides with the free end of a spring that obeys Hooke's Law. The spring constant is 100 N m^{-1} .

- a. How much strain potential energy is stored in the spring when the car comes to a stop?
- b. What is the maximum compression of the spring?

7.4.4 Gravitational potential energy

Gravitational potential energy is the energy stored in an object as a result of its position relative to another object to which it is attracted by the force of gravity. The gravitational potential energy of an object increases as it moves away from the object to which it is attracted and decreases as it moves towards an object to which it is attracted.

When you drop an object, the gravitational force does work on it, transforming gravitational potential energy to kinetic energy as it falls. When you lift an object, you do work on the object to increase its gravitational potential energy. (Energy is transferred from your body to the object.)

Calculating gravitational potential energy

A quantitative definition of gravitational potential energy can be stated by determining how much work is done in lifting an object of mass m through a height Δh . To lift an object without changing its kinetic energy, a force, F , equal to the force due to gravity acting on the object is needed. The work done is:

$$W = \vec{F} s$$

$$= m\vec{g} \Delta h$$

$$\Rightarrow \Delta E_g = m\vec{g} \Delta h$$

where: ΔE_g is the change in gravitational potential energy, in J

m is the mass of the object, in kg

$\vec{g}$ is the acceleration due to gravity, in m s^{-2}

Δh is the height of an object, in m

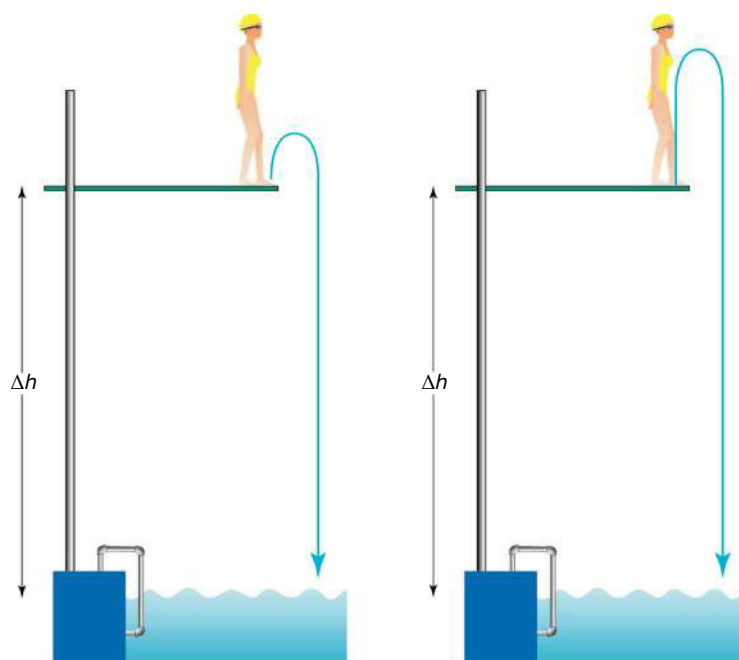
This formula provides a way of calculating changes in gravitational potential energy. If the gravitational potential energy of an object is defined to be a zero at a reference height, a formula for the quantity of gravitational potential energy can be found for an object at height h above the reference height:

$$\begin{aligned}\Delta E_g &= mg\Delta h \\ \Rightarrow E_g - 0 &= mg(h - 0) \\ \Rightarrow E_g &= mgh\end{aligned}$$

Usually the reference height is ground or floor level. Sometimes it might be more convenient to choose another reference height. However, it is the *change* in gravitational potential energy that is most important in investigating energy transformations.

It is important to remember that the change in gravitational potential energy as a result of a particular change in height is independent of the path taken. The change in gravitational potential energy of the diver in figure 7.9 is the same whether she falls from rest, jumps upwards first or completes a complicated dive with twists and somersaults.

FIGURE 7.9 The change in gravitational potential energy of the diver is independent of the path taken.



SAMPLE PROBLEM 10

A water slide has a drop of 9.0 m. A child of mass 35 kg sits at the top.

- What is the child's gravitational potential energy?
- How fast will the child be travelling when they hit the water? Ignore any frictional losses.

 **Teacher-led video:** SP10 (tlvd-0169)

THINK

- Determine the gravitational energy of the child using $\Delta E_g = mg\Delta h$, where $m = 35$ kg, $g = 9.8 \text{ m s}^{-2}$ and $\Delta h = 9.0$ m.

WRITE

$$\begin{aligned}\text{a. } \Delta E_g &= mg\Delta h \\ &= 35 \times 9.8 \times 9.0 \\ &= 3100 \text{ J}\end{aligned}$$

- b. Determine the gravitational energy of the child using $\frac{1}{2}mv^2 = mg\Delta h$.

$$\begin{aligned} \text{b. } \frac{1}{2}mv^2 &= mg\Delta h \\ \Rightarrow v^2 &= 2g\Delta h \\ v &= \sqrt{2 \times 9.8 \text{ m s}^{-2} \times 9.0 \text{ m}} \\ &= 13 \text{ m s}^{-1} \end{aligned}$$

PRACTICE PROBLEM 10

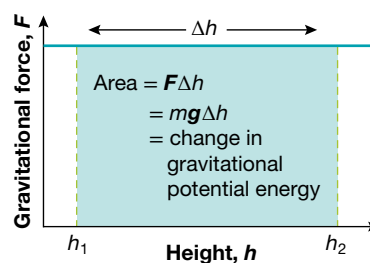
The maximum height of a roller-coaster ride is 30 m above the ground. The lowest height of the ride is 5.0 m.

- What is the change in gravitational potential energy of a 60 kg passenger?
- If the passenger was travelling at 0.5 m s^{-1} at the top, what would be their maximum speed at the lowest point?

Calculating gravitational potential energy using a graph of force versus height

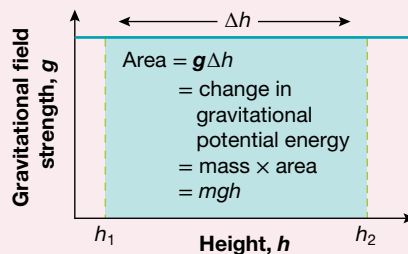
Because a change in gravitational potential energy is equal to the work done on an object by, or against, the gravitational force, it can be found by calculating the area under a graph of force versus height.

FIGURE 7.10 The area under a force-versus-height graph can be used to calculate the change in gravitational potential energy.



The quantity $\vec{g}$ is known as the gravitational field strength (sometimes just referred to as gravitational field).

The change in gravitational potential energy of an object can also be determined by calculating the area under a graph of gravitational field strength versus height (equal to $\vec{g} \Delta h$) and multiplied by its mass.



7.4.5 Energy transformations in collisions

Whether or not a collision is elastic depends on what happens to the colliding objects during the collision. When two objects collide, each of the objects is deformed. Each object applies a force on the other — in fact, the forces are equal and opposite! The size of the applied force increases as the deformation increases (just like a compressed spring). If each object behaves elastically, all the energy stored as strain potential energy during deformation is returned to the other object as kinetic energy. The collision is therefore elastic.

In the collision between the two billiard balls discussed earlier, the work done on each billiard ball as it returns to its original shape is almost as much as the work done during deformation. Therefore, almost all the strain potential energy stored in each ball while they are in contact with each other is returned as kinetic energy.

The graph in figure 7.11 shows that, in an elastic collision, the work done on an object during deformation (the area under the force versus deformation graph) is equal to the work that the object does on the other object as it returns to its original shape. The graph in figure 7.12 illustrates a collision between an electron and a second electron. The work done to slow down the approaching electron is the same as the work done to increase its speed during separation.

FIGURE 7.11 A graph of force versus deformation for an object involved in an elastic collision

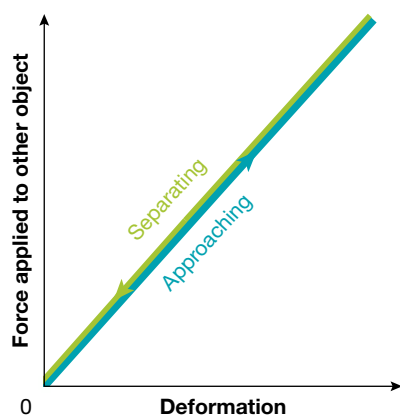


FIGURE 7.12 A graph of force versus separation for an electron approaching another electron

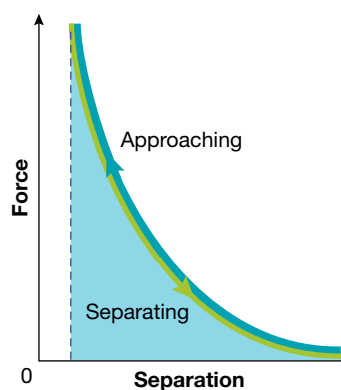
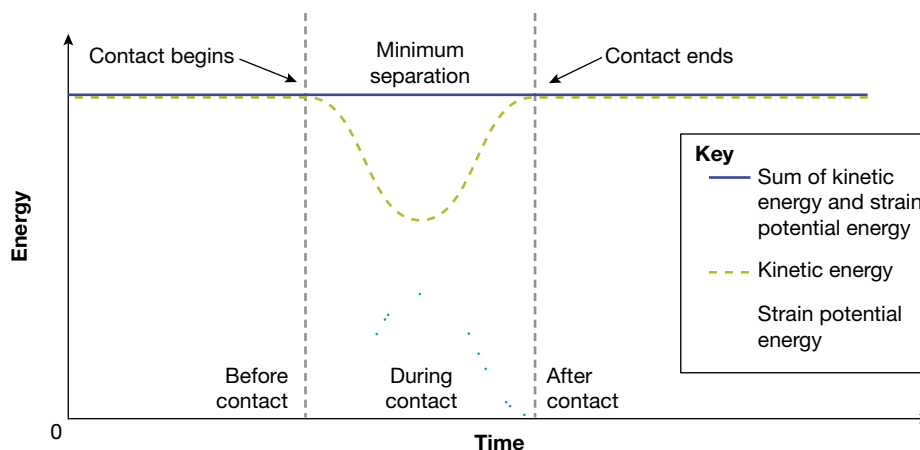


Figure 7.13 illustrates that, even though the total kinetic energy and total strain potential energy change during an elastic collision, the sum of the kinetic energy and strain potential energy is constant. In an inelastic collision, the sum of the kinetic energy and strain potential energy decreases because energy is dissipated from the system of objects to the environment as heat, permanent deformation of the objects and sound.

FIGURE 7.13 Energy transformations during an elastic collision



CRUMPLE ZONES

The crumple zones at the front and rear of cars are designed to reduce injuries by ensuring that the collisions are not elastic. Between the crumple zones is the more rigid passenger 'cell', designed to protect occupants from the intrusion of the engine or other solid objects that would injure or even kill them.

In the previous section on momentum, an analysis using Newton's Second Law of Motion reveals that the acceleration of the occupants is decreased because the time during which the velocity changes is increased if the car is designed to crumple.

The reason that crumple zones work can be also understood by analysing a collision in terms of energy transformations. When a car collides with a rigid object, the object does work on the car, transforming its kinetic energy into other forms of energy and transferring some of this energy to the surroundings. A lot of the kinetic energy of the car is used to heat the body of the car and the surrounding air. Without the crumple zone, the distance over which the force acts would be less, and the cars would be more inclined to rebound. The result would be a greater acceleration (in magnitude) of occupants, and therefore a greater chance of serious injury or death.

The effectiveness of gloves in baseball and cricket can also be analysed in terms of energy. Like the crumple zones of cars, they are designed to ensure that collisions are inelastic.

FIGURE 7.14 Crumple zones at the front and rear of cars absorb energy and reduce the magnitude of acceleration during an accident.



SAMPLE PROBLEM 11

A white car of mass 800 kg is driven along a slippery straight road with a speed of 20 m s^{-1} (72 km h^{-1}). It collides with a stationary blue car of mass 700 kg. During the collision, the blue car is pushed forward with a speed of 12 m s^{-1} .

- What is the speed of the white car after the collision?
- Show that the collision is not elastic.

 **Teacher-led video:** SP11 (tlvd-0170)

THINK

- Assign the direction in which the white car is moving as positive. Assume that friction is negligible. Momentum is calculated using the formula, $p = mv$. The mass of the white car is 800 kg and the initial velocity was 20 m s^{-1} , and the mass of the blue car is 700 kg and the initial velocity was 0 m s^{-1} .
- Determine the final momentum of the system, using the formula, $p = mv$. The mass of the white car is 800 kg and the mass of the blue car is 700 kg and the final velocity was 12 m s^{-1} .
- Recall that $p_f = p_i$.

WRITE

- The initial momentum of the system, p_i , is given by:

$$\begin{aligned} p_{\text{white}} + p_{\text{blue}} &= (800 \times 20) + (700 \times 0) \\ &= 16\,000 + 0 \\ &= 16\,000 \text{ kg m s}^{-1} \end{aligned}$$

The final momentum of the system, p_f , is given by:

$$\begin{aligned} p_{\text{white}} + p_{\text{blue}} &= (800 \times v_{\text{white}}) + (700 \times 12) \\ &= 800 \times v_{\text{white}} + 8400 \\ v_{\text{white}} &= \text{velocity of the white car after the collision} \end{aligned}$$

$$800 v_{\text{white}} + 8400 = 16\,000$$

$$800 v_{\text{white}} = 7600$$

$$\Rightarrow v_{\text{white}} = 9.5 \text{ m s}^{-1}$$

The speed of the white car after the collision is 9.5 m s^{-1} .

- b. 1. If the collision is elastic, the total kinetic energy after the collision will be the same as the total kinetic energy before the collision. Calculate the total kinetic energy using $\frac{1}{2}mv^2$ for both the white and the blue car and adding these together.

2. Show that the collision is not elastic.

$$\begin{aligned} \text{b. } m_{\text{white}} &= 800 \text{ kg, } v_{\text{white initial}} = 20 \text{ m s}^{-1}, \\ v_{\text{white final}} &= 9.5 \text{ m s}^{-1} \\ m_{\text{blue}} &= 700 \text{ kg, } v_{\text{blue initial}} = 0 \text{ m s}^{-1}, \\ v_{\text{blue final}} &= 12 \text{ m s}^{-1} \end{aligned}$$

Total kinetic energy before the collision is given by:

$$\frac{1}{2} \times 800 \times 20^2 + \frac{1}{2} \times 700 \times 0^2 = 160\,000 \text{ J}$$

Total kinetic energy after the collision is given by:

$$\frac{1}{2} \times 800 \times 9.5^2 + \frac{1}{2} \times 700 \times 12^2$$

$$= 86\,500 \text{ J}$$

Kinetic energy is not conserved. The collision is not elastic.

PRACTICE PROBLEM 11

- a. A green dodgem car of mass 400 kg has a head-on collision with a red dodgem car of mass 300 kg. Both dodgem cars were travelling at a speed of 2.0 m s^{-1} before the collision. What is the rebound speed of the green dodgem car if the red dodgem car rebounds at a speed of:
- 1.0 m s^{-1}
 - 2.0 m s^{-1} ?
- b. Are either of the collisions in part (a) elastic? If so, which one?

THE IMPORTANCE OF AIRBAGS

Most deaths and injuries in car crashes are caused by collisions between occupants and the interior of the car. Driver airbags are designed to reduce the injuries caused by impact with the steering wheel. They should inflate only in head-on collisions.

Airbags inflate when the crash sensors in the car detect a large deceleration. When the sensors are activated, an electric current is used to ignite a chemical called sodium azide (NaN_3). The sodium azide stored in a metal container at the opening of the airbag burns rapidly, producing sodium compounds and nitrogen gas. The reaction is explosive, causing a noise like the sound of gunfire. The nitrogen gas inflates the airbag to a volume of about 45 L in only 30 ms. When the driver's head makes contact with the airbag, the airbag deflates as the nitrogen gas escapes through vents in the bag. The dust produced when an airbag is activated is a mixture of the talcum powder used to lubricate the bags and the sodium compounds produced by the chemical reaction. Deflation must be rapid enough to allow the driver to see ahead after the accident. The collision of the driver with the airbag is inelastic. Most of the kinetic energy of the driver's body is transferred to the nitrogen gas as the kinetic energy of its molecules.

FIGURE 7.15 Testing airbags



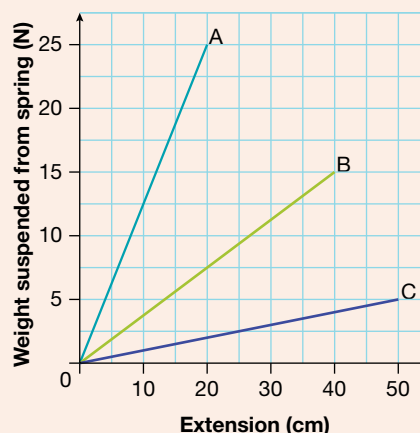
 **Digital document** Investigation 7.3 Elastic and inelastic interactions (doc-31604)

 **Weblink** Car safety systems

7.4 EXERCISE

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- Consider a tennis ball that has been dropped vertically onto a hard surface.
 - Is the collision of the falling tennis ball with the ground elastic?
 - How do you know?
 - Is momentum conserved during this collision?
- Two cars of equal mass and travelling in opposite directions on a wet and slippery road collide and lock together after impact. Neither car brakes before the collision. The tangled wreck moves off in an easterly direction at 5.0 m s^{-1} immediately after the collision. One car was travelling due west at 20 m s^{-1} immediately before the collision.
 - What was the velocity of the other car?
 - What fraction of the initial kinetic energy was 'conserved' during the collision?
- The graph shown describes the behaviour of three springs as known masses are suspended from one end.
 - What is the force applied by spring A to a 1.0 kg mass suspended from one end?
 - What is the spring constant of spring B?
 - Which spring has the greatest stiffness?
 - How much work is done by a 500 g mass on spring C to extend it fully?
 - Which spring has the greatest strain energy at maximum extension?
- A weightlifter raises a barbell of mass 150 kg vertically through a height of 1.20 m .
 - Sketch a graph of gravitational field strength versus height of the barbell.
 - Use the graph to determine the change in gravitational potential energy of the barbell.
 - How much work did the weightlifter do on the barbell?
- Calculate the gravitational potential energy of the following objects.
 - A 70 kg pole vaulter 6.0 metres above the ground
 - A pile driver of mass 80 kg raised 7.0 m above the pile
 - A 400 kg lift at the bottom of an 80 m mine shaft relative to the ground
- A 900 kg car travelling at 20 m s^{-1} on an icy road collides with a stationary truck. The car comes to rest over a distance of 40 cm .
 - What is the initial kinetic energy of the car?
 - How much work is done by the truck to stop the car?
 - What average force does the car apply to the truck during the collision?
- A rock is dropped from a height into mud and penetrates. If it was dropped from twice the height, what would be the depth of penetration compared to the depth from the first drop?



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7.5 Review

7.5.1 Summary

- Impulse is the product of a force and the time interval over which it acts. Impulse is a vector quantity with SI units of N s (or kg m s^{-1}).
- The change in momentum of an object is equal to the impulse of the net force acting on it.
- The impulse delivered to an object by a force can be determined from the area under the graph of force versus time.
- If there are no external forces acting on a system, the total momentum of the system remains constant. This statement is an expression of the Law of Conservation of Momentum.
- The Law of Conservation of Momentum can be applied to collisions between two objects moving along a straight line, as long as external forces such as friction are negligible.
- When two objects collide, the impulse applied to the first object by the second object is equal and opposite in direction to the impulse applied to the second object by the first object.
- The amount of energy transferred to or from another object, or transformed to or from another form, by the action of a force is called work.
- The work done on an object by the net force is equal to the object's change in kinetic energy.
- A change in gravitational potential energy is equal to the work done by or against a gravitational force and is equal to $mg\Delta h$. It can also be determined by calculating the area under a graph of force versus height.
- The work done when a force causes a movement of an object along the line of action of the force is equal to the product of the magnitude of the force and the distance the object moved. This can be written as $W = Fd$.
- Strain potential energy is the energy stored in an object as a result of a reversible change in shape.
- When an elastic spring is compressed or extended, the spring applies a restoring force in a direction that would restore the spring to its natural length. The restoring force F is related to the displacement of the spring from its natural length by the equation $F = -k\Delta x$, where k is the spring constant and Δx is the displacement from the spring's natural length. This equation is an expression of Hooke's Law. The strain potential energy stored in a spring that obeys Hooke's Law is equal to $\frac{1}{2}k(\Delta x)^2$.
- The Law of Conservation of Energy applies to collisions as it applies to all interactions between objects. However, the total energy of the objects that collide is not conserved because, when the objects make contact, some of their energy is transferred to the surroundings.
- Elastic collisions are collisions in which the total kinetic energy of the objects is conserved. In such collisions, the work done on each object during deformation is the same as the work done as each object resumes its original shape. Inelastic collisions are collisions in which the total energy is not conserved.
- Momentum is conserved in both elastic and inelastic collisions as long as the external forces are negligible.
- Many safety features of motor vehicles are designed to reduce injuries by ensuring that collisions between vehicles, or between vehicles and other objects, are not elastic.

Resources

study

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7.5.2 Key terms

An **elastic collision** is a collision in which the total kinetic energy is conserved.

An **isolated system** is one on which no external forces act. The only forces acting on objects in the system are those applied by other objects in the system.

Gravitational potential energy is the energy stored in an object as a result of its position relative to another object to which it is attracted by the force of gravity.

Impulse is the product of a force and the time interval over which it acts. Impulse is a vector quantity with SI units of N s.

An **inelastic collision** is a collision in which the total kinetic energy is not conserved.

Kinetic energy is the energy associated with the movement of an object. Like all forms of energy, it is a scalar quantity.

The **restoring force** applied by a spring is the force it applies to resist compression or extension.

Strain potential energy is the energy stored in an object as a result of a reversible change in shape.

Work is the energy transferred to or from another object by the action of a force. Work is a scalar quantity.



Resources



Digital document Key terms glossary (doc-32263)

7.5.3 Practical work and investigations

Investigation 7.1

Who's pulling whom?

Aim:

- a. To demonstrate that the 'action' and 'reaction' described in Newton's third law are equal in magnitude, opposite in direction and act on different objects
- b. To demonstrate that the total momentum of a system remains constant if there are no unbalanced external forces acting on the system

Digital document: doc-31602

Investigation 7.2

The properties of a coil spring

Aim: To determine whether the force applied by a coil spring extending a suspended weight is directly proportional to the extension of the coil spring. The purpose is to verify Hooke's Law.

Digital document: doc-31603

Teacher-led video: tlvd-0240



Investigation 7.3

Elastic and inelastic interactions

Aim:

- a. To record the motion of two objects during an interaction between them and determine the velocity of each object before and after the interaction
- b. To determine the momentum of two objects before and after three different types of interaction and, subsequently, determine whether the total momentum is conserved
- c. To determine the kinetic energy of two objects before and after three different types of interaction and, subsequently, determine whether the total kinetic energy is conserved
- d. To distinguish between elastic and inelastic collisions

Digital document: doc-31604

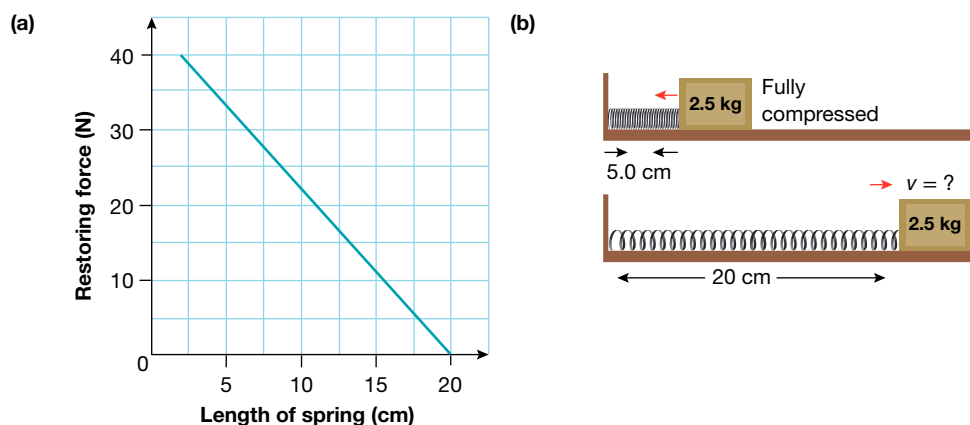
7.5 Exercises

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

7.5 Exercise 1: Multiple choice questions

- Boxers are trained to move their head backwards when they see they are going to take a hit to the head. Why is this a useful tactic?
 - It increases the momentum of the punch and decreases the force.
 - It extends the contact time, which decreases the force.
 - It reduces the contact time, which decreases the force.
 - It extends the contact time, which increases the force.
- A student holds their heavy school bag as they wait to enter class. How much work is done by the student?
 - 0 J
 - $\frac{1}{2}mv^2$
 - mgh
 - $E_k - E_g$
- When a bullet is fired from a rigidly held rifle, the force exerted by the rifle on the bullet is equal and opposite to the force exerted by the bullet on the rifle. In most cases when a rifle is fired, the shooter's shoulder moves back as the rifle recoils. If a 4.0 kg rifle fires a 20 g bullet with an initial speed of 300 m s^{-1} , what is the initial recoil speed of the rifle?
 - 6 m s^{-1}
 - $180\,000 \text{ m s}^{-1}$
 - -1.5 m s^{-1}
 - $+1.5 \text{ m s}^{-1}$

Use the following information to answer Questions 4, 5 and 6.



The graph in part (a) shows how the restoring force of a spring changes as it is compressed. A 2.5 kg mass is pushed against the spring so that its length is 5.0 cm and then released. Friction can be assumed to be negligible.

4. How much energy is stored in the spring?
 - A. 122.5 J
 - B. 2.475 J
 - C. 4.0 J
 - D. 1.0 J
5. What will be the speed of the mass when the spring returns to its original length of 20 cm?
 - A. 0 m s^{-1}
 - B. 0.48 m s^{-1}
 - C. 1.4 m s^{-1}
 - D. 9.8 m s^{-2}
6. What is the spring constant of the spring?
 - A. 220 N m^{-1}
 - B. 278.43 N m^{-1}
 - C. 2.475 N m^{-1}
 - D. 20 N m^{-1}

Use the following information to answer Questions 7, 8 and 9.

A mountaineer, whose mass is 65.00 kg, climbs an overhanging cliff and reaches a height of 35.00 m. Suddenly, she loses her grip and begins to fall. Luckily, she is wearing a safety harness and rope, which stops her fall after 14.00 m of free fall.

7. What is the potential energy of the mountaineer, relative to the bottom of the cliff, at the instant she loses her grip?
 - A. 8918 J
 - B. 13 377 J
 - C. 22 295 J
 - D. 9.8 m s^{-2}
8. What is the kinetic energy of the mountaineer after she has fallen 14 m?
 - A. 9.8 m s^{-2}
 - B. 22 296 J
 - C. 13 377 J
 - D. 8918 J
9. What is her velocity at the moment she has fallen 14 m?
 - A. 274.4 m s^{-1}
 - B. 411.6 m s^{-1}
 - C. 20.29 m s^{-1}
 - D. 16.57 m s^{-1}
10. A car with a total mass of 1400 kg is travelling at 30 m s^{-1} . What is the kinetic energy of the car?
 - A. 21 000 J
 - B. 42 000 J
 - C. 630 000 J
 - D. 1 260 000 J

7.5 Exercise 2: Short answer questions

- Regarding momentum, what is the fundamental purpose of airbags, collapsible steering wheels and padded dashboards in passenger vehicles?
- Can an object have energy but no momentum? Explain. Can an object have momentum, but no energy?
- Consider a collision between two cars on an icy intersection where road friction is insignificant. Assume that the cars bounce off each other.
 - How do you know without performing any calculations that the collision is not elastic?
 - Is momentum conserved in such a collision?
- Two billiard balls with identical mass, m , collide with one another. Ball 1 has an initial velocity of 5 m s^{-1} to the right. After the collision, ball 1 continues to move to the right, now with a velocity of 0.8 m s^{-1} .

Calculate the velocity of ball 2 before the collision if the collision is completely elastic. Assume the system is isolated and has no external forces acting on it.
- A contractor lifts a 10 kg tool box up 0.4 m to hand to a colleague, at constant speed. Calculate the work done by the contractor.
- The ancient Egyptians relied on knowledge of the physics of energy transformations to build the Great Pyramids at Giza. They used ramps to push limestone blocks with an average mass of 2300 kg to heights of almost 150 m. The ramps were sloped at about 10° to the horizontal. Friction was reduced by pumping water onto the ramps.
 - How much work would have been done to lift an average limestone block vertically through a height of 150 m?
 - How much work would have been done to push an average limestone block to the same height along a ramp inclined at 10° to the horizontal? Assume that friction is negligible.
- A 60 kg bungee-jumper falls from a bridge 50 m above a deep river. The length of the bungee cord when it is not under tension is 30 m. Calculate the:
 - kinetic energy of the bungee-jumper at the instant that the cord begins to stretch beyond its natural length
 - strain energy of the bungee cord at the instant that the tip of the jumper's head touches the water. (Her head just makes contact with the water before she is pulled upwards by the cord.) The height of the bungee-jumper is 170 cm.
- Use the ideas presented in this topic to explain why:
 - dashboards of cars are padded
 - cars are deliberately designed to crumple at the front and rear
 - the compulsory wearing of bicycle helmets has dramatically reduced the number of serious head injuries in bicycle accidents.

A single answer (rather than three separate answers) is acceptable.

7.5 Exercise 3: Exam practice questions

Question 1 (9 marks)

Two ice skaters, Melita and Dean, are performing an ice dancing routine in which Dean (with a mass of 70 kg) glides smoothly at a velocity of 2.0 m s^{-1} due east towards a stationary Melita (with a mass of 50 kg), holds her around the waist, and then they both move off together. During the whole move, no significant frictional force is applied by the ice.

- What is Dean's momentum before making contact with Melita? **2 marks**
- Where is the centre of mass of the system comprising Dean and Melita 3.0 s before impact? **2 marks**
- What is the velocity of the centre of mass of the system before impact? **2 marks**
- Calculate the common velocity of Melita and Dean immediately after impact. **1 mark**
- What impulse is applied to Melita during the collision? **2 marks**

Question 2 (5 marks)

A car travelling at 60 km h^{-1} collides with a large tree. The front crumple zone folds, allowing the car to come to a complete stop over a distance of 70 cm. The driver, of mass 70 kg, is wearing a properly fitted seatbelt. As a result, the driver's body comes to rest over the same distance as the rest of the car behind the crumple zone.

- a. Determine the amount of work done by the seatbelt in stopping the driver. **2 marks**
- b. What is the magnitude of the average force applied to the driver by the seatbelt? **1 mark**
- c. Estimate the magnitude of the force that would be exerted by the front interior of the car on an unrestrained driver in the same accident. Assume that the driver does not crash through the windscreen. **2 marks**

Question 3 (5 marks)

Estimate the gravitational potential energy of the following objects.

- a. The roller-coaster (as shown in the following image) when it is at the top of the loop, with reference to the bottom of the loop **1 mark**
- b. The high jumper (as shown in the following image) with reference to the ground **1 mark**
- c. This textbook with reference to the floor **1 mark**
- d. A tennis ball about to be hit during a serve with reference to the ground **1 mark**
- e. A 20-storey building with reference to the ground **1 mark**



Question 4 (7 marks)

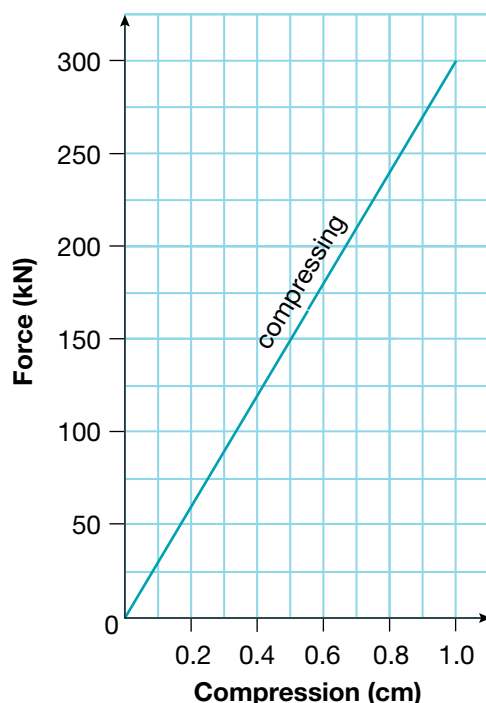
Angela rides a toboggan down a slope inclined at 30° to the horizontal. She starts from rest and rides a distance of 25 m down the slope. Angela and her toboggan have a combined mass of 60 kg.

- a. How much work is done on Angela by the force of gravity? **2 marks**
- b. If friction is negligible, what would her speed be at the end of her ride? **2 marks**
- c. How much work is done on Angela by the normal reaction? **1 mark**
- d. In reality, the frictional force on Angela is not negligible. Her speed at the end of her ride is measured to be 7.2 m s^{-1} . What is the magnitude of the frictional force? **2 marks**

Question 5 (5 marks)

The following graph shows how the force applied by the rubber bumper at the front of a 450 kg dodgem car changes as it is compressed during factory testing.

- a. If the dodgem car collides head-on with a solid wall at a speed of 2.0 m s^{-1} , what will be the maximum compression of the front rubber bumper? **3 marks**
- b. How much work is done on the dodgem car by the rubber bumper as it is compressed? **1 mark**
- c. If the rubber bumper obeys Hooke's Law, with what speed will the dodgem car rebound from the wall? **1 mark**



Question 6 (9 marks)

A car of mass 1500 kg travelling due west at a speed of 20 m s^{-1} on an icy road collides with a truck of mass 2000 kg travelling at the same speed in the opposite direction. The vehicles lock together after impact.

- What is the velocity of the tangled wreck immediately after the collision? **2 marks**
- Use your answer to part (a) to determine what impulse is applied to the truck during the collision. **2 marks**
- Which vehicle experiences the greatest (in magnitude) change in velocity? **2 marks**
- Which vehicle experiences the greatest change in momentum? **2 marks**
- Which vehicle experiences the greatest force? **1 mark**

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8 Special relativity

8.1 Overview

Numerous **videos** and **interactivities** are available just where you need them, at the point of learning, in your digital formats, learnON and eBookPLUS at www.jacplus.com.au.

8.1.1 Introduction

Newton's laws of motion revolutionised humanity's understanding of the movement of bodies, gravity and motion. For almost 200 years, they remained unchallenged as some of the most elegant theories the world had ever seen. However, over the course of the nineteenth and twentieth centuries, scientists' understanding of concepts such as electromagnetism improved, which Newton's laws were not able to fully explain.

FIGURE 8.1 The velocity of a yacht can be measured relative to wind, land, water or other yachts, and all of these measurements can be different.



Albert Einstein built on the work of many scientists before him and used ‘thought experiments’ to show that space and time are not absolute but, rather, relative to the physical environment. Einstein was named *Time Magazine*’s ‘Person of the Century’ in 1999. Not only was he a great humanitarian, having fought for the rights of Jewish and Arab people (after he escaped Nazi Germany) and for the rights of African Americans, but his work on relativity changed the way scientists understand the universe. Topic 8 will introduce you to modern physics and an even better understanding of the workings of the universe.

8.1.2 What you will learn

KEY KNOWLEDGE

After completing this topic, you will be able to:

- describe Einstein’s two postulates for his Theory of Special Relativity, which state that
 - the laws of physics are the same in all inertial (non-accelerated) frames of reference
 - the speed of light has a constant value for all observers regardless of their motion or the motion of the source.
- compare Einstein’s Theory of Special Relativity with the principles of classical physics
- describe proper time (t_0) as the time interval between two events in a reference frame where the two events occur at the same point in space
- describe proper length (L_0) as the length that is measured in the frame of reference in which objects are at rest
- model mathematically time dilation and length contraction at speeds approaching c using the equations:

$$t = t_0 \gamma \text{ and } L = \frac{L_0}{\gamma} \text{ where } \gamma = \left(1 - \frac{v^2}{c^2}\right)^{-\frac{1}{2}}$$

- explain why muons can reach Earth even though their half-lives would suggest that they should decay in the outer atmosphere
- interpret Einstein’s prediction by showing that the total ‘mass–energy’ of an object is given by: $E_{\text{tot}} = E_k + E_0 = \gamma mc^2$, where $E_0 = mc^2$, and where kinetic energy can be calculated by: $E_k = (\gamma - 1) mc^2$
- describe how matter is converted to energy by nuclear fusion in the Sun, which leads to its mass decreasing and the emission of electromagnetic radiation.

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Resources



Digital documents Key science skills — VCE Units 1–4 (doc-32112)

Key terms glossary (doc-32295)



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8.2 Einstein's Theory of Special Relativity

KEY CONCEPTS

- Describe Einstein's two postulates for his Theory of Special Relativity, which state that
 - the laws of physics are the same in all inertial (non-accelerated) frames of reference
 - the speed of light has a constant value for all observers regardless of their motion or the motion of the source.
- Compare Einstein's Theory of Special Relativity with the principles of classical physics.

8.2.1 What is relativity?

Newton's laws held that all observers, regardless of their location and the nature of their motion, were the same in terms of what they observed in the world around them. However, today it is understood that the measurement of the speed of an object depends on the **relative** motion of the observer. So do the measurements of the object's time, kinetic energy, length and mass; that is, these properties are relative rather than fixed. Albert Einstein discovered that some of the physical properties that people assumed to be fixed for all observers actually depend on the observers' motions. But not everything is relative. The laws of physics and the speed of light are the same for all observers. Major developments in physics have come about at times when physicists such as Galileo and Einstein developed a clearer understanding of what is relative and what is not.

Albert Einstein (1879–1955) is one of the most famous figures in history, largely due to his work on relativity. Einstein did not invent the idea of relativity — it dates back to Galileo — but he brought it into line with nineteenth-century developments in the understanding of light and electricity, leading to some striking changes in how physicists viewed the world. In this topic, you will look at the first revolution in relativity, then explore some of the ideas of Einstein's Theory of Special Relativity.

FIGURE 8.2 Albert Einstein (1879–1955)



There is no rest

Let's start with a theoretical scenario. Consider a police officer pointing her radar gun at an approaching sports car from her car parked on the roadside. She measures the sports car's speed to be 90 km h^{-1} . This agrees with the speed measured by the driver of the sports car on his car's speedometer. However, another police car drives towards the sports car in the opposite direction at 60 km h^{-1} . A speed radar is also operating in this car, and it measures the speed of the sports car to be 150 km h^{-1} . So each police officer has a different measurement for the speed of the sports car. Which measurement is correct? The answer is that they are both correct — the speed measured for the car is measured relative to the velocity of the observer — but only the speed measured by the officer at rest on the roadside is relevant when a speeding ticket is issued.

FIGURE 8.3 Two different measurements of the speed of a car



The sports car is approaching the oncoming police car at the same rate as if the police car was parked and the sports car had a reading of 150 km h^{-1} on its speedometer. The speed of the car is relative to the observer, rather than being an absolute quantity agreed on by all observers.

Newton's First Law of Motion states that an object will continue at constant velocity unless acted on by an unbalanced net force. The speed itself does not matter. In the example shown in figure 8.3, this law works for both of the police officers, as do the other laws of motion.

FIGURE 8.4 A speed limit is the maximum allowed speed relative to the road.



FIGURE 8.5 The radar gun would measure a different speed if it was in a moving vehicle.



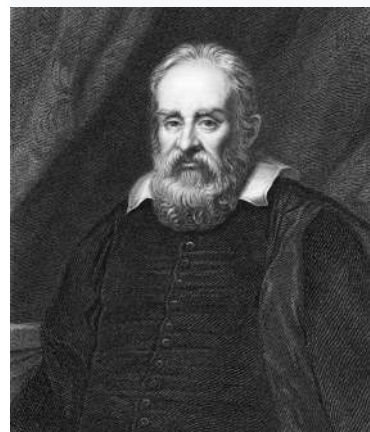
Source: Alan Porritt/AAP Image

The significance of relative speed becomes all too clear in head-on collisions. For example, you might be driving at only 60 km h^{-1} , but if you collide head-on with someone doing the same speed in the opposite direction, the impact occurs for both cars at 120 km h^{-1} ; if one car was stationary, the impact would occur at 60 km h^{-1} for both.

The Italian scientist Galileo Galilei (1564–1642) did not know about police cars and speed limits. His examples featured sailing ships and cannon balls, but the physics ideas were the same. In Galileo's time, much of physics was still based on ancient ideas recorded by the Greek philosopher Aristotle (384–322 BC). Aristotle taught that the Earth was stationary in the centre of the universe. Motion relative to the centre of Earth was a basis for Aristotelian physics, so a form of relativity was key to physics even before Galileo. But Galileo had to establish a new understanding of relativity before it became widely accepted that the Earth moved around the Sun.

Galileo's insight helped provide the platform for physics as it is known today, but the idea of a fixed frame of reference persisted. Following on from Galileo, Isaac Newton considered the centre of mass of the solar system to be at absolute rest. James Clerk Maxwell (1831–1879), who put forward the theory of electromagnetism, regarded the medium for electromagnetic waves (light) to be at rest. It was Einstein who let go of the concept of absolute rest, declaring that it was impossible to detect a place at absolute rest and therefore the idea had no

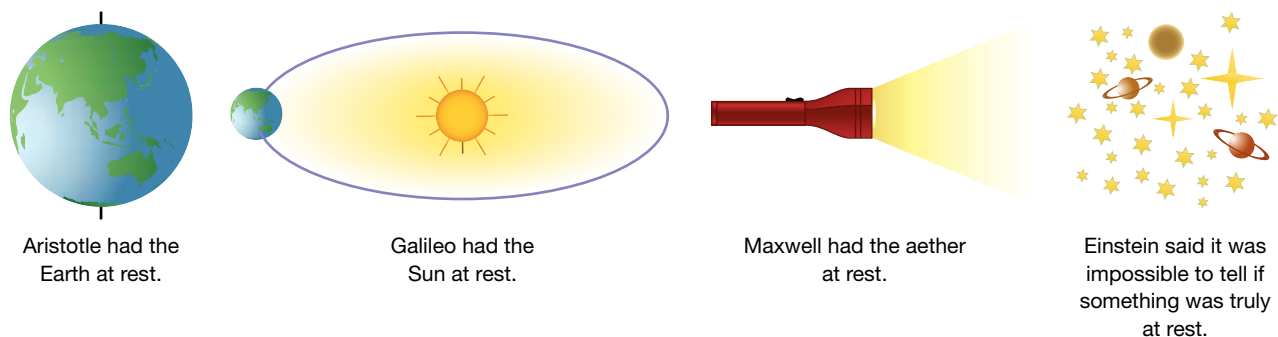
FIGURE 8.6 Galileo Galilei (1564–1642), from a nineteenth-century engraving



consequence. Once again, ideas about relativity were updated to take into account the latest discoveries and enable physics to make enormous leaps of progress.

The measured speed (velocity) of bodies in motion is truly relative to whoever is measuring it. You will return to Einstein's advances shortly, but it's now time to look at some more examples from Galilean relativity.

FIGURE 8.7 What should speed be measured relative to?



Galileo and the principle of relativity

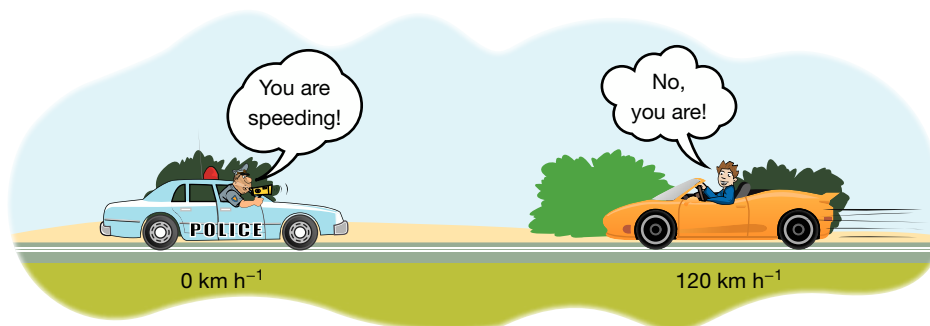
Consider the driver of the sports car discussed earlier. His position relative to features of the landscape he drives through is continuously changing, but inside the car life goes on as normal. He has the same position relative to the car, the size of the force due to gravity on him is unchanged, and his mass and height have the same measured value as when he was stationary. Everything inside the car behaves just as he remembers it from when the car was parked. On a smooth road at constant speed, his passenger could pour a drink without difficulty. The effect of the bumps in the road would be indistinguishable from a situation in which the car was stationary and someone outside was rocking it. Therefore, even when a car is driving at a different constant velocity (for example, at 150 km h^{-1}), the driver would not experience any difference compared to when he was driving at a constant velocity of 90 km h^{-1} .

Nothing inside a vehicle moving with constant velocity can be affected by the magnitude of the velocity. If it was, the following question would need to be asked: which velocity? If a velocity of 90 km h^{-1} caused a passenger to have a mass of 50 kg , but a velocity of 150 km h^{-1} caused the passenger to have a mass of 60 kg , a problem would exist. The driver cannot simultaneously observe his passenger to have two different masses.

This is known as the Theory of Special Relativity. The Theory of Special Relativity states that the laws of physics do not depend on the velocity of the observer. Galileo played a major role in the development of relativity, and Newton's laws of motion are fully consistent with it. Another way of describing relativity is that there is no way that anyone in the car can measure its velocity without making reference to something external to the car. The sports car driver can measure his speed relative to the two police officers mentioned earlier. He would measure that he is moving relative to each of them at different speeds, but he would not feel any difference. As long as the road is straight and smooth and the car is travelling at a constant speed, there is no way to detect that the car is moving at all! He could be stationary while one police car is approaching him at 90 km h^{-1} and the other at 150 km h^{-1} .

Even on an aeroplane travelling smoothly at 700 km h^{-1} , travellers feel essentially the same as they do at rest. The only giveaway is the turbulence the aircraft experiences and the change in air pressure in the travellers' ears (particularly during ascent and descent). Neither of these effects is dependent on the forward velocity of the plane. The laws of physics are the same: you can pour your can of drink safely, walk down the aisle, and drop a pencil and notice it fall vertically to the floor just as it would if you were on the ground.

FIGURE 8.8 How can the vehicle that is actually speeding be identified?



By introducing the principle of relativity, Galileo provided the necessary framework for important developments in physics. Physics builds on the premise that the universe follows some order that can be expressed as a set of physical laws. The Aristotelian ideas that were held at the time of Galileo suggested that a force is necessary to keep objects moving. This led to one of the major arguments against Earth's motion around the Sun: everyone would be hurled off the Earth's surface as it hurtled through space, and the Moon would be left behind rather than remaining in orbit around Earth. Galileo's physics, including the principle of relativity, helped to explain why this argument was wrong. Forces are not required to keep objects moving, only to change their motion.

The science of Galileo and Newton was spectacularly successful: it explained the motion of everything from cannon balls to planets. Later, however, as new theories of physics developed in the nineteenth century, physicists faced the challenge of how to make everything fit together. It was not until the early twentieth century that Einstein found a way to make sense of it all.

Examples of Galilean relativity

Here are some examples that support the Galilean principle of relativity:

1. If you are in a car stopped at the lights and another car next to yours slowly rolls past, it is difficult to tell whether you or the other car is moving if nothing but the other car is in view.
2. In IMAX and similar films, viewers can feel as though they are going on a thrilling ride, even though they are actually sitting on a fixed seat in a cinema. Theme parks enhance this effect in virtual reality rides by jolting the chairs in a way that mimics movements you would feel on a real ride. Virtual reality rides are very convincing because what you see and feel corresponds with an expected movement, and your senses do not tell you otherwise. As long as the jolts correspond with the visual effects, there is no way of telling the difference. The motion or lack of motion of the seat is irrelevant.
3. Acceleration does not depend on the velocity of the observer. An astronaut in a spacecraft travelling through deep space with constant velocity feels weightless, regardless of the magnitude of the velocity. She moves along with the same velocity as the spacecraft, as Newton's first law would suggest. When the spacecraft accelerates due to the force of its rocket engines, the force on the person by the rocket is in the forward direction. The effect of the acceleration on the astronaut is noticeable, and may even cause the astronaut to lose consciousness if the acceleration is too great.
4. When you are riding in a car with the window down, most of the wind you feel on your face is due to the motion of the car through the air. It is present even on a still day. Only very severe winds exceed 60 km h^{-1} ; whenever you drive at greater than 60 km h^{-1} , your windscreen is saving you from

FIGURE 8.9 A virtual reality ride

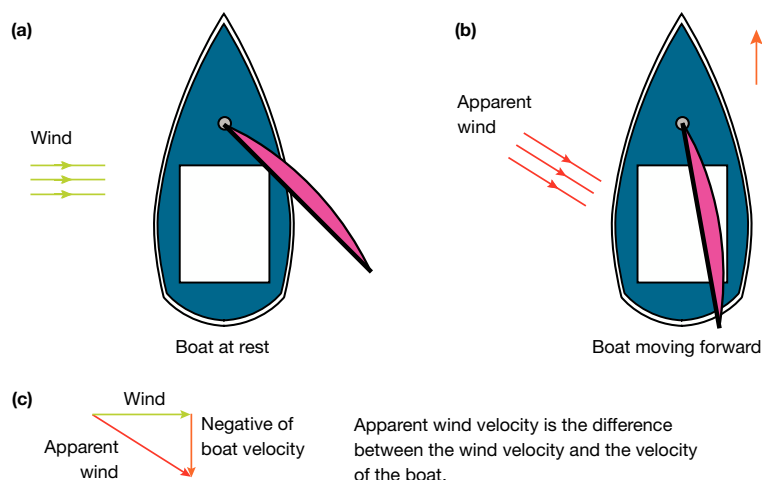


Source: News Ltd/Newspix

gale-force winds! Similarly, it is always windy on moving boats. This is because on deck you are not as well protected from the apparent wind as you are in a car.

- Apparent wind becomes especially significant when sailing, as seen in figure 8.10. As the boat increases its speed, the sailor notices that he is heading more into the wind, even though neither he nor the wind has changed direction relative to the shore. This leads the sailor to change the sail setting to suit the new wind direction.

FIGURE 8.10 The faster the boat moves, the more the wind appears to blow from in front.



SAMPLE PROBLEM 1

Determine the relative velocity in each of the three scenarios and compare each scenario in terms of velocity.

- A car travelling down the highway at 80 km h^{-1} collides with a stationary car.
- A car travelling down the highway at 100 km h^{-1} collides with a car travelling at 20 km h^{-1} in the same direction.
- A car travelling down the highway at 100 km h^{-1} collides with a car travelling at 20 km h^{-1} in the opposite direction.

Teacher-led video: SP1 (tlvd-0171)

THINK

- To determine the relative velocity, you need to consider that the velocity of the first car (car A) relative to the second car (car B) is shown using the formula

$$v_{A \text{ relative to } B} = v_A - v_B$$

and that the direction of movement is positive.

- Provide a comparison of the relative velocities in each scenario.

WRITE

Scenario 1

$$v_A - v_B = 80 - 0 = 80 \text{ km h}^{-1}$$

Scenario 2

$$v_A - v_B = 100 - 20 = 80 \text{ km h}^{-1}$$

Scenario 3

$$v_A - v_B = 100 - (-20) = 120 \text{ km h}^{-1}$$

Although in each case the velocities relative to the road are different, the relative velocities of the cars in scenarios 1 and 2 are the same and will cause similar effects upon colliding. When examining scenarios 2 and 3, the cars are travelling at the same speeds but in opposite directions, and therefore the relative velocities are different and there will be different effects upon the cars colliding.

PRACTICE PROBLEM 1

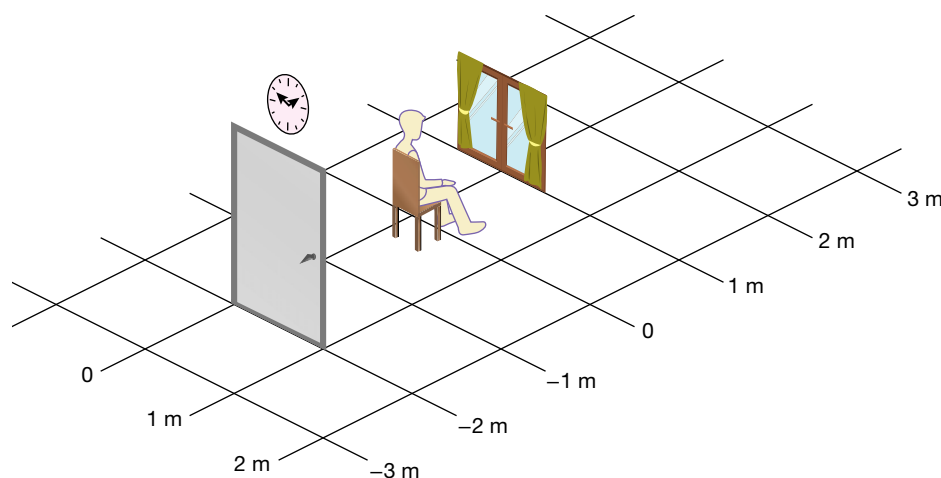
According to Galilean relativity, which one (or more) of the following is relative?

- a. acceleration
- b. velocity
- c. time
- d. mass

8.2.2 Frames of reference

To help make sense of all the possible velocities, physicists consider frames of reference. A frame of reference involves a system of coordinates. For example, where you are sitting reading this book, you view the world through your frame of reference. You can map the position of things around you by choosing an origin (probably the point where you are), then noting where everything else is in reference to that: the window is one metre in front of you, the door is two metres behind you, and so on. Your reference frame also includes time, so you can see that the position of the window in front of you is not changing and you can therefore say its velocity is zero.

FIGURE 8.11 A reference frame is a set of space and time coordinates that are stationary relative to an observer.



When something is said to be ‘at rest’, it is at rest in the reference frame in which the observer views the world. In everyday life, there is a tendency to take a somewhat Aristotelian point of view and regard everything from the perspective that the Earth is at rest. For example, another student walking behind you has her own reference frame. As she walks, your position in her frame of reference is moving. However, she could say that she is moving past you while you are stationary, rather than saying that she is stationary while you and the rest of the room are on the move!

In many situations, considering the Earth to be at rest is a convenient assumption. In more complex examples of motion, such as sports events, car accidents involving two moving vehicles, or the motions of the solar system, it can be useful to choose alternative frames of reference.

In classical physics, the differences between frames of reference are their motion and position. (‘Classical physics’ is the physics that predated Einstein’s discoveries leading to the laws of relativity and quantum mechanics.) In other words, position and speed are relative in classical physics. For example, one person might record an object to have a different position than a second person would (it might be three metres in front of the first person but four metres behind the second), and the first person might also record it as having a different speed (maybe it is stationary in their frame of reference but approaching the second person at 2 m s^{-1}). The position and speed are dependent on the observer. However, in classical physics all observers can agree on what three metres and 2 m s^{-1} are. The rulers in the first person’s frame of

reference are the same as the ones they see in the second person's, and the clocks in the first person's frame of reference tick at the same rate as they measure those ticking in the second person's. Time and space are seen as absolute in the classical physics established by Galileo, Newton and the other early physicists.

Frames of reference that are not accelerating are called **inertial reference frames**. An inertial reference frame moves in a straight line at a constant speed relative to other inertial reference frames.

An **invariant** quantity is a quantity that has the same value in all reference frames. In classical physics, mass is the same in all reference frames, so all observers will observe that Newton's second law holds. In sample problem 2, all observers would agree on the forces acting on the astronauts. Unlike velocity, acceleration in Galilean relativity does not depend on the motion of the frame of reference; it is also invariant.

SAMPLE PROBLEM 2

Consider the reference frame in which a spacecraft is initially at rest (reference frame A). Effie is positioned in another reference frame (reference frame B). Astronaut Axel is in the spacecraft and he fires its rockets for 10 s, achieving a final velocity of 100 m s^{-1} . Show that the acceleration of the rocket does not depend on the reference frame.

THINK

1. Calculate the acceleration of the rocket in reference frame A.

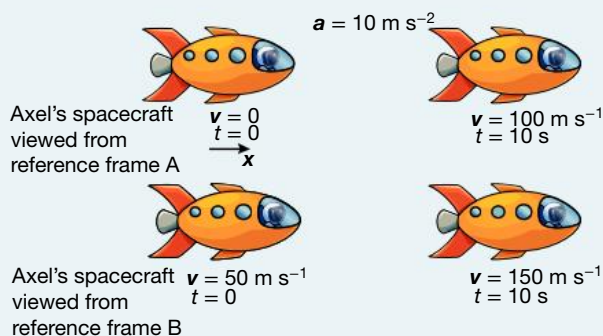
WRITE

According to the measurements made in A, the rocket accelerated for 10 s at:

$$\begin{aligned} a &= \frac{\Delta v}{t} \\ &= \frac{100 - 0}{10} \\ &= \frac{100}{10} \\ &= 10 \text{ m s}^{-2} \end{aligned}$$

2. Now choose a different reference frame. Effie is in reference frame B in another spacecraft, moving at 50 m s^{-1} relative to A.

Axel would feel a force in the forward direction.



3. Calculate the acceleration of the rocket in reference frame B.

Effie measures the velocity of Axel's spacecraft to change from 50 m s^{-1} to $(50 + 100) \text{ m s}^{-1}$ in 10 s. From B:

$$\begin{aligned} a &= \frac{\Delta v}{t} \\ &= \frac{150 - 50}{10} \\ &= \frac{100}{10} \\ &= 10 \text{ m s}^{-2} \end{aligned}$$

4. Compare the acceleration of the rocket in both reference frames.

The acceleration is the same whether it is measured from frame A or frame B. It will still be 10 m s^{-2} regardless of the speed of the reference frame.

PRACTICE PROBLEM 2

- a. Explain what is meant by the statement 'speed is relative to the frame of reference'.
b. By referring to Newton's laws of motion, explain why it is important for acceleration to be invariant but that velocity can be relative.

In sample problem 2, it is interesting to consider the motion of Axel's spacecraft as viewed by Effie in reference frame B. Reference frame B is in an inertial reference frame as it is not accelerating. Axel, however, looks back at Effie and sees her falling behind at an increasing rate. Is it Axel or Effie that is accelerating? The answer is clear to them: the force experienced by Axel is not felt by Effie. The acceleration can be measured by this force without any reference to the relative motions of other objects; an object's velocity cannot.

8.2.3 Comparing Einstein's theories to earlier principles

Galilean relativity seemed to work well for the motion of massive bodies but, by the nineteenth century, physicists were learning much more about other physical phenomena.

In 1865, James Clerk Maxwell's theory of electromagnetism drew together the key findings of electricity and magnetism to completely describe the behaviour of electric and magnetic fields using a set of four equations. One of the outcomes of this was an understanding of electromagnetic waves. The equations dictated the speed of these waves, and Maxwell noticed that this speed was the same as the speed that had been measured for light. He suggested that light was an electromagnetic wave and predicted the existence of waves with other wavelengths that were soon discovered, such as radio waves. A medium for these fields and waves was proposed, called the luminiferous aether. The speed of light, c , was the speed of light relative to this aether.

The understanding was that if light moves through the aether, then the Earth must also be moving through the aether. Changes in the speed of light as the Earth orbits the Sun should be detectable. Maxwell predicted that electromagnetic waves would behave like sound and water waves in that the speed of electromagnetic waves in the medium would not depend on the motion of the source or the detector through the medium.

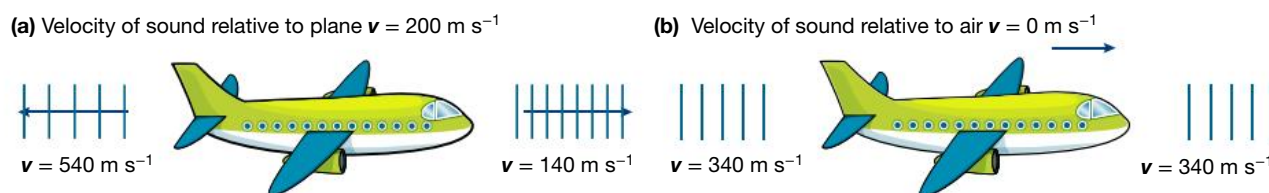
To understand the significance of this aether, consider the sound produced by a jet plane. When the plane is stationary on the runway preparing for takeoff, the sound travels away from the plane at the speed of sound in air, about 340 m s^{-1} . When the plane is flying at a constant speed, say 200 m s^{-1} , the speed

of sound is still 340 m s^{-1} in the air. However, to find the speed relative to the reference frame of the plane, the speed of the plane relative to the air must be subtracted. From this it is found that the sound is travelling at:

$$340 - 200 = 140 \text{ m s}^{-1} \text{ in the forward direction relative to the plane}$$

$$340 - (-200) = 540 \text{ m s}^{-1} \text{ in the backward direction relative to the plane.}$$

FIGURE 8.12 Sound moving away from a plane



In this example, the speed of the plane through the air could be measured by knowing the speed of sound in air (340 m s^{-1}) and measuring the speed of a sound sent from the back of the plane to the front (140 m s^{-1}) in the reference frame of the plane. As long as the plane is flying straight, the speed of the plane relative to the air can be inferred by setting the forward direction as positive and subtracting the velocities:

$$340 - 140 = 200 \text{ m s}^{-1}$$

The speed of the plane has been measured relative to an external reference frame, that of the air, and therefore this example has not violated Galilean relativity. As light had been shown to travel in waves, scientists felt they should be able to measure Earth's speed through the aether in the same way.

SAMPLE PROBLEM 3

Explain how Maxwell's concept of electromagnetic waves such as light challenged the Galilean principle of relativity.

 **Teacher-led video:** SP3 (tlvd-0173)

THINK

The principle of relativity states that the laws of physics hold true in all inertial reference frames.

WRITE

Galileo proposed that all inertial frames of reference are equally valid. Maxwell's concept of electromagnetic waves suggested the presence of an absolute frame of reference — the luminiferous aether. That is, observers moving relative to the aether should experience light at different velocities, and therefore not all inertial frames of reference are equally valid, as stated by Galileo.

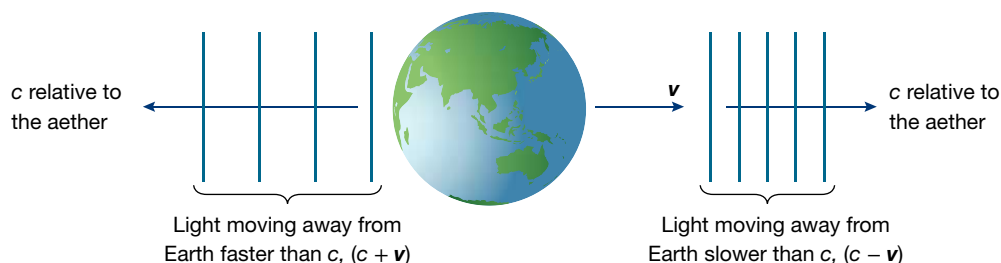
PRACTICE PROBLEM 3

Assuming that electromagnetic waves travel at c relative to the aether, determine the speed of light shining from the rear of a spacecraft that is moving at half the speed of light relative to the aether.

The Michelson–Morley experiment

In 1887, Albert Michelson and Edward Morley devised a method of using interference effects to detect slight changes in the time taken for light to travel through different paths in their apparatus. As with sound travelling from the front and rear of a plane through the air, the light was expected to take different amounts of time to travel in different directions through the luminiferous aether as the Earth moved through it. Much to their astonishment, the predicted change in the interference pattern was not observed. It was as though the speed of light was unaffected by the motion of the reference frame of its observer or its source!

FIGURE 8.13 The idea behind the Michelson–Morley experiment



Resources



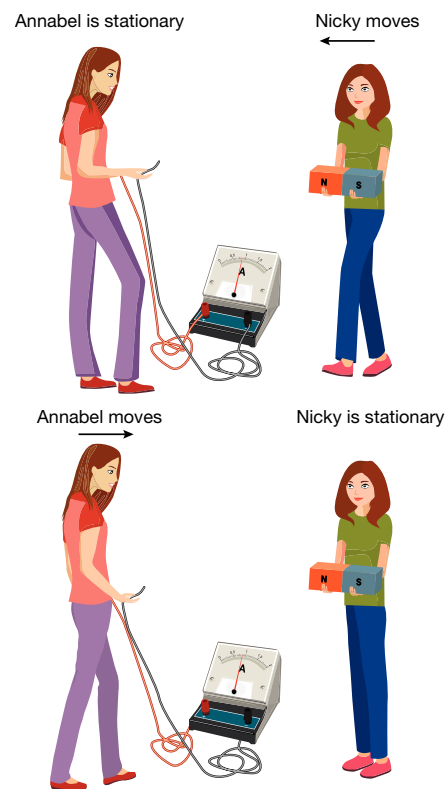
Video eLesson Michelson–Morley experiment (eles-2561)

Developing Einstein's Theory of Special Relativity

Understanding electromagnetic phenomena was the foundation for Einstein's special relativity. In particular, the physicists of the nineteenth century, such as Michael Faraday, knew that they could induce a current in a wire by moving a magnet near the wire. They also knew that if they moved a wire through a magnetic field, a current would be induced in the wire. They saw these as two separate phenomena.

Imagine this: two students are in different physics classes. Annabel has learned in her class that electrons moving in a magnetic field experience a force perpendicular to their direction of motion and in proportion to their speed. Her friend Nicky has learned in her class that a current is induced in a loop of wire when the magnetic flux through the wire changes. Are these two different phenomena? Because they have also learned about the principle of relativity, Annabel and Nicky have doubts. They get together after class to perform experiments. The force depends on the speed. Annabel holds a stationary loop of conducting wire. Nicky moves the north pole of a magnet towards the loop, and they notice that a current is present in the wire as she does this. Nicky says that this is consistent with what she has learned. The conclusion is that a current is induced by a changing magnetic field. Then Nicky holds the magnet still so that the magnetic field is not changing. Annabel moves her loop of wire towards Nicky's magnet. Annabel states that the result agrees with what she learned in class — that electrons and other charged particles experience a force when moving in a magnetic field.

FIGURE 8.14 An experiment in electromagnetism



Einstein realised that there was only one phenomenon at work here. Both experiments are doing exactly the same thing, and it is only the relative speeds of the coil and the magnet that are important. This may seem obvious, but to make this jump it was necessary to discard the idea that the electric and magnetic fields depended on the luminiferous aether. It was the relative motion that was important, not whether the magnet or charge was moving through the aether.

8.2.4 Einstein's two postulates of special relativity

Physicists tried all sorts of experiments to detect the motion of Earth through the luminiferous aether, and they attempted to interpret the data in ways that would match the behaviour of light with what they expected would happen. Their attempts were unsuccessful.

Einstein managed to restore order to our understanding of the universe. While others suspected the new theory of electromagnetism to be wrong, Einstein took apart the established theory of Newtonian mechanics, even though its success had given physicists reason to believe in relativity in the first place. Einstein dared to see what would happen if he embraced the results of the Maxwell equations and the experiments with light, and accepted that the speed of light was invariant. The results were surprising and shocking, but this bold insight helped usher in the modern understanding of physics.

Einstein agreed with Galileo that the laws of physics must be the same for all observers, but he added a second requirement: that the speed of light in a vacuum is the same for all observers. The speed of light is invariant and does not differ in different reference frames. He set these two principles down as requirements for the development of theoretical physics. They are known as Einstein's two postulates of special relativity.

Einstein's postulates state that:

- 1. The laws of physics are the same in all inertial (non-accelerated) frames of reference.**
- 2. The speed of light has a constant value for all observers regardless of their motion or the motion of the source.**

The physics based on these postulates has become known as special relativity. It is 'special' because it deals with the special case of uniform (non-accelerating) motion. To deal with gravity and acceleration, Einstein went on to formulate his Theory of General Relativity, but that is beyond the scope of this course.

Einstein's postulates were radical. Ideas that had been taken for granted for centuries had to be completely reconsidered, as their limitations became more obvious with the development of Einstein's postulates. As well as the removal of the luminiferous aether, the intuitive notions that time passed at the same rate for everyone, that two simultaneous events would be simultaneous for all observers, and that distance and mass are the same for all observers had to be discarded.

Einstein's work explained why the velocity of Earth with respect to the aether could not be detected. His first postulate implied that there is no experiment that can be done on Earth to measure the speed of Earth. An external reference point must be taken, and the speed of Earth must be measured relative to that point in order for the speed of Earth to have any meaning. With his second postulate, Einstein also declared that it does not matter in which direction the Michelson–Morley apparatus was pointing in; the light would still travel at the same speed. No change in the interference pattern should be detected when the apparatus was rotated.

SAMPLE PROBLEM 4

How do Einstein's postulates differ from the physics that preceded them?

 **Teacher-led video:** SP4 (tlvd-0174)

THINK

1. Consider Einstein's first postulate, in which the laws of physics are the same in all inertial frames of reference.
2. Consider Einstein's second postulate, in which the speed of light has a constant value for all observers regardless of their motion.

WRITE

Firstly, the principle of relativity is applied to all laws of physics, not just the mechanics of Galileo and Newton.

Secondly, the speed of light is constant for all observers. Before Einstein, the speed of light was assumed to be relative to its medium, the luminiferous aether.

PRACTICE PROBLEM 4

Einstein realised that measurements that had been regarded as relative (or changing depending on the motion of the observer) were actually invariant. As a result of this, measurements that had been regarded as invariant now had to be regarded as relative. What did he find to be invariant and what relative?

Broadening the horizons of understanding

Why did scientists before Einstein (and most people after Einstein) not notice the effects of light speed being invariant? Newton's laws provided a very good approximation for the world experienced by people before the twentieth century. By the beginning of the twentieth century, however, physicists were able to take measurements with incredible accuracy. They were also discovering new particles, such as electrons, that could travel at extremely high speeds. Indeed, these speeds were completely outside the realm of human experience. Light travels at $c = 3.0 \times 10^8 \text{ m s}^{-1}$ or $300\,000 \text{ km s}^{-1}$. (To be precise, $c = 299\,792\,458 \text{ m s}^{-1}$.) At this speed, light covers the distance to the Moon in roughly 1.3 seconds!

Note: When considering speeds at a significant fraction of the speed of light, it is easier to use the speed of light as the unit. For example, instead of $1.5 \times 10^8 \text{ m s}^{-1}$, a physicist can simply write $0.5c$.

SAMPLE PROBLEM 5

To get a sense of how fast light travels, Andrei considers how long it would take to accelerate from rest to a tenth of this great speed at the familiar rate of 9.8 m s^{-2} — the acceleration of an object in free fall near the surface of Earth. Calculate how long it would take to reach this speed.

 **Teacher-led video:** SP5 (tlvd-0175)

THINK

1. List the known information.
2. As acceleration is constant, use the relationship $v = u + at$ to determine the time taken for an object to accelerate from rest to a speed that is a tenth of the speed of light.

WRITE

$$u = 0 \text{ m s}^{-1}, v = 0.1c = 3.0 \times 10^7 \text{ m s}^{-1}, a = 9.8 \text{ m s}^{-2}, t = ?$$

$$v = u + at$$

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

$$= \frac{3.0 \times 10^7 - 0}{9.8}$$

$$= 3.06 \times 10^6 \text{ seconds}$$

$$= 35.4 \text{ days}$$

It would take more than 35 days to achieve a speed of $0.1c$!
(This is the fastest speed for which use of Newtonian kinematics still gives a reasonable approximation.)

PRACTICE PROBLEM 5

With an acceleration of 9.8 m s^{-2} , occupants of a spacecraft in deep space would reassuringly feel the same force due to gravity that they feel on Earth. What would happen to the astronauts if the acceleration of the spacecraft was much greater, to enable faster space travel?

Light speed really is beyond our normal experience! Maybe Einstein's predictions would not be so surprising if people had more direct experience with objects travelling at great speeds but, as it is, they seem very strange.

AS A MATTER OF FACT

The distance light travels in a year is known as a light-year. Even on Earth, distance is now measured in terms of the speed of light. One metre is defined as the distance light travels in exactly $\frac{1}{c} = \frac{1}{299\,792\,458}$ of a second.

The speed of light is constant

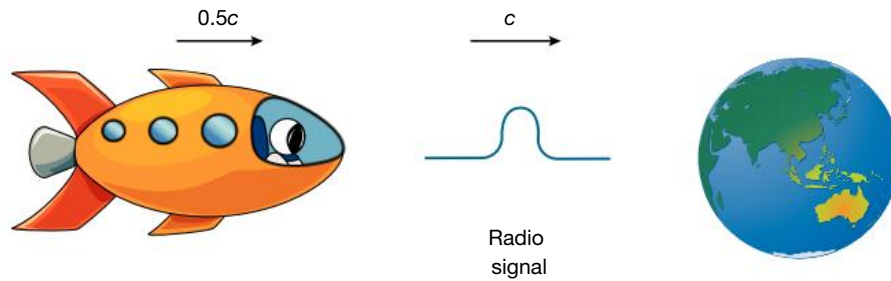
This simple statement of Einstein's second postulate may not seem remarkable. To highlight what it means, light will again be compared with sound. In the nineteenth century, sound and light were thought to have a lot in common, because they both exhibited similar wavelike behaviours, such as diffraction and interference. However, sound is a disturbance of a medium, whereas light does not require any medium at all. Sound has a speed that is relative to its medium. If the source of the sound is moving through the medium, then the speed of the sound relative to the source is different to the speed of sound relative to the medium. Its speed can be different again for an observer depending on the reference frame.

Einstein was saying there is no medium for light, so the concept of the speed of light relative to its medium is not meaningful. Light always moves away from its source at $299\,792\,458 \text{ m s}^{-1}$ and always meets its observer at $299\,792\,458 \text{ m s}^{-1}$, no matter what the relative speeds of the observer and the source. Even if the Earth were hurtling along its orbit at $0.9c$, the result of the Michelson–Morley experiment would have been the same.

As an example, consider a spacecraft in the distant future hurtling towards Earth at $0.5c$. The astronaut sends out a radio message to alert Earth of his impending visit. (Radio waves, as part of the electromagnetic spectrum, have the same speed as visible light.) He notices that, in agreement with the Michelson–Morley measurements of centuries before, the radio waves move away from the spacecraft at speed c . With what speed do they hit the Earth? Relative velocity, as treated by Galileo, insists that as the spacecraft already has a speed of $0.5c$ relative to the Earth, then the radio waves must strike the Earth at $1.5c$. However, this does not happen. The radio waves travel at speed c regardless of the motion of the source and the receiver.

This concept was very difficult for physicists to comprehend, and many resisted Einstein's ideas. But the evidence is irrefutable. Newtonian physics works as a very good approximation only for velocities much less than c . The faster something moves, the more obvious it is that the Newtonian world view does not match reality. It was not until the twentieth century that scientists investigated objects (such as cosmic rays) moving at great speeds. Many technologies and objects (such as satellites in orbit) need to be programmed according to Einsteinian physics rather than Newtonian classical physics.

FIGURE 8.15 A spacecraft approaching Earth at $0.5c$. The radio signal is travelling at c relative to both Earth and the spacecraft!

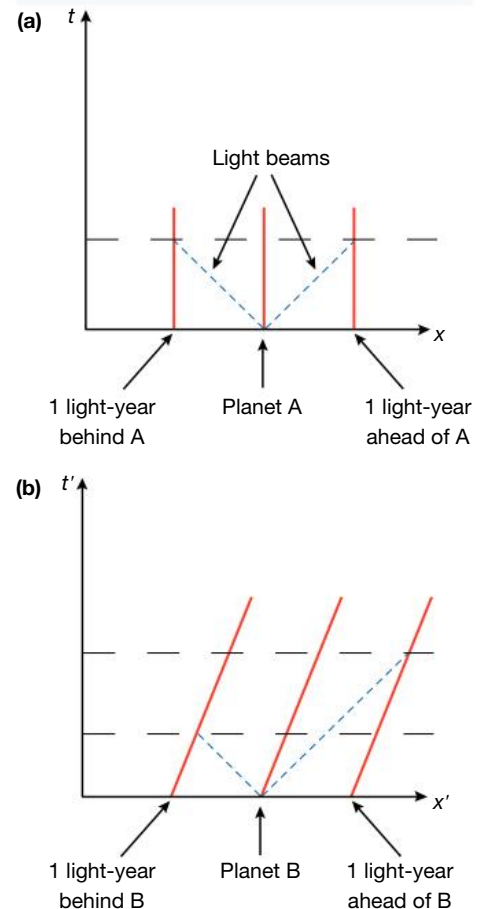


Space-time diagrams

In 1908, Hermann Minkowski invented a useful method of depicting situations similar to the spacecraft scenario just described. His diagrams are like distance–time graphs with the axes switched around. However, they differ from time–distance graphs in an important way. When reading these diagrams, the markings on the scales for time and position are only correct for the reference frame in which the axes are stationary. Straight lines are drawn diagonally outwards from the source, indicating the constant motion of the light away from the source over time.

Consider this scenario. Light reflecting from planet A radiates in all directions at c so that, after one year, the light that left the planet forms a sphere one light-year in radius. Another planet, B, passes planet A at great speed, just missing it. Light from planet B's surface also leaves at c , according to the second postulate, forming a sphere around it. However, from planet A's perspective, the light from planet B reaches a distance of one light-year behind planet B before it reaches a distance of one light-year ahead of planet B. Figure 8.16 shows examples of Minkowski diagrams for this scenario. Each diagram is drawn from planet A's reference frame. Diagram (a) shows the situation for planet A, and diagram (b) shows what is happening on planet B according to observers on planet A.

FIGURE 8.16 Minkowski diagrams from planet A's frame of reference



Simultaneity

Simultaneity is the relationship between two separate events that are assumed to be happening at the same time, in a particular reference frame. However, Einstein's Theory of Special Relativity shows that an event that is simultaneous in one frame of reference will not necessarily be simultaneous when viewed from another frame of reference. This is known as the relativity of simultaneity.

SAMPLE PROBLEM 6

Using figure 8.16, explain how both planets A and B can be at the centre of their light circles as the postulates demand.

 **Teacher-led video:** SP6 (tlvd-0176)

THINK

Use the diagrams to explain how both planets can be at the centre of their light circles as the postulates demand.

WRITE

Diagram (a) shows the situation for planet A. The light radiates in all directions at the same rate, and the diagram shows where the light in one direction and the opposite direction would be after one year.

Diagram (b) shows what is happening on planet B according to observers on planet A. The light moving out behind the moving planet reaches the one-light-year distance sooner than the light moving out from the front! But it is known that planet B is at the centre of this light circle. The way to achieve this is to move away from absolute space and time and understand that these are relative to the observer. When this is done, it is seen as possible for planet B to be at the centre of the light circle. However, this requires that A and B disagree about when two events occur. According to planet A, the different sides of the light circle reach the light-year radius at different times, but from planet B this must occur simultaneously.

PRACTICE PROBLEM 6

State whether the simultaneity of events is invariant or relative in:

- a. classical physics
- b. special relativity.

8.2 EXERCISE

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1. What do physicists mean when they say that velocity is relative?
2. What is a frame of reference?
3. Two cars drive in opposite directions along a suburban street at 50 km h^{-1} . What is the velocity of one car relative to the other?
4. Earth varies from motion in a straight line by less than 1° each day due to its motion around the Sun.
 - (a) Explain, with the help of the principle of relativity, why you do not feel Earth moving, even though it is travelling around the Sun at great speed.
 - (b) What are the other motions Earth undergoes that you cannot feel?
 - (c) Earth is not an inertial reference frame. Explain why it is often referred to as though it is.
5. If Earth is moving at 100 km s^{-1} relative to the supposed aether, what speed would Michelson have hypothesised for light emitted in the same direction that Earth is travelling?
6.
 - (a) Why did Newton's laws seem correct for so long?
 - (b) Why are Newton's laws still useful?
7. Why is Einstein's second postulate surprising? Give an example to show why Newtonian physicists would think it wrong.
8. A star emits light at speed c . A second star is hurtling towards it at speed $0.3c$. What is the speed of the light when it hits the second star relative to this second star?

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8.3 Time dilation

KEY CONCEPTS

- Describe proper time (t_0) as the time interval between two events in a reference frame where the two events occur at the same point in space
- Model mathematically time dilation and length contraction at speeds approaching c using the equations:

$$t = t_0\gamma \text{ and } L = \frac{L_0}{\gamma} \text{ where } \gamma = \left(1 - \frac{v^2}{c^2}\right)^{-\frac{1}{2}}$$

The passing of time can be measured in many ways, including using the position of the Sun in the sky, the position of hands on a watch, the changing of the seasons and the signs of a person ageing. Galileo is known to have made use of the beat of his pulse, the swinging of a pendulum and the dripping of water. As already stated, Newtonian physics assumed that each of these clocks ticked at the same rate regardless of who was observing them. However, the theory of relativity shows that this assumption — that time is absolute — is actually wrong. This error becomes apparent when the motion of the clock relative to the observer approaches the speed of light.

Consider a simple clock consisting of two mirrors, A and B, with light reflecting back and forth between them. This is an unusual clock, but it is very useful for illustrating how time is affected by relativity. Experiments that involve pursuing an idea on paper without actually performing them are common in explanations of relativity. They are known as **thought experiments**.

Let the separation of the mirrors be L . The time for the pulse of light to pass from mirror A to mirror B and back is calculated in the conventional way:

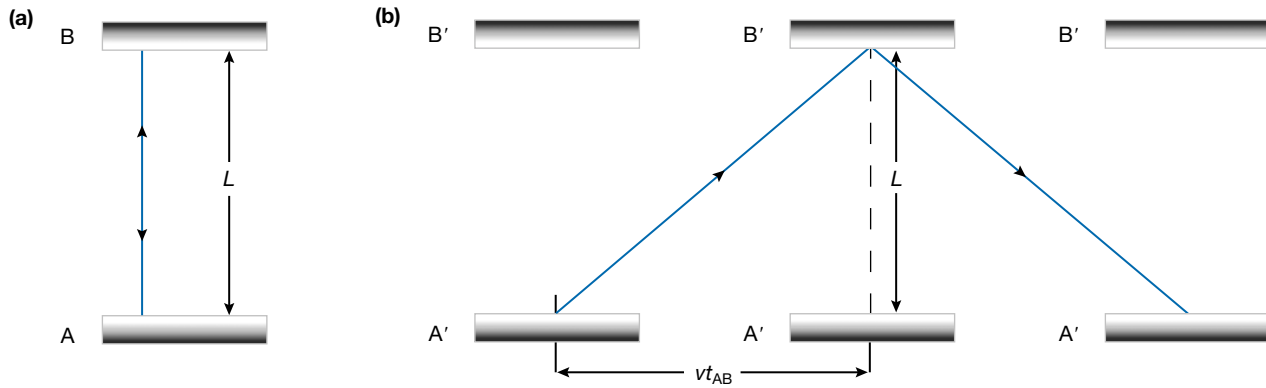
$$c = \frac{2L}{t_0}$$
$$t_0 = \frac{2L}{c}$$

where t_0 is the time for light to travel from A to B and back, as measured in the frame of reference in which the clock is at rest.

This time, t_0 , will be defined as one tick of the clock. In this case, the position of the clock does not change in the frame of reference. The passing of time can be indicated by two events separated by time but not by space — the event of the photon of light first being at A and the event of the photon being back at A.

Imagine an identical clock, with mirrors A' and B', moving past this light clock at speed v . At what rate does time pass on this moving clock according to the observer? Label the time interval measured by this clock t to distinguish it from t_0 . The light leaves A' and moves towards B' at speed c . The speed is still c even though the clock is moving, as stated by Einstein's second postulate. In the time the light makes this journey, the clock moves a distance $d = vt_{AB}$, where t_{AB} is the time the light takes to travel from A' to B'. Figure 8.17b depicts this situation and shows that the light in the moving frame of reference has further

FIGURE 8.17 A light clock (a) at rest relative to the observer, and (b) in motion relative to the observer



to travel than the light in the rest frame. Using Pythagoras's theorem, the light has travelled a distance of $2\sqrt{L^2 + (vt_{AB})^2}$ from A' to B' and back to A' . This is a greater distance than $2L$, given $v \neq 0$ and c is constant. Therefore, the time the light takes to complete the tick must be greater than for the rest clock.

The speed of the light relative to the observer is:

$$c = \frac{d}{t}$$

$$c = \frac{2\sqrt{L^2 + (vt_{AB})^2}}{2t_{AB}}$$

Transpose the equation to make a formula for t :

$$2ct_{AB} = 2\sqrt{L^2 + v^2(t_{AB})^2}$$

$$c^2(t_{AB})^2 = L^2 + v^2(t_{AB})^2$$

But $t_{AB} = \frac{t}{2}$:

$$\frac{c^2 t^2}{4} - \frac{v^2 t^2}{4} = L^2$$

$$t^2 (c^2 - v^2) = 4L^2$$

$$t = \frac{2L}{\sqrt{c^2 - v^2}}$$

$$= \frac{2L}{c\sqrt{1 - \frac{v^2}{c^2}}}$$

It has already been determined that $t_0 = \frac{2L}{c}$, so

$$t = \frac{t_0}{\sqrt{1 - \frac{v^2}{c^2}}}$$

The expression $\frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}$ appears frequently in special relativity. It is known as the Lorentz factor and is denoted by gamma, γ .

The equation can now be written as:

$$t = t_0 \gamma$$

where: $\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}$ is the Lorentz factor

v is the speed of the moving frame of reference, in m s^{-1}
 c is the speed of light in a vacuum, in m s^{-1}
 t is the time measured in the reference frame of the observer, in second
 t_0 is the time measured in the reference frame of the observed object, or the reference frame where two events occur at the same point in space (proper time), in second

The equation $t = t_0 \gamma$ is known as the **time dilation** formula. This formula enables the determination of the time interval between two events in a reference frame moving relative to an observer.

Note that gamma is always greater than 1. As a result, t will always be greater than t_0 , hence the term ‘time dilation’. In a reference frame moving relative to the observer like this, the two events that are being used to mark the time interval (the time between the light being at A) occur at different points in space. The time t_0 is the time measured in a frame of reference where the events occur at the same points in space. It is known as the **proper time**. This is not proper in the sense of correct, but in the sense of property. It is the time in the clock’s own reference frame, whatever that clock might be.

Examples:

1. A mechanical clock’s large hand moves from the 12 to the 3, showing that 15 minutes have passed. Fifteen minutes is the proper time between the two events of the clock showing the hour and the clock showing quarter past the hour. However, if that clock was moving relative to an observer at great speed, the observer would notice that the time between these two events was longer than 15 minutes. The time is dilated.
2. A candle burns 2 centimetres in 1 hour. One hour is the proper time between the events of the candle being at a particular length and the candle being 2 centimetres shorter. If the candle was moving relative to an observer, the observer would notice that it took longer than 1 hour for the candle to burn down 2 centimetres.
3. A man dies at 89 years of age. His life of 89 years is the time between the events of his birth and his death in his reference frame. To an observer moving past at great speed, the man appears to live longer than 89 years. He does not fit any more into his life; everything he does appears to the observer as if it was slowed down.

SAMPLE PROBLEM 7

James observes a clock held by his friend Mabry moving past at $0.5c$. He notices the hands change from 12 pm to 12.05 pm, indicating that 5 minutes have passed for the clock. How much time has passed for James?

 **Teacher-led video:** SP7 (tlvd-0177)



THINK

1. Determine the proper time of the clock.

2. Calculate the Lorentz factor using

$$\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}, \text{ where } v = 0.5c.$$

3. Calculate the time taken for the hands to change from 12 pm to 12.05 pm in James's frame of reference, using $t = t_0\gamma$. Ensure you use the non-rounded value for the Lorentz factor in your calculation.

WRITE

The proper time t_0 is the time interval between the two events: when the clock shows 12 pm and when the clock shows 12.05 pm. The difference is 5 minutes.

$$\begin{aligned} \gamma &= \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}} \\ &= \frac{1}{\sqrt{1 - \frac{(0.5c)^2}{c^2}}} \\ &= \frac{1}{\sqrt{1 - \frac{0.25c^2}{c^2}}} \\ &= \frac{1}{\sqrt{1 - 0.25}} \\ &= 1.155 \end{aligned}$$

$$\begin{aligned} t &= t_0\gamma \\ &= 5 \text{ minutes} \times 1.155 \\ &= 5.774 \text{ minutes} \end{aligned}$$

James notices that the moving clock takes 5.774 minutes (or 5 minutes, 46.4 seconds) for its hands to move from 12 pm to 12.05 pm.

PRACTICE PROBLEM 7

In another measurement, James looks at his own watch and waits the 5 minutes it takes for the watch to change from 1 pm to 1.05 pm. He then looks at Mabry's clock as she moves past at $0.5c$. How much time has passed on her clock?

Unlike in Newtonian physics, time intervals in special relativity are not invariant. Rather, they are relative to the observer.

SAMPLE PROBLEM 8

Mabry is travelling past James at $0.5c$. She looks at James and sees his watch ticking. How long does she observe it to take for his watch to indicate the passing of 5 minutes?

 **Teacher-led video:** SP8 (tlvd-0178)

THINK

In this case it is James's watch that is showing the proper time. The situation in sample problem 7 and this situation are symmetrical. Mabry sees James as moving at $0.5c$, and James sees Mabry moving at $0.5c$, so Mabry's measurement of time passing on James's watch is the same as James's measurement of time passing on Mabry's watch.

WRITE

Mabry notices that 5.774 minutes pass when James's watch shows 5 minutes passing.

PRACTICE PROBLEM 8

Aixi listens to a three-minute song on her phone. As soon as she starts the song, she sees her friend Xiaobo start wrestling with his brother on a spaceship moving by at $0.8c$. When the song finishes, she sees Xiaobo stop wrestling. How long were the two boys wrestling?

SAMPLE PROBLEM 9

A car passes Eleanor at 20 m s^{-1} . Compare the rate that a clock in the car ticks with the rate the clock in her hand ticks.

 Teacher-led video: SP9 (tlvd-0179)

THINK

1. Determine the Lorentz factor

$$\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}} \text{ when } v = 20 \text{ m s}^{-1}.$$

2. Calculate the time that passes on the clock in the car in Eleanor's frame of reference using $t = t_0\gamma$.

WRITE

$$\begin{aligned}\gamma &= \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}} \\ &= \frac{1}{\sqrt{1 - \frac{20^2}{(3 \times 10^8)^2}}} \\ &= 1.000\,000\,000\,000\,0022\end{aligned}$$

$$\begin{aligned}t &= t_0\gamma \\ &= 1.000\,000\,000\,000\,0022t_0\end{aligned}$$

The difference between the rates of time in the two perspectives is so small that it is difficult to calculate, much less notice it.

PRACTICE PROBLEM 9

Jonathan observes a clock on a passing spaceship to be ticking at half the rate of his identical clock. What is the relative speed of Jonathan and the passing spaceship?

Newton's assumption that all clocks tick at the same rate, regardless of their inertial reference frame, was very reasonable. Learning the very good approximation of Newton's laws is well justified. They are simpler than Einstein's laws, and they work for all but the highest speeds. A good theory in science has to fit the facts, and Newton's physics fit the data very successfully for 200 years. It was a great theory, but Einstein's is even better.

If Newton knew then what is known now, he would realise that his theories were in trouble. At speeds humans normally experience, time dilation is negligible, but the dilation increases dramatically as objects approach the speed of light. If you passed a planet at $2.9 \times 10^8 \text{ m s}^{-1}$, you would measure the aliens' usual school lessons of 50 minutes as taking 195 minutes. An increase in speed to $2.99 \times 10^8 \text{ m s}^{-1}$ would dilate the period to 613 minutes. If you could achieve the speed of light, the period would last forever — time would stop.

Photons do not age, as they do not experience time passing!

8.3.1 Time dilation and modern technology

Time dilation has great practical significance. A global positioning system (GPS) is able to tell you where you are, anywhere on Earth, in terms of longitude, latitude and altitude, to within a few metres. To achieve this precision, the system has to compensate for relativistic effects, including time dilation, because it depends on satellites moving in orbit. Einstein's general relativity also shows that the difference in gravity acting on a satellite in orbit affects the time significantly. Nanosecond accuracy is required for a GPS but, if Newtonian physics was used, the timing would be out by more than 30 microseconds. GPSs are widely used in satellite navigation, and ships, planes, car drivers and bushwalkers can find their bearings far more accurately than they ever could using a compass.

FIGURE 8.18 With a GPS device you can know your position to within a few metres.



8.3 EXERCISE

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

1. What is time dilation? In your explanation, give an example of where time dilation would occur.
2. Which clock runs slow: yours or one in motion relative to you?
3. Draw diagrams of a light clock in motion and at rest to explain why time dilation occurs for moving clocks.
4. Explain the difference between t_0 and t in the time dilation formula.
5. Two spacecraft pass each other with a relative speed of $0.3c$.
 - (a) Calculate γ .
 - (b) A drummer pounds a drum at 100 beats per minute on one of the spacecraft. How many beats per minute would those on the other spacecraft measure as a result of time dilation?

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8.4 Length contraction

KEY CONCEPTS

- Describe proper length (L_0) as the length that is measured in the frame of reference in which objects are at rest
- Model mathematically time dilation and length contraction at speeds approaching c using the equations:

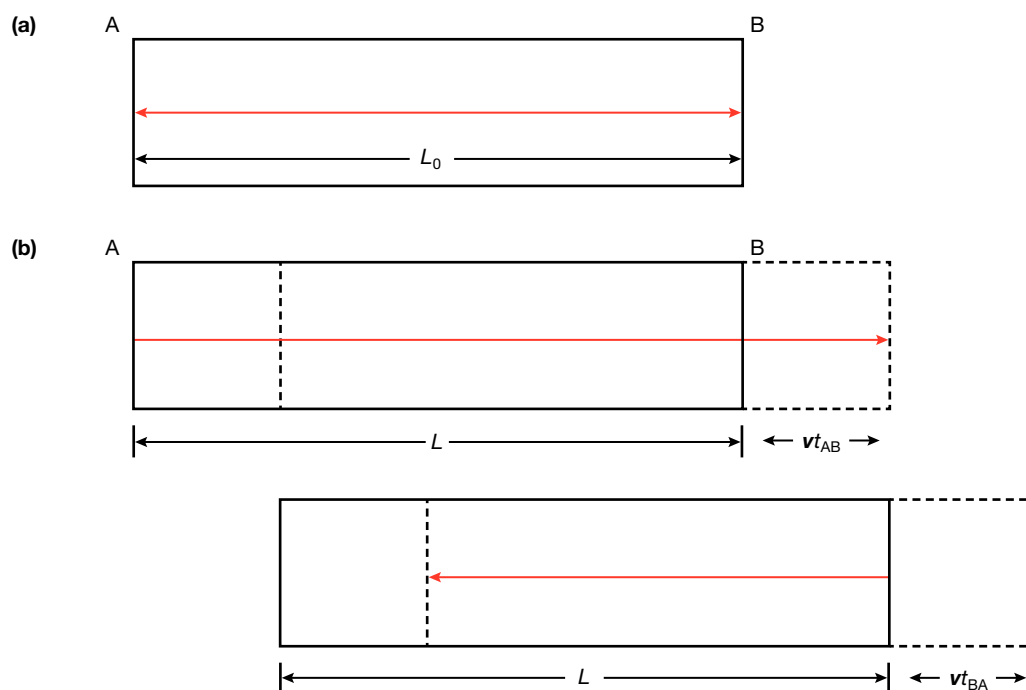
$$t = t_0\gamma \text{ and } L = \frac{L_0}{\gamma} \text{ where } \gamma = \left(1 - \frac{v^2}{c^2}\right)^{-\frac{1}{2}}$$

Once it is accepted that simultaneity of events and the rate that time passes are dependent on the speed of the observer, it has to be accepted that length must be relative as well. The length of an object is simply the distance between the two ends of the object. To find that distance, the positions of both ends must be noted at the same time. If they were measured at different times, a moving object would have changed position, so the distance between the end that was measured second and the end that was measured first would have changed. The fact that any two inertial reference frames do not agree on which events are simultaneous is going to cause the measurement of length to be different in different reference frames. The speed of light is invariant and time is relative, so there is even more reason to doubt that lengths will be the same for all observers.

A clever thought experiment of Einstein's enables the determination of the effect that the speed of an observer has on a length to be measured. It is essentially the same as the thought experiment used to derive the time dilation equation but with the light clock tipped on its side so that its length is aligned with the direction of its motion.

From the reference frame of the clock, again $t_0 = \frac{2L}{c}$. What about the reference frame of an observer with a speed of v relative to the clock? The distance between the ends of the clock can be measured using the time for light to travel from one end to the other and back, as seen in figure 8.19.

FIGURE 8.19 Light journeys in (a) a clock at rest and (b) a clock moving to the right at speed v



Looking at figure 8.19, the following formulae can be derived.

From A to B:

$$L + v t_{AB} = c t_{AB}$$

where:

L = the length of the clock as observed by the moving observer

$v t_{AB}$ = the distance the clock has moved in the time the light passes from A to B

$c t_{AB}$ = the distance the light has travelled passing from A to B.

Transposing the equation to make t_{AB} the subject:

$$t_{AB} = \frac{L}{c - v}$$

From B to A:

$$L - vt_{BA} = ct_{BA}$$

where:

vt_{BA} = the distance the clock has moved in the time the light passes from B back to A

ct_{BA} = the distance the light has travelled passing from B back to A.

Transposing the equation to make t_{BA} the subject:

$$t_{BA} = \frac{L}{c + v}$$

As A moves to meet the light, the time t_{BA} is less than t_{AB} . The total time is:

$$\begin{aligned} t &= t_{AB} + t_{BA} \\ &= \frac{L}{c - v} + \frac{L}{c + v} \\ &= \frac{2Lc}{c^2 - v^2} \\ &= \frac{2L}{c \left(1 - \frac{v^2}{c^2} \right)} \end{aligned}$$

According to the time dilation formula:

$$t = \frac{t_0}{\sqrt{1 - \frac{v^2}{c^2}}}$$

Substituting this for the time in the moving clock gives:

$$\begin{aligned} \frac{t_0}{\sqrt{1 - \frac{v^2}{c^2}}} &= \frac{2L}{c \left(1 - \frac{v^2}{c^2} \right)} \\ t_0 &= \frac{2L}{c \sqrt{1 - \frac{v^2}{c^2}}} \end{aligned}$$

Substituting $t_0 = \frac{2L_0}{c}$ gives:

$$\frac{2L_0}{c} = \frac{2L}{c\sqrt{1 - \frac{v^2}{c^2}}}$$

$$\Rightarrow L_0 = \frac{L}{\sqrt{1 - \frac{v^2}{c^2}}} \text{ or } L = L_0\sqrt{1 - \frac{v^2}{c^2}}$$

The formula $L = L_0\sqrt{1 - \frac{v^2}{c^2}}$ is known as the length contraction formula or the Lorentz contraction formula after one of the early pioneers of relativity theory, Hendrik Antoon Lorentz (1853–1928). Length contraction is the shortening of an object in its direction of motion when measured from a reference frame in motion relative to the object.

The **proper length** of an object, L_0 , is the length measured in the frame of reference where the object is at rest. L is the length as measured from an inertial reference frame travelling at a velocity v relative to the object. This change in length applies only to the length along the direction of motion. The other dimensions are not affected by this contraction.

The proper length is contracted by a factor of $\frac{1}{\gamma}$:

$$L = \frac{L_0}{\gamma}$$

where: $\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}$ is the Lorentz factor

$\vec{v}$ is the speed of the moving frame of reference, in m s^{-1}

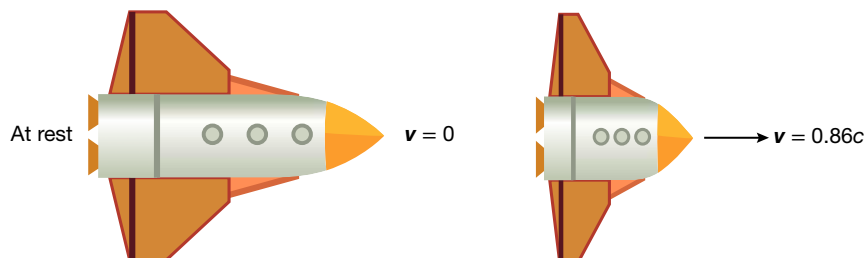
c is the speed of light in a vacuum, in m s^{-1}

L is the length measured in the reference frame of the observer, in m

L_0 is the length measured in the reference frame of the observed object (proper length), in m

The Lorentz contraction is negligible at velocities that are commonly experienced. Even at a relative speed of 10% the speed of light, the contraction is less than 1%. As speed increases beyond $0.1c$, however, the contraction increases until at relative speed c , the length becomes zero.

FIGURE 8.20 A spaceship travelling at high speed has its length contracted (in the direction of motion)



AS A MATTER OF FACT

George Fitzgerald and Hendrik Lorentz independently proposed an explanation for the result of the Michelson–Morley experiment (in 1889 and 1892 respectively). If the length of the apparatus contracted in the direction of Earth’s movement, then the light would take the same time to travel the two paths. This explanation assumed that the aether existed and that light would travel at constant speed through it; therefore, light would travel at different speeds relative to Earth as Earth moved through the aether. This explanation was not completely satisfying as there was no known force that would cause the contraction, and the aether had never been directly detected. The contraction would be measured by those in the reference frame at rest with respect to the aether.

In special relativity, any observer in motion relative to an object measures a contraction. As the contraction is simply a feature of observation from different reference frames, no force is required to cause the contraction. Nothing actually happens to the object in its reference frame.

SAMPLE PROBLEM 10

Observers on Earth see that the length of a spacecraft travelling at $0.5c$ has contracted. By what percentage of its proper length is the spacecraft contracted according to the observers?

 **Teacher-led video:** SP10 (tlvd-0180)

THINK

1. Determine the Lorentz factor,

$$\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}, \text{ for } v = 0.5c.$$

WRITE

$$\begin{aligned} \gamma &= \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}} \\ &= \frac{1}{\sqrt{1 - \frac{(0.5c)^2}{c^2}}} \\ &= \frac{1}{\sqrt{1 - \frac{0.25c^2}{c^2}}} \\ &= \frac{1}{\sqrt{1 - 0.25}} \\ &= 1.155 \end{aligned}$$

2. Using the Lorentz contraction formula, determine the ratio $\frac{L}{L_0}$.

$$\begin{aligned} L &= \frac{L_0}{\gamma} \\ \frac{L}{L_0} &= \frac{1}{\gamma} \\ &= \frac{1}{1.155} \\ &= 0.866 \end{aligned}$$

3. Interpret the ratio $\frac{L}{L_0}$ as a percentage.

The spacecraft appears to be only 0.866 or 86.6% of its proper length. This is a contraction of 13.4%.

PRACTICE PROBLEM 10

Rebecca and Madeline take measurements of the journey from Melbourne to Sydney. Rebecca stays in Melbourne and stretches a hypothetical tape measure between the two cities. Madeline travels towards Sydney at great speed and measures the distance with her own measuring tape that is in her own reference frame.

- How would the two measurements compare, assuming that perfect precision could be achieved?
- Which measurement could be considered to be the proper length of the journey? Explain.

THE TWINS PARADOX

A paradox is a seemingly absurd or contradictory statement. Relativity provides a few paradoxes that are useful in teaching the implications of relativity. The ‘twins paradox’ is probably the best known. Despite its name, the twins paradox is explained fully by the logic of relativity.

Imagine a spacecraft that starts its journey from Earth. After three years in Earth time, it will turn around and come back, so that those on Earth measure the total time between the events of the launch and the return to take six years. The astronaut, Peter, leaves his twin brother, Mark, on Earth. During this time, Peter and Mark agree that Earth has not moved from its path through space; it is Peter in his spaceship who has gone on a journey and has experienced the effects of acceleration that Mark has not. Mark measures the length of Peter’s journey from Earth. His measurement is longer than Peter’s due to length contraction, but the speed of Peter is measured relative to Earth. They disagree on distance travelled but not speed, so they must disagree on time taken. This is not just an intellectual dispute — the difference in time will show in their ageing, with Peter actually being younger than Mark on his return to Earth.

People all go on a journey into the future; time cannot be stopped. Relativity shows that the rate at which time progresses depends on the movements made through space on the journey. Coasting along in an inertial reference frame is the longest path to take. Zipping through different reference frames then returning home enables objects to reach the future in a shorter time: they take a longer journey through space but a shorter journey through time.

The twins scenario may sound incredible, but it has been verified experimentally. The most accurate clocks ever built are atomic clocks. They make use of the oscillations of the atoms of particular elements. The period of this oscillation is unaffected even by quite extreme temperatures and accelerations, making the clocks without rival in terms of accuracy. These clocks have been flown around the world on airliners, recording less elapsed time than for similar clocks that remained on the ground. The effect is tiny, but the clocks have more than adequate precision to detect the difference. The difference measured is consistent with the time difference predicted by special relativity.

THE PARKING SPOT PARADOX

Can a long car enter a parking spot that is too short for it by making use of length contraction? The answer is yes and no. To explain, consider another famous paradox of relativity.

Charlotte’s car is 8 m long and she proudly drives it at a speed of $0.8c$. She observes her friend Alexandra, who is stationary on the roadside, and asks her to measure the length of her car. (For the sake of argument, the issues of how a car could travel at such a huge speed, and how Alexandra communicates with Charlotte and measures the car will be ignored.)

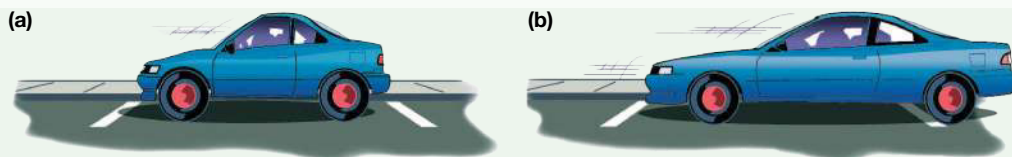
Alexandra says that Charlotte must be dreaming if she thinks her car is 8 m long, because she measures it to be only 4.8 m long. She believes her measurements are accurate.

To prove her point, Alexandra marks out a parking spot 4.8 m long. She says that if Charlotte can park her car in the spot, then the car is not as long as she thinks. Charlotte argues that her car will not fit into a parking spot 4.8 m long, but she agrees to the test.

From Charlotte’s frame of reference, the parking spot would be merely 2.9 m long. This is because it has a length contraction due to the car’s relative motion of $0.8c$. Alexandra’s measuring equipment detects that the front of the car reaches the front of the parking spot at the same instant as the back of the car arrives at the back. However, much to Alexandra’s amazement, the stopped car is 8 m long. Charlotte and Alexandra now agree

that the stopped car does not fit the 4.8 m parking spot, and that it has a length of 8 m. This may at first seem impossible, which is why it is sometimes called a paradox. Once you consider that Charlotte and Alexandra do not agree on which events are simultaneous, the paradox is resolved. Alexandra measured the front and the back of the car to be within the parking spot at the same time but did not check that the front and back had stopped.

The parking spot paradox, where (a) shows Alexandra's view and (b) shows the view from Charlotte's frame of reference



8.4 EXERCISE

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1. If a box was moving away from you at nearly light speed, which dimensions of the box would undergo length contraction from your perspective: width, height or depth?
2. The twins paradox shows that less time passes for the travelling twin. Does this also mean that the twin will return shortened due to length contraction? Explain.
3. An alien spacecraft speeds through the solar system at $0.8c$.
 - (a) What is the effect of its speed on the length of the spacecraft from the perspective of an alien on board?
 - (b) What is the effect of its speed on the length of the spacecraft from the perspective of the Sun?
 - (c) At what speed does light from the Sun reach it?
4. A high-energy physicist detects a particle in a particle accelerator that has a half-life of 20 s when travelling at $0.99c$.
 - (a) Calculate the particle's half-life in its rest frame.
 - (b) The detector is 5 m long. How long would it be in the rest frame of the particle?
5. An astronaut on a spacewalk sees a spacecraft passing at $0.9c$. The spacecraft has a proper length of 100 m. What is the length of the spacecraft L due to length contraction according to the astronaut?

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8.5 Seeing relativistic effects

KEY CONCEPT

- Explain why muons can reach Earth even though their half-lives would suggest that they should decay in the outer atmosphere.

In this topic, the term observer is frequently used. Much of the imagery used in teaching relativity is in principle true but in practicality it is fantasy. Seeing anything in detail that is moving at close to the speed of light is not feasible. However, measuring distances and times associated with these objects is

reasonable. Images formed of objects moving at speeds approaching c will be the result of time dilation, length contraction and other effects including the relativistic Doppler effect and the aberration of light.

Imagine speeding through space in a very fast spacecraft. When you planned your trip on Earth, you forgot to take relativity into account. Everything on board would appear normal throughout the trip, but when you looked out the front window, the effects of relative speed would be obvious. Some examples of what you would see include: the aberration of light, causing the stars to group closer together so that your forward field of vision would be increased; the Doppler effect, causing the colours of stars to change; and the voyage taking much less time than you expected.

8.5.1 The journey of muons

Bruno Rossi and David Hall performed a beautiful experiment in 1941, the results of which are consistent with both time dilation and length contraction.

Earth is constantly bombarded by energetic radiation from space, known as cosmic radiation. These rays collide with the upper atmosphere, producing particles known as muons. Muons are known to have a very short half-life, measured in the laboratory to be 1.56 microseconds. Given the speed at which they travel and the distance they travel through the atmosphere, the vast majority of muons would decay before they hit the ground.

The Rossi–Hall experiment involved measuring the number of muons colliding with a detector on top of a tall mountain and comparing this number with how many muons were detected at a lower point. They found that far more muons survived the journey through the atmosphere than would be predicted without time dilation. The muons were travelling so fast relative to Earth that the muons decayed at a much slower rate for observers on Earth than they would at rest in the laboratory. The journey between the detectors took about 6.5 microseconds according to Earth-based clocks, but the muons decayed as though only 0.7 microseconds had passed. Due to length contraction, the muons did not see the tall mountain but, rather, a small hill. Rossi and Hall were not surprised that the muons survived the journey.

FIGURE 8.21 Muons are a measurable example of special relativistic effects.

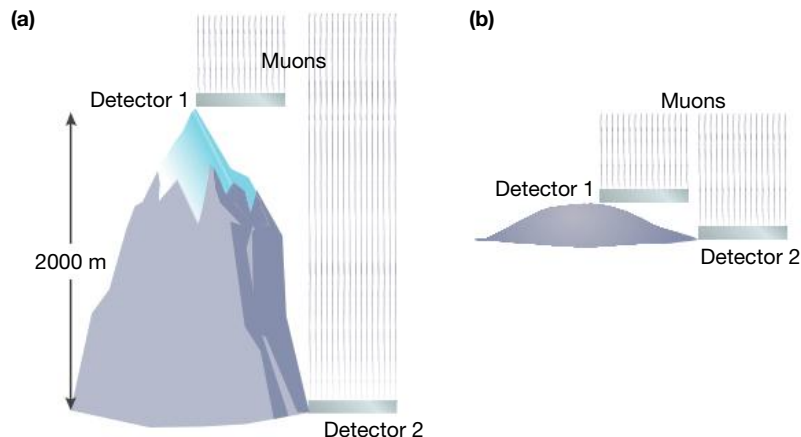


Figure 8.21 shows how the Rossi–Hall experiment was conducted. In figure 8.21a, the number of muons decaying between detectors 1 and 2 implies that less time has passed for the muons than Earth-based clocks suggest. In figure 8.21b, the muons see the distance between the detectors greatly contracted.

SAMPLE PROBLEM 11

Use the description of the Rossi–Hall experiment to answer the following questions.

- What is the proper time for the half-life of muons?
- What is the value of gamma as determined from the journey times from the different reference frames?
- How fast were the muons travelling through the atmosphere according to the value for gamma?
- Calculate the half-life of the muons from the reference frame of the Earth.

 **Teacher-led video:** SP11 (tlvd-0181)

THINK

- The proper time for the half-life is in the reference frame of the muon.
- Use the time dilation formula with $t = 6.5$ and $t_0 = 0.7$ to calculate the value of gamma.

- Use the expression for the Lorentz factor, $\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}$, to calculate the velocity of the muons.

- Use the time dilation formula, $t = \gamma t_0$, to calculate the half-life of the muons from the reference frame of the Earth.

WRITE

- The proper time for the half-life of muons is 1.56 microseconds.

b. $t = t_0 \gamma$

$$\begin{aligned}\gamma &= \frac{t}{t_0} \\ &= \frac{6.5}{0.7} \\ &= 9.29\end{aligned}$$

c. $\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}$

$$\begin{aligned}v &= c \sqrt{1 - \frac{1}{\gamma^2}} \\ &= c \sqrt{1 - \frac{1}{9.29^2}} \\ &= 0.994c\end{aligned}$$

The muons were travelling at 99.4% of the speed of light.

d. $t = \gamma t_0$
 $= 9.29 \times 1.56 \mu\text{s}$
 $= 14.5 \mu\text{s}$

The half-life of muons as viewed from Earth is 14.5 microseconds compared to the 1.56 microseconds as experienced by the muons.

PRACTICE PROBLEM 11

Use the description of the Rossi–Hall experiment introduced earlier to answer the following questions.

- Use the travel time from the Earth reference frame and the speed of the muons to calculate the height of the mountain.
- Use the travel time of the muons to determine how high the mountain appeared to the muons.

8.5 EXERCISE

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

1. Explain why muons reach the surface of the Earth in greater numbers than would be predicted by classical physics, given their speed, their half-lives and the distance they need to travel through the atmosphere.
2. A muon forms 30 km above the Earth's surface and travels straight down at $0.98c$. From its frame of reference, what is the distance it has to travel through the atmosphere?
3. The proper time for the half-life of a muon is 1.56 microseconds. If the muon moves at $0.98c$ relative to an observer, what does the observer measure its half-life as?
4. Explain how muons produced by cosmic rays became an early confirmation of special relativity.

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8.6 Einstein's relationship between mass and energy

KEY CONCEPTS

- Interpret Einstein's prediction by showing that the total 'mass-energy' of an object is given by: $E_{\text{tot}} = E_k + E_0 = \gamma mc^2$ where $E_0 = mc^2$, and where kinetic energy can be calculated by: $E_k = (\gamma - 1)mc^2$
- Describe how matter is converted to energy by nuclear fusion in the Sun, which leads to its mass decreasing and the emission of electromagnetic radiation.

In Newtonian physics, the work done in accelerating an object is equal to the increase in the kinetic energy of the object, and energy is conserved.

Work done (W) = Force ($\vec{F}$) $\times$ displacement ($\Delta \vec{s}$) = Gain in kinetic energy (ΔE_k)

And since $E_k = \frac{1}{2}m\vec{v}^2$:

$$\Delta E_k = \frac{1}{2}m(\vec{v}^2 - \vec{u}^2) = \vec{F} \times \Delta \vec{s}$$

Newton's laws show that energy is conserved. However, this equation does not hold in Einstein's Theory of Special Relativity, because the laws of physics need to hold true in all reference frames.

It was in exploring these ideas that Einstein came up with the idea that energy and mass were equivalent and interchangeable, leading to the result of special relativity that people are most familiar with: the equation $E = mc^2$. In fact, it is probably the most well-known equation of all. This formula expresses an equivalence of mass and energy. If work, E , is done on an object, that is, its energy is increased, its mass will increase. Usually, however, this increase in mass is not noticed because it is very small compared to the factor $c^2 = 9.0 \times 10^{16} \text{ m}^2 \text{ s}^{-2}$. According to $\Delta E = \Delta mc^2$, it would take $9.0 \times 10^{16} \text{ J}$ of energy to increase a mass by 1 kg. This is similar to the amount of electrical energy produced in Victoria every year. Conversely, if a 1 kg mass could be converted into electricity, Victoria's electricity needs would be supplied for a year. Nuclear fission reactors produce electricity from the small loss of mass that

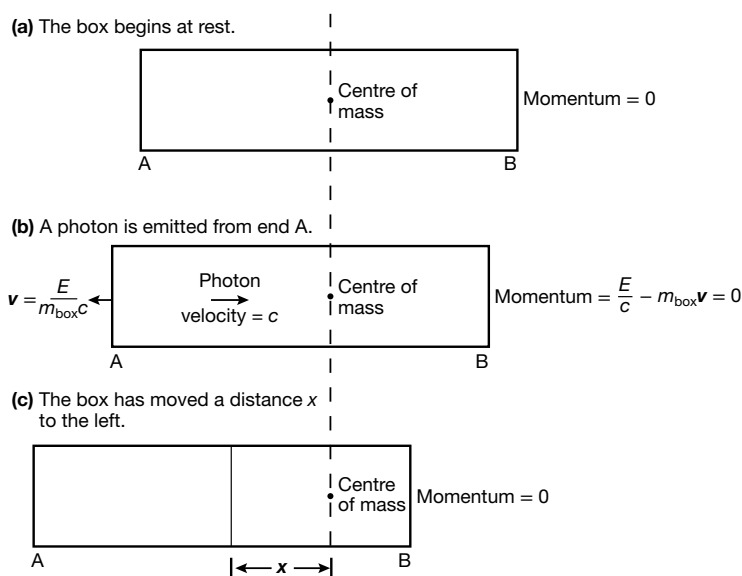
occurs when large nuclei such as those of uranium-235 undergo fission. The Sun and other stars generate their energy by losing mass to nuclear fusion.

A simplified derivation of this equation can help to gain a sense of the physics involved. Consider a box suspended in space, with no external forces acting on it, as shown in figure 8.22. Maxwell found that electromagnetic radiation carries momentum $p = \frac{E}{c}$ where E is the energy transmitted and c is the speed of light. In the context of photons, each photon carries a momentum $p = \frac{E}{c}$. As a result, light exerts pressure on surfaces. This effect can nudge satellites out of orbit over time.

In diagram (a) of figure 8.22, the box begins at rest. The total momentum is zero and its centre of mass is in the centre.

In diagram (b) of figure 8.22, a photon of energy E is emitted from end A travelling to the right, carrying momentum with it. To conserve momentum, the box moves in the direction opposite to the movement of the photon, to the left.

FIGURE 8.22 Einstein's box suspended in space



$$p_{\text{photon}} + p_{\text{box}} = 0$$

$$\Rightarrow \frac{E}{c} - m_{\text{box}}v = 0$$

Rearranging gives the velocity of the box in the leftward direction, $v = \frac{E}{m_{\text{box}}c}$, a very small number!

In diagram (c) of figure 8.22, after time Δt , the light pulse strikes the other end of the box and is absorbed. The momentum of the photon is also absorbed into the box, bringing the box to a stop. In this process, the box has moved a distance x where $x = v\Delta t$.

Substituting $v = \frac{E}{m_{\text{box}}c}$ from diagram (b) gives:

$$x = \frac{E\Delta t}{m_{\text{box}}c}$$

As v is very small (almost non-existent), it can be assumed that the photon travels the full length of the box, and put $\Delta t = \frac{L}{c}$. Substituting this into $x = \frac{E\Delta t}{m_{\text{box}}c}$ gives:

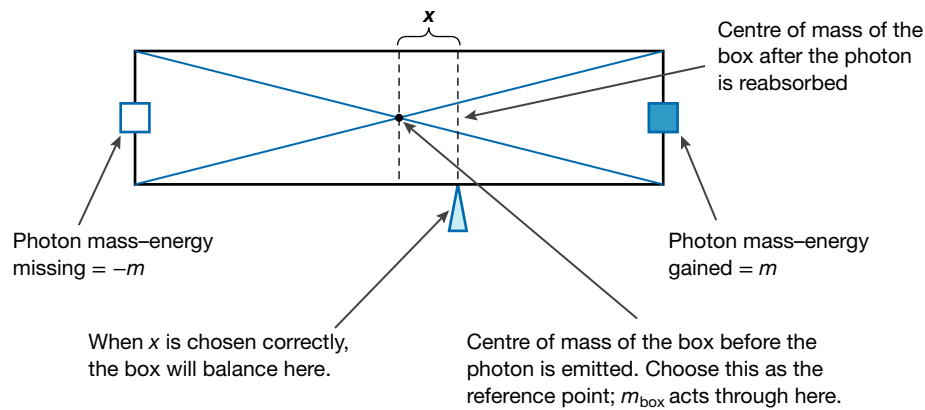
$$x = \frac{EL}{m_{\text{box}}c^2}$$

$$\text{or } E = \frac{xm_{\text{box}}c^2}{L}.$$

There are no external forces acting on the box, so the position of the centre of mass must remain unchanged (see the dotted line in the diagram). The box moved to the left as a result of the transfer of the energy of the photon to the right. Therefore, the transfer of the photon must be the equivalent of a transfer of mass. If you can show that $\frac{xm_{\text{box}}}{L}$ is the same as the mass equivalent of the transferred energy, you have your answer. To show this, attention must be paid the shift in the box relative to the centre of mass of the system.

The centre of mass is the point where the box would balance if suspended. This can be determined by balancing moments — the mass times the distance from a reference point. The centre of the box is chosen as the reference point to ensure that the distance x is in the calculations. The moment for the box is $m_{\text{box}}x$ anticlockwise, because the mass of the box can be considered to be acting through a point at distance x to the left of the reference point. The photon's equivalent mass is acting at distance $\frac{L}{2}$ to the right of the reference point, so its moment is $m\frac{L}{2}$ clockwise. However, this moment was acting on the other end of the box before the photon was emitted, so you can consider its absence from that end of the box as an equal moment in the same direction. Therefore:

FIGURE 8.23 Balancing Einstein's box



$$m_{\text{box}}x = m\frac{L}{2} + m\frac{L}{2}$$

$$\text{or } m = \frac{m_{\text{box}}x}{L} \text{ as required.}$$

Substitute this into $E = \frac{xm_{\text{box}}c^2}{L}$ and $E = mc^2$ is obtained.

$$\Delta E = \Delta mc^2$$

where: ΔE is the change in energy
 Δm is the change in mass
 c is the speed of light

In other words, when the photon carried energy to the other end of the box, it had the same effect as if it had carried mass. In fact, Einstein concluded that energy and mass are equivalent. If you say that some energy has passed from one end of the box to the other, you are equally justified in saying that mass has passed as well. Note the distinction: the photon carries an amount of energy that is equivalent to an amount of mass, but the photon itself does not have mass.

One implication of this is that the measurement of mass depends on the relative motion of the observer. The kinetic energy of a body depends on the inertial reference frame from which it is measured. The faster the motion, the greater the kinetic energy. So kinetic energy is relative, and so is mass! Energy is equivalent to mass, so the mass of an object increases as its velocity relative to an observer increases.

The mass of an object that is in the same inertial frame as the observer is called its **rest mass** (m_0). When measured from other reference frames, the mass is given by $m = m_0\gamma$. The derivation of this is complex, so it will not be addressed here.

SAMPLE PROBLEM 12

Use $m = m_0\gamma$ to show that it is not possible for a mass to exceed the speed of light.

 **Teacher-led video:** SP12 (tlvd-0182)

THINK

1. Consider the effect on gamma as $v \rightarrow c$.
2. Consider the effect on m as $v \rightarrow c$.
3. Consider the effect on gamma if $v > c$.

WRITE

As $v \rightarrow c$,

$$\gamma \rightarrow \frac{1}{\sqrt{1 - \frac{c^2}{c^2}}} \rightarrow \infty$$

So, as $v \rightarrow c$, γ becomes infinitely large.

$m = m_0\gamma$, so as $v \rightarrow c$, $\gamma \rightarrow \infty$, $m \rightarrow \infty$.

An object travelling at c would have infinite mass.

$$\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}$$

If $v > c$, then $\frac{v^2}{c^2} > 1$ and $1 - \frac{v^2}{c^2} < 0$.

Speeds larger than c would produce a negative under the square root sign, so these speeds are not possible.

PRACTICE PROBLEM 12

The Earth ($m = 6 \times 10^{24}$ kg) moves around the Sun at close to $30\,000 \text{ m s}^{-1}$. From the Sun's frame of reference, how much additional mass does the Earth have?

SAMPLE PROBLEM 13

Calculate the mass increase of a proton that is accelerated from rest using 11 GeV of energy, an energy that can be achieved in particle accelerators.

 **Teacher-led video:** SP13 (tlvd-0183)

THINK

1. Convert 11 GeV into joules.
2. Use the equation $\Delta E = \Delta mc^2$ to determine the mass increase that corresponds with a change in energy of 11 GeV.

WRITE

$$\begin{aligned}\Delta E &= 11 \text{ GeV} \\ &= 11 \times 10^9 \times 1.6 \times 10^{-19} \text{ J} \\ &= 1.76 \times 10^{-9} \text{ J}\end{aligned}$$

$$\begin{aligned}\Delta E &= \Delta mc^2 \\ \Delta m &= \frac{\Delta E}{c^2} \\ &= \frac{1.76 \times 10^{-9} \text{ J}}{(3 \times 10^8 \text{ m s}^{-1})^2} \\ &= 1.96 \times 10^{-26} \text{ kg}\end{aligned}$$

Note that the rest mass of a proton is $1.67 \times 10^{-27} \text{ kg}$, so the accelerated proton behaves as though its mass is nearly 12 times its rest mass.

PRACTICE PROBLEM 13

A particle physicist accelerates a proton from rest using $3.45 \times 10^{-10} \text{ J}$ of energy. What is the mass increase of the proton if the rest mass of the proton is $1.67 \times 10^{-27} \text{ kg}$?

SAMPLE PROBLEM 14

In Newtonian physics, if a proton is given 11 GeV of kinetic energy, what would its speed be?

 **Teacher-led video:** SP14 (tlvd-0184)

Solution:**THINK**

Use the formula $E_k = \frac{1}{2}mv^2$ to determine the speed of the proton, ensuring that the value for kinetic energy used in the formula is in joules.

Where the kinetic energy, $E_k = 11 \text{ GeV}$ or $1.76 \times 10^{-9} \text{ J}$, and the mass of a proton, $m = 1.67 \times 10^{-27} \text{ kg}$.

WRITE

$$\begin{aligned}E_k &= \frac{1}{2}mv^2 \\ v &= \sqrt{\frac{2E_k}{m}} \\ &= \sqrt{\frac{2 \times 11 \times 10^9 \times 1.6 \times 10^{-19}}{1.67 \times 10^{-27}}} \\ &= 1.45 \times 10^9 \text{ m s}^{-1}\end{aligned}$$

This speed is not possible as the maximum speed attainable is $3.0 \times 10^8 \text{ m s}^{-1}$.

PRACTICE PROBLEM 14

Use Newton's laws to determine the speed of the proton from practice problem 13. What conclusions can you make about Newtonian physics compared to Einstein's physics?

The solution to sample problem 14 is well in excess of the speed of light and is an example of the limitations of Newtonian physics. In relativity, when more energy is given to a particle that is approaching the speed of light, the energy causes a large change in mass and a small change in speed. By doing work on the particle, the particle gains inertia, so the increase in energy has an ever-decreasing effect on the speed. The speed cannot increase beyond the speed of light, no matter how much energy the particle is given.

In particle accelerators, where particles are accelerated to near the speed of light, every tiny increase in the speed of the particles requires huge amounts of energy. Physicists working in this field rely on ever-higher energies to make new discoveries. This costs huge amounts of money. Nonetheless, a number of accelerators have been built that are used by scientists from around the world. This area of research is often called high-energy physics. At these high energies, Newtonian mechanics is hopelessly inadequate and Einstein's relativity is essential.

FIGURE 8.24 Particle accelerators such as the Australian Synchrotron in Melbourne accelerate subatomic particles to near-light speeds, where special relativity is essential for understanding the behaviour of the particles. Electrons in the Australian Synchrotron have kinetic energies up to 3 GeV.



Source: Australian Synchrotron

8.6.1 Kinetic energy in special relativity

This equivalence of mass and energy has resulted in the term mass–energy. The **mass–energy** of any object is given by $E = mc^2$. With mass–energy, a moving particle has kinetic energy and rest energy. Rest energy is the energy equivalent of the mass at rest given by $E_0 = m_0c^2$.

Therefore:

$$E_{\text{tot}} = E_k + E_0$$

Substituting for E_{tot} and E_0 :

$$mc^2 = E_k + m_0c^2$$

Rearranging and substituting,

$$\begin{aligned} E_k &= mc^2 - m_0c^2 \\ &= m_0\gamma c^2 - m_0c^2 \\ &= (\gamma - 1)m_0c^2 \end{aligned}$$

The kinetic energy of a particle can be calculated using:

$$E_k = (\gamma - 1)m_0c^2$$

where: E_k is the kinetic energy of the particle, in J
 γ is the Lorentz factor $\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}$
 m_0 is the rest mass of the particle, in kg
 c is the speed of light, in ms^{-1}

This is the expression we must use for kinetic energy when dealing with high speeds, particularly those exceeding 10% of the speed of light.

SAMPLE PROBLEM 15

Calculate the kinetic energy of a 10 000 kg spacecraft travelling at $0.5c$ and compare this with the kinetic energy that you would calculate using classical physics ($E_k = \frac{1}{2}mv^2$).

 Teacher-led video: SP15 (tlvd-0185)

Solution:

THINK

1. Use the formula $E_k = (\gamma - 1)m_0c^2$ to calculate the kinetic energy of the spacecraft using special relativity, with $v = 0.5c$
2. Use the formula $E_k = \frac{1}{2}mv^2$ to calculate the kinetic energy of the spacecraft using classical physics, with $v = 0.5c = 0.5 \times 3 \times 10^8 \text{ m s}^{-1}$.
3. Compare the values for the kinetic energy of the spacecraft using special relativity and classical physics.

WRITE

$$\begin{aligned} E_k &= (\gamma - 1)m_0c^2 \\ &= \left(\frac{1}{\sqrt{1 - 0.5^2}} - 1 \right) \times 10\,000 \times (3 \times 10^8)^2 \\ &= 1.39 \times 10^{20} \text{ J} \\ E_k &= \frac{1}{2}mv^2 \\ &= \frac{1}{2} \times 10\,000 \times (0.5 \times 3 \times 10^8)^2 \\ &= 1.13 \times 10^{20} \text{ J} \end{aligned}$$

The kinetic energy is $\frac{1.39}{1.13} = 1.23$ times the value predicted by classical physics.

PRACTICE PROBLEM 15

A particle accelerator is designed to give electrons 3 GeV of kinetic energy. How fast can it make electrons travel?

8.6.2 Mass conversion in the Sun

In Unit 1, you learned about the generation of energy in the core of the Sun and other stars. One of the consequences of Einstein's great contribution to the understanding of relativity is that scientists now understand a great deal about how energy is generated by the Sun. At the centre of it all is the equation $E = mc^2$. The Sun continuously converts mass—energy stored as mass into radiant light and heat. Each second, the Sun radiates enough energy to meet current human requirements for billions of years. It takes the energy generated in the core about 100 000 years to reach the surface. Even if the fusion in the Sun stopped today, it would take tens of thousands of years before there was a significant impact on Earth.

Nuclear fusion

Nuclear fusion is the process of joining smaller nuclei to form one larger, more stable nucleus. Extremely high temperatures are required for nuclear fusion to occur, such as those found on the Sun and other stars.

The Sun is a ball made up mostly of hydrogen plasma and some ionised atoms of lighter elements. The temperatures in the Sun ensure that virtually all of the atoms are ionised. The composition of the Sun is shown in table 8.1.

FIGURE 8.25 The Sun's energy comes from nuclear fusion converting mass into energy.

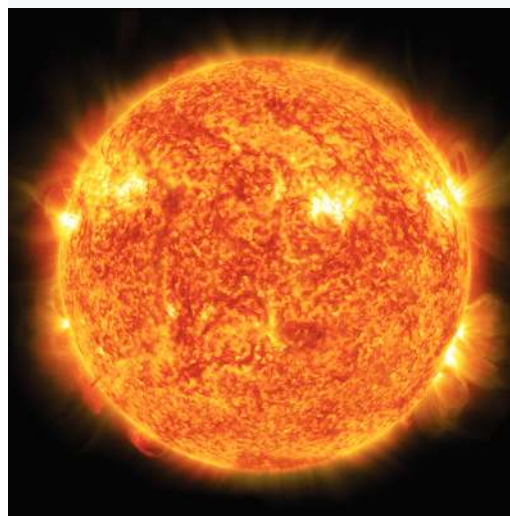


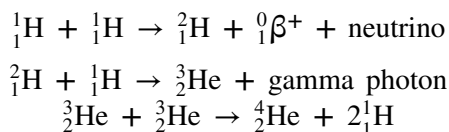
TABLE 8.1 The composition of the Sun

Element	Percentage of total number of nuclei in the Sun	Percentage of total mass of the Sun
Hydrogen	91.2	71.0
Helium	8.7	27.1
Oxygen	0.078	0.97
Carbon	0.043	0.40
Nitrogen	0.0088	0.096
Silicon	0.0045	0.099
Magnesium	0.0038	0.076
Neon	0.0035	0.058
Iron	0.0030	0.14
Sulfur	0.0015	0.040

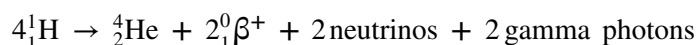
At this stage of the Sun's life cycle, ionised hydrogen atoms (i.e. protons) provide the energy. The abundance of protons and the temperatures and pressures in the core of the Sun are sufficient to fuse

hydrogen, but not heavier nuclei. The energies of the protons in the Sun have a wide distribution from cool, slow protons to extremely hot, fast protons. Only the most energetic protons, about one in a hundred billion, have the energy required to overcome the electrostatic repulsion and undergo fusion. The Sun is in a very stable phase of fusing hydrogen that is expected to last for billions of years to come.

Fusion in the Sun occurs mainly through the following process:



which can be summed up by the following equation:



The energy is released mainly through the gamma photons and the annihilation of the positrons when they meet free electrons in the Sun. The net result is an enormous release of energy and a corresponding loss of mass. The mass loss has been measured to be 4.4 Tg (4.4×10^9 kg) per second. As the mass of the Sun is around 2.0×10^{30} kg, even at this incredible rate, there is plenty of hydrogen to sustain it for about twice its age of four and a half billion years.

SAMPLE PROBLEM 16

A nucleus of hydrogen-2 made of one proton and one neutron has a smaller mass than the total of an individual proton and an individual neutron. Account for this mass difference.

 **Teacher-led video:** SP16 (tlvd-0186)

THINK

Consider the mass–energy of the hydrogen-2 nucleus compared to the mass–energy of the separate proton and neutron.

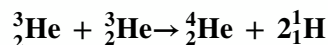
WRITE

Deuterium (or hydrogen-2) has a mass of 3.3435×10^{-27} kg. A proton has a mass of 1.6726×10^{-27} kg and a neutron has a mass of 1.6759×10^{-27} kg. This leads to a combined mass of 3.3475×10^{-27} kg, showing a mass difference of 0.004×10^{-27} kg or 4.0×10^{-30} kg. Deuterium has a rest-mass and also binding energy that account for this mass deficit. Using $\Delta E = mc^2$, the energy difference from this mass deficit would be 3.6×10^{-13} J.

It is clear that the mass of the nucleus is different to the mass of the individual particles, but when the binding energy of the hydrogen-2 nucleus is included, the mass–energy of both is found to be the same. The separate particles have their mass and zero potential energy. The particles bound in the nucleus have a reduced mass and the binding energy of the nucleus. (The binding energy is the energy required to separate the particles. It is released as a combination of increased kinetic energy of the particles and gamma rays.)

PRACTICE PROBLEM 16

Consider the following fusion reaction:



If 30 MeV of energy is released through this reaction, determine how much mass is lost through this reaction. Do not forget to convert MeV to J.

SAMPLE PROBLEM 17

At the Sun's core, a huge number of fusion reactions are constantly taking place. As such, the Sun loses approximately 4.4 Tg of mass every second. What is the power output of the Sun?

 Teacher-led video: SP17 (tlvd-0187)

THINK

1. Use the relationship $E = mc^2$ to calculate the energy released by the Sun when its mass loss is 4.4×10^9 kg.
2. Use the relationship $P = \frac{E}{t}$ to calculate the power output that corresponds to a mass loss of 4.4×10^9 kg s⁻¹.

WRITE

$$\begin{aligned} E &= mc^2 \\ &= 4.4 \times 10^9 \times (3.0 \times 10^8)^2 \text{ J} \\ &= 4.0 \times 10^{26} \text{ J} \\ P &= \frac{E}{t} \\ &= \frac{4.0 \times 10^{26} \text{ J}}{1 \text{ s}} \\ &= 4.0 \times 10^{26} \text{ W} \end{aligned}$$

The mass loss of 4.4×10^9 kg s⁻¹ equates to a power output of 4.0×10^{26} W.

PRACTICE PROBLEM 17

If the mass of the Sun is approximately 2.0×10^{30} kg and it is estimated that the Sun loses 4.4×10^9 kg s⁻¹ during nuclear fusion, how long would you estimate the Sun to be able to continue providing energy for life on Earth?

8.6 EXERCISE

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

1. Use your knowledge of relativity to argue that matter cannot travel at the speed of light.
2. How much energy would be required to accelerate 1000 kg to:
 - (a) 0.1c
 - (b) 0.5c
 - (c) 0.8c
 - (d) 0.9c?
3. Sketch a graph of energy versus speed using your answers to the previous question.
4. Explain in words what $E = mc^2$ says about energy and mass.
5. Calculate the rest energy of Earth, which has a rest mass of 5.98×10^{24} kg.

6. Consider Earth to be a mass moving at 30 km s^{-1} relative to a stationary observer. Given that the rest mass of Earth is $5.98 \times 10^{24} \text{ kg}$, what would be the difference between this rest mass and the mass from the point of view of the stationary observer?
7. What is happening to the mass of the Sun over time? Why?
8. Where in the fusion process in the Sun is electromagnetic radiation produced that is later radiated by the Sun?

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8.7 Review

8.7.1 Summary

- There is no frame of reference that is at absolute rest. Velocity is always relative to a chosen reference frame.
- Classical physics is the physics established by Galileo, Newton and other scientists before the twentieth century. It does not include twentieth-century developments in physics, such as special relativity and quantum mechanics.
- In classical physics, velocity is relative, but time, distance and mass measurements are invariant — they are the same for all observers. Classical physics provides a good approximation at low velocities but it does not provide accurate values as relative speeds approach the speed of light.
- In special relativity, velocities of masses are still relative but the speed of light is invariant. As a result, it is recognised that the measurement of time intervals, lengths and masses is relative to the reference frame of the observer.
- Einstein's two postulates of special relativity are:
 - the laws of physics are the same in all inertial (non-accelerated) frames of reference
 - the speed of light has a constant value for all observers regardless of their motion or the motion of the source.
- Proper time is the time interval between two events in a reference frame where the two events occur at the same point in space, that is, the reference frame in which the clock is stationary.
- Proper length is the length that is measured in the frame of reference in which objects are at rest.
- In reference frames in motion relative to the observer, time is dilated according to $t = t_0\gamma$, where

$$\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}$$

- In reference frames in motion relative to the observer, length is contracted along the line of motion according to $L = \frac{L_0}{\gamma}$.
- In reference frames in motion relative to the observer, mass increases according to $m = m_0\gamma$.
- An example of where the effects of special relativity can be observed is muons formed in the upper atmosphere. They travel to Earth at nearly the speed of light, so that even though most would decay in the time it takes them to reach the surface according to classical physics, many survive the journey as

they see the distance contracted. From the perspective of the Earth, the time is dilated so that the muons have time to reach the surface.

- Kinetic energy is given by the formula $E_k = (\gamma - 1)m_0c^2$.
- $E = mc^2$ expresses the equivalence of mass and energy.
- Fusion is the source of the Sun's energy. The Sun is constantly losing mass as it radiates energy in accordance with mass–energy equivalence.

Resources

studyon

To access key concept summaries and past VCAA exam questions download and print the **studyON: Revision and past VCAA exam question booklet** (sonr-0057).

8.7.2 Key terms

An **inertial reference frame** is a reference frame that is not accelerating.

An **invariant** quantity is a quantity that has the same value in all reference frames.

As mass and energy are equivalent, they can be described as a single concept, **mass–energy**. The mass–energy of an object is given by $E = mc^2$.

The **proper length** of an object is the length measured in the rest frame of the object.

The **proper time** between two events is the time measured in a frame of reference where the events occur at the same point in space. The proper time of a clock is the time the clock measures in its own reference frame.

A quantity is **relative** when it has different values for different observers.

The **rest mass** is the mass of an object measured at rest.

A **thought experiment** (also known as a gedanken experiment) is an imaginary scenario designed to explore what the laws of physics predict would happen.

The term **time dilation** describes the slowing of time by clocks moving relative to the observer.

Resources

 **Digital documents** Key terms glossary (doc-32295)

8.7 Exercises

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

8.7 Exercise 1: Multiple choice questions

1. According to Maxwell, who would see light travelling the fastest?
 - A. Someone moving towards a light source that is stationary in the aether
 - B. Someone who is stationary in the aether with the light source moving away
 - C. Someone who is stationary in the aether with the light source moving towards them
 - D. Someone who is moving away from a light source that is stationary in the aether
2. Which of the following would be a consequence of the relativistic mass increase of a person travelling past you at near light speed?
 - A. They would appear physically larger.
 - B. They would weigh more on a balance.
 - C. They would require more force to accelerate.
 - D. All of the above.

3. Einstein's second postulate of special relativity states that the speed of light:
 - A. is constant regardless of the speed of the observer or the light source
 - B. can decrease if the speed of the observer decreases
 - C. randomly changes depending upon its original light source
 - D. can increase if the speed of the light source increases.
4. John is riding an e-scooter through campus and travelling at 6 m s^{-1} . What is the speed of a ball relative to the ground if John throws it forward at 2 m s^{-1} while riding his e-scooter?
 - A. 8 m s^{-1}
 - B. 6 m s^{-1}
 - C. 4 m s^{-1}
 - D. 2 m s^{-1}
5. If a spacecraft travels towards a light beacon at four-tenths the speed of light ($0.4c$), what would the spacecraft measure the speed of light from the beacon to be?
 - A. $0.6c$
 - B. $0.4c$
 - C. $1.0c$
 - D. $1.4c$
6. Twins Bob and Rob are 30 years old. Rob travels to outer space in a rocket at $0.8c$ for what he experiences as 12 years. How old is Bob (who remained on Earth) when Rob returns from his travels?
 - A. 50 years old
 - B. 70 years old
 - C. 42 years old
 - D. 37 years old
7. A vehicle parked on a street corner is 12 m long. It then starts up and travels around the block at $0.8c$ past an observer on the street corner. What length does the observer on the street corner measure the vehicle to have?
 - A. 20 m
 - B. 5.7 m
 - C. 0.6 m
 - D. 7.2 m
8. A scientist is sitting in her stationary laboratory. She observes a spaceship with a mass of 8000 kg moving past her. She observes that the clocks on the ship, which are operating normally, are running 6 times slower than the clocks in her laboratory, which are also running normally. What is the kinetic energy of the spaceship in the scientist's frame of reference?
 - A. $12 \times 10^{12} \text{ J}$
 - B. $-6 \times 10^{20} \text{ J}$
 - C. $3.6 \times 10^{21} \text{ J}$
 - D. $3.6 \times 10^{24} \text{ J}$
9. A particle of mass m_0 travels at a speed of $0.8c$. The relativistic kinetic energy of the particle is:
 - A. $1.66 m_0 c^2$
 - B. $0.66 m_0 c^2$
 - C. $m_0 c^2$
 - D. $0.32 m_0 c^2$
10. How much kinetic energy does a proton having a rest mass (m_0) equal to $1.67 \times 10^{-27} \text{ kg}$ and γ equal to 1.8 gain when it is accelerated from rest?
 - A. 0 J
 - B. $1.50 \times 10^{-10} \text{ J}$
 - C. $1.20 \times 10^{10} \text{ J}$
 - D. $1.20 \times 10^{-10} \text{ J}$

8.7 Exercise 2: Short answer questions

1. What is the difference between an inertial and a non-inertial reference frame?
2. How can you determine whether your car is accelerating or moving with constant velocity?
3. Explain, using the concept of velocity, why head-on collisions are particularly dangerous. Use an example.
4.
 - a. What are Einstein's two postulates of special relativity?
 - b. What is in these postulates that was not present in previous physics?
5. You observe that an astronaut moving very quickly away from you ages at a slower rate than you. The astronaut views you as ageing faster than she ages. True or false? Explain.
6. It takes 5 min for an astronaut to eat his breakfast, according to the clock on his spacecraft. The clock on a passing spacecraft records that 8 minutes passed while he ate his breakfast.
 - a. Which time is proper time?
 - b. What is the relative speed of the two spacecraft?
7. Travelling at near light speed would enable astronauts to cover enormous distances. Explain the difficulties in terms of energy of achieving space travel at near light speed.
8. If a 250 g apple could be converted into electricity with 100% efficiency, how many joules of electricity would be produced?
9. Much of Victoria's electricity is produced by burning coal. What can you say about the mass of the coal and its chemical combustion products as a result of burning it?
10. Part of the fusion process in the Sun involves the fusion of two protons into a deuteron. This results in the release of 0.42 MeV of energy. What is the mass equivalent of this energy release?

8.7 Exercise 3: Exam practice questions

Question 1 (3 marks)

A car accelerates from 0 to 100 km h^{-1} in 10 s.

- a. What is its acceleration relative to the road? **1 mark**
- b. What is its acceleration relative to a car travelling at 100 km h^{-1} in the opposite direction? **1 mark**
- c. Would you describe the acceleration as absolute, relative, invariant or arbitrary? **1 mark**

Question 2 (2 marks)

Explain how Einstein's second postulate makes sense of the results of the Michelson–Morley experiment.

Question 3 (2 marks)

Explain why time dilation must occur for all clocks, not just the light clock.

Question 4 (4 marks)

The nearest star, apart from the Sun, is 4.2 light-years distant.

- a. How far is it to that star according to astronauts in a spacecraft travelling at $0.7c$? **2 marks**
- b. How long would it take to get there in this spacecraft? **1 mark**
- c. How long will the journey take, based on measurements from Earth? (Assume that Earth is stationary relative to the star.) **1 mark**

Question 5 (6 marks)

A spacecraft ($L_0 = 80 \text{ m}$) travels past a space station at speed $0.7c$. Its radio receiver is on the tip of its nose. The space station sends a radio signal the instant the tail of the spacecraft passes the space station.

- a. What is the length of the spacecraft in the reference frame of the space station? **2 marks**
- b. How far from the space station is the nose of the spacecraft when it receives the radio signal from the reference frame of the space station? **2 marks**
- c. What is the time taken for the radio signal to reach the nose of the spacecraft, according to those on the space station? **1 mark**
- d. What is the time taken for the radio signal to reach the nose, according to those on the spacecraft? **1 mark**

Question 6 (3 marks)

An astronaut in a spacecraft moves past Earth at $0.8c$ and measures his mass. (He has no weight in his inertial reference frame.) According to him, his mass is 70 kg.

- a. What is his mass according to an observer on Earth?
- b. How much energy was required to give him the extra mass?

2 marks**1 mark****Question 7 (1 mark)**

Calculate the kinetic energy of a 10 000 kg asteroid travelling at $0.6c$.

Question 8 (3 marks)

Calculate the speed of a 10 kg meteorite that has 5.0×10^8 J of kinetic energy.

Question 9 (5 marks)

- a. Write the most common sequence of nuclear fusion reactions in the Sun. **3 marks**
- b. How does the total mass of the particles on the left-hand side of the arrow in each equation compare with the total mass of the particles on the right-hand side? **2 marks**

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UNIT 3 | AREA OF STUDY 3 REVIEW

AREA OF STUDY 3 How fast can things go?

OUTCOME 3

Investigate motion and related energy transformations experimentally, analyse motion using Newton's laws of motion in one and two dimensions, and explain the motion of objects moving at very large speeds using Einstein's Theory of Special Relativity.

PRACTICE EXAMINATION

STRUCTURE OF PRACTICE EXAMINATION		
Section	Number of questions	Number of marks
A	20	20
B	5	20
Total		40

Duration: 50 minutes

Information:

- This practice examination consists of two parts. You must answer all question sections.
- Pens, pencils, highlighters, erasers, rulers and a scientific calculator are permitted.
- You may use the VCAA Physics formula sheet for this task.



Resources



Weblink VCAA Physics formula sheet

SECTION A — Multiple choice questions

All correct answers are worth 1 mark each; an incorrect answer is worth 0.

Use the following information to answer questions 1, 2 and 3:

A small van, with a mass of 2500 kg, was travelling at 25 m s^{-1} south when it collided with the rear of a car travelling in the same direction. The velocity of the van is reduced to 15 m s^{-1} south over a time interval of 0.80 s.

- Which of the following best describes the average acceleration of the van?

A. 12.5 m s^{-2} north	B. 12.5 m s^{-2} south
C. 8.0 m s^{-2} north	D. 8.0 m s^{-2} south
- What is the impulse on the car by the van? You may assume the collision is isolated.

A. 12 500 N s north	B. 12 500 N s south
C. 25 000 N s north	D. 25 000 N s south
- How much kinetic energy was lost by the van during the collision?

A. $1.3 \times 10^4 \text{ J}$	B. $2.8 \times 10^5 \text{ J}$
C. $5.0 \times 10^5 \text{ J}$	D. $7.8 \times 10^5 \text{ J}$

Use the following information to answer questions 4, 5 and 6:

A golfer tees off by hitting a golf ball with a velocity of 40 m s^{-1} at an angle of 34° to the horizontal. You may ignore the effects of air resistance.

4. Assuming the ball lands at the same height as the height from which it was hit, which of the following is the closest to the expected range of the golf ball?
A. 61 m
B. 99 m
C. 134 m
D. 151 m
5. What is the maximum height the ball attains above the point where it was hit?
A. 26 m
B. 46 m
C. 56 m
D. 68 m
6. If the effects of air resistance are taken into consideration, what would happen to the range and the maximum height attained by the golf ball?
A. The range would increase and the maximum height would decrease.
B. The range would increase and the maximum height would increase.
C. The range would decrease and the maximum height would increase.
D. The range would decrease and the maximum height would decrease.

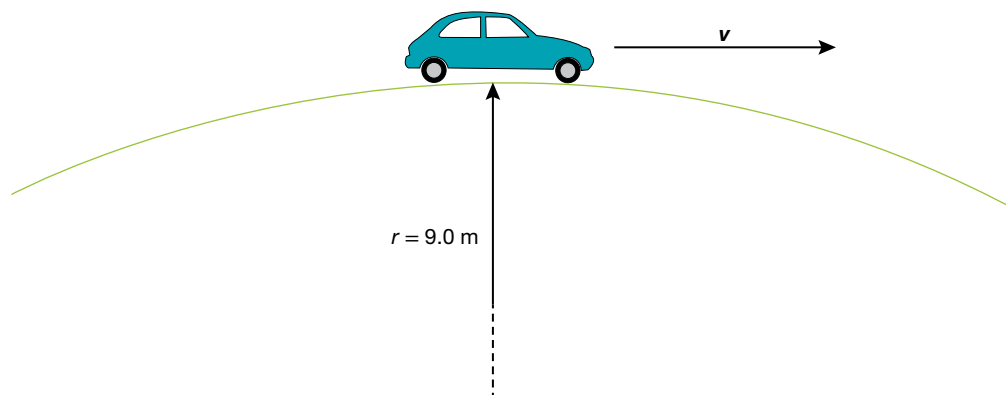
Use the following information to answer questions 7 and 8:

A cyclist and her bicycle, total mass of 78 kg, negotiates a roundabout at a constant speed of 12 m s^{-1} . The diameter of her path around the roundabout is 18 m.

7. What is nearest value for the net force on the tyres of the bicycle?
A. 52 N
B. 100 N
C. 620 N
D. 1200 N
8. The cyclist increases her speed to 14 m s^{-1} ; however, she decides to change the diameter of her path around the roundabout so that the net force on the bicycle tyres remains the same. What should she do?
A. Increase the diameter of her path
B. Decrease the diameter of her path
C. Retain the same diameter of her path
D. There is insufficient information to determine the change required.

Use the following information to answer questions 9 and 10:

A car is travelling over a crest with a radius of 9.0 m at a constant speed, v , as shown in the following diagram.



9. The normal force on the car when it is at the top of the crest is zero ($F_N = 0 \text{ N}$). At what speed is the car travelling?
A. 4.9 m s^{-1}
B. 9.4 m s^{-1}
C. 77 m s^{-1}
D. 96 m s^{-1}
10. The car travels over the crest again but this time at a lower speed. Which of the following is the expected normal force on the car?
A. $F_N = 0 \text{ N}$
B. $F_N < 0 \text{ N}$
C. $F_N > 0 \text{ N}$
D. Unknown, since there is insufficient information

Use the following information to answer questions 11 and 12:

A spaceship travels past Earth at a velocity of $v = 0.7c$ and is heading towards the Moon. It transmits an electromagnetic signal that propagates in all directions at the speed of light, c .

11. To an observer on Earth, what is the speed of the electromagnetic signal just as the spaceship passes Earth?
- A. $0.3c$
 - B. $0.7c$
 - C. c
 - D. $1.7c$
12. An observer on the Moon happens to also observe the spaceship and detect the electromagnetic signal. What is the speed of the electromagnetic signal, to this observer, as the spaceship approaches the Moon?
- A. $0.3c$
 - B. $0.7c$
 - C. c
 - D. $1.7c$

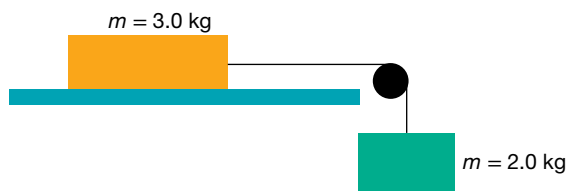
Use the following information to answer questions 13 and 14:

A particle accelerator is used to accelerate electrons. The kinetic energy imparted to each electron is estimated to be 8.2×10^{-14} J, and this is achieved with a uniform electric field between two parallel plates.

13. What is the voltage difference between the two parallel plates?
- A. 5.1×10^3 V
 - B. 5.1×10^4 V
 - C. 5.1×10^5 V
 - D. 5.1×10^6 V
14. The accelerated electrons attain relativistic velocities. Which of the following is closest to the value of the Lorentz factor of the electrons?
- A. 1.0
 - B. 1.5
 - C. 2.0
 - D. 2.5
15. Neutrino particles from the Sun often pass through the Earth without interacting at all gravitationally, electrically or magnetically. One such neutrino passes through the Earth at a velocity of $v = 0.87c$. The Earth's diameter is 1.3×10^7 m measured in our frame of reference. Measured from the neutrino's frame of reference, what is the Earth's diameter?
- A. 3.2×10^6 m
 - B. 6.4×10^6 m
 - C. 1.3×10^7 m
 - D. 2.6×10^7 m

Use the following information to answer questions 16 and 17:

A 3 kg mass is resting on a frictionless surface. It is connected via a frictionless pulley to a 2 kg mass by a massless cable. The 2 kg mass is then allowed to fall due to gravity.

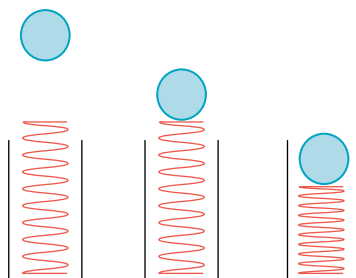


16. What is the magnitude of the acceleration of both masses?
- A. 1.9 m s^{-2}
 - B. 3.9 m s^{-2}
 - C. 5.9 m s^{-2}
 - D. 7.9 m s^{-2}

17. If the two masses are swapped, what would happen to the magnitude of the acceleration in question 16 when the falling mass (3.0 kg) is allowed to fall?
- It would increase.
 - It would decrease.
 - It would stay the same.
 - There is insufficient information to determine this.
18. Astronaut David Scott landed on the Moon in 1971. He dropped a hammer and a feather from a height of about 1.0 m onto the surface of the Moon. Both the hammer and feather landed at the same instant. Which is the best explanation for this observation compared with what usually happens on Earth?
- The gravitational field strength of the Moon is less than that of the Earth.
 - The gravitational field strength of the Moon is greater than that of the Earth.
 - There is no air on the Moon.
 - There is no water on the Moon.

Use the following information to answer questions 19 and 20:

A bowling ball is allowed to fall, due to gravity, onto a spring, as shown in the following diagram. As it comes into contact with the spring, it begins to compress the spring. The ball continues to compress the spring until it stops momentarily. After this moment, the spring begins to rebound and push up against the bowling ball. Air resistance may be ignored.



19. The magnitude of the acceleration of the bowling ball when it just touches the spring is:
- Equal to g
 - Less than g
 - Greater than g
 - Equal to 0
20. What is the direction of the acceleration of the bowling ball just after it touches the spring?
- Upwards
 - Downwards
 - Neither upwards nor downwards
 - Unknown, since there is insufficient information

SECTION B — Short answer questions

Question 1 (4 marks)

A minibus of mass 1700 kg travelling with a velocity of 25 m s^{-1} west collides head-on with a solid wall. The minibus rebounds with a velocity of 5.0 m s^{-1} east. The minibus is in contact with the wall for 0.80 s. Assume that no external force acts on this system.

- What is the initial momentum of the minibus? **1 mark**
- What is the change of momentum of the minibus while it is in contact with the wall? **1 mark**
- Calculate the average force that the wall exerts on the minibus during the collision. **1 mark**
- State the average force that the minibus exerts on the wall during the collision. **1 mark**

Question 2 (5 marks)

A 3.0 kg model car starts from rest on an inclined plane. The car is initially 1.7 m above ground level. After descending the ramp, the car comes to rest along a rough carpet surface, taking 4.0 m to completely stop. Ignore any friction effects on the ramp.

- a. Determine the initial gravitational potential energy of the car. **1 mark**
- b. What is the kinetic energy of the car as it first leaves the ramp and meets the carpet? **1 mark**
- c. Calculate the maximum speed of the car. **1 mark**
- d. What is the work done on the car by the carpet? **1 mark**
- e. Determine the average force exerted on the car by the carpet. **1 mark**

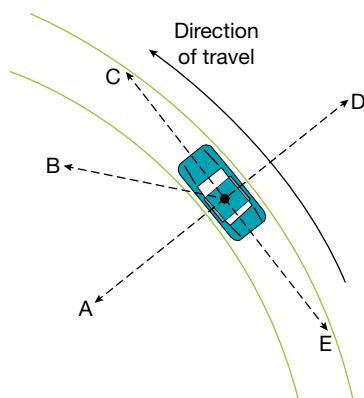
Question 3 (4 marks)

A student is carrying out an experiment to investigate projectile motion. She fires a metal ball horizontally from a bench top. The bench top is 0.90 m above the floor, and the ball hits the floor at a distance of 1.6 m from a point directly below the edge of the bench. Assume that the floor is horizontal, and air resistance is negligible.

- a. What is the elapsed time from when the ball leaves the edge of the bench to when it hits the floor? **1 mark**
- b. At what speed did the ball leave the bench? **1 mark**
- c. What is the speed of the ball just before it strikes the floor? **2 marks**

Question 4 (3 marks)

A car of mass 1100 kg is travelling at a constant speed of 12 m s^{-1} on a flat section of road that forms an arc of a circle of radius 30 m. This situation is shown in the following diagram.



- a. What is the magnitude of the net force acting on the car? **1 mark**
- b. Which of the arrows A to E gives the direction of the net force acting on the car at the instant shown? **1 mark**

A road engineer has proposed replacing this flat section of road with a banked curve. The angle of the curve is such that the same car, mass 1100 kg, could travel at the same speed of 12 m s^{-1} around the banked curve, without any sideways friction on the tyres.

- c. What should be the angle of the banked curve to the horizontal? **1 mark**

Question 5 (4 marks)

Travelling at 70% of the speed of light, a spaceship sets out on a journey to a star that is $3.9 \times 10^{18} \text{ m}$ from Earth.

- a. Calculate the Lorentz factor for this spaceship, to 4 significant figures. **1 mark**
- b. How long does the trip take, according to observers on Earth? **1 mark**
- c. How long does the trip take according to the astronauts on the spaceship? **2 marks**

ASSESSMENT TASK — DATA ANALYSIS

In this task, you will be required to evaluate the data related to a test collision between two cars and evaluate the collision from the perspectives of both momentum and energy.

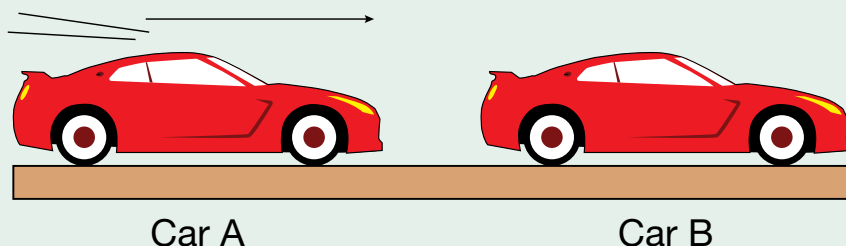
- This practice SAC requires you to respond to the provided stimulus material and analyse data.
- You may use the VCAA Physics formula sheet and a scientific calculator for this task.

Total time: 55 minutes (5 minutes reading, 50 minutes writing)

Total marks: 36 marks

INVESTIGATING COLLISIONS BETWEEN CARS

At a vehicle testing facility, collisions between cars are used to determine safety measures for passengers. In one test, car A, of mass 1400 kg, collides with stationary car B, of mass 800 kg.



In the following table, the velocities of the two cars A and B are given for each 2.0 millisecond interval during which the collision is occurring. The table is incomplete.

Time (ms)	Velocity of car A (m s^{-1})	Velocity of car B (m s^{-1})
0.0	14.0	0
2.0	13.0	1.4
4.0	12.0	2.8
6.0		
8.0		
10.0		
12.0	8.0	8.4
14.0	7.0	9.8
16.0	7.0	9.8

You must answer all questions in both part A and part B.

PART A: Analysing the collision from the perspective of momentum

1. Calculate the initial momentum for car A and the initial momentum for car B and hence the total momentum of the two cars before the collision.
2. Assuming the acceleration of both cars A and B is uniform, complete the missing entries for velocity in the table.
3. Graph the velocities (using a line graph) of both car A and car B versus time on the one set of axes. Label the axes and each graph clearly, using a well-chosen scale for your graph.
4. Use your graph to estimate the time when the cars are travelling at the same speed.

5. Calculate the final momentum for car A and the final momentum for car B and hence the total momentum of the two cars after the collision.
6. Does it appear that the collision between the two cars is an isolated one? What evidence do you have to support your choice?
7. Is it likely that the road surface exerted a force on both cars during the collision? Give an explanation to support your choice.
8. Use your graph to calculate the average acceleration of each of the cars during the collision.
9. Determine the average force acting on car A and the average force acting on car B during the collision. Are the two forces the same or different in value? Explain your answer. Under what conditions would the two forces be the same?
10. Calculate the distance travelled by car B during the collision.

PART B: Analysing the collision from the perspective of energy

11. Calculate the initial kinetic energy for each of car A and car B and hence the total kinetic energy of the two cars before the collision.
12. Calculate the final kinetic energy for each of car A and car B and hence the total kinetic energy of the two cars after the collision.
13. Is the collision an elastic collision? Explain your choice using your results for questions 11 and 12.
14. Calculate the amount of energy that has been transformed from the initial kinetic energy of car A into other forms. State the most likely form of the transformed energy.



Resources

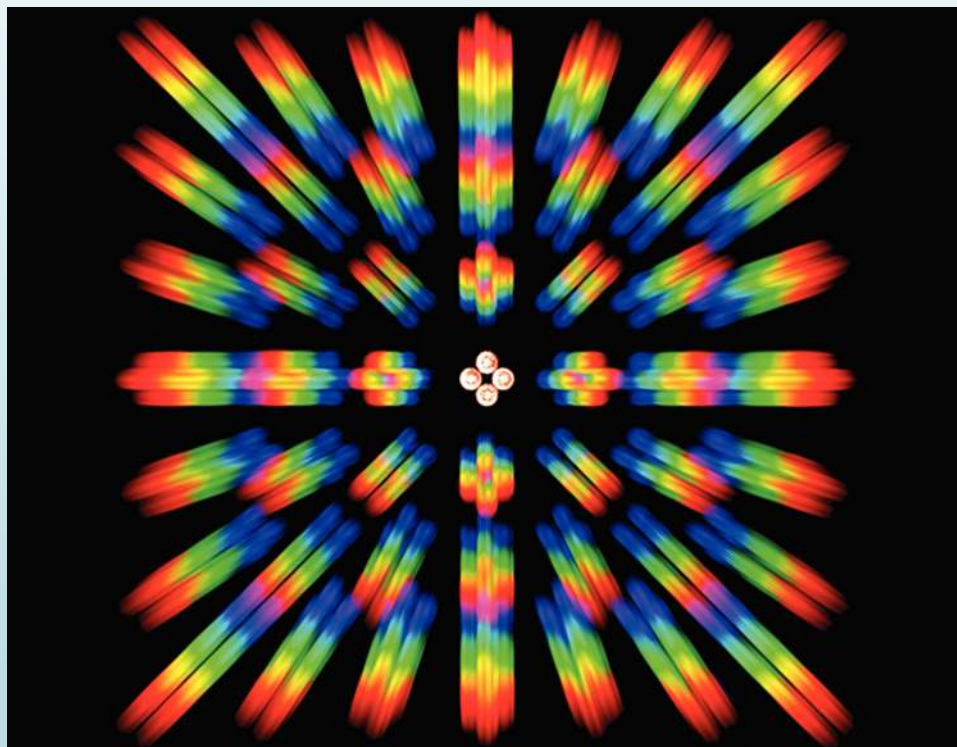


Digital document School-assessed coursework (doc-32301)

UNIT 4

HOW CAN TWO CONTRADICTORY MODELS EXPLAIN BOTH LIGHT AND MATTER?

In this unit, you will explore the wave and particle theories, and how they are used to model phenomena related to both light and matter, which have remarkable similarities in their properties. You will gain an understanding of waves and develop knowledge on how the wave theory has challenged previous thinking about the relationship between light and matter. You will also conduct a practical investigation related to the knowledge and skills developed across Units 3 and 4.



AREA OF STUDY	OUTCOME	TOPICS
1. How can waves explain the behaviour of light?	Apply wave concepts to analyse, interpret and explain the behaviour of light.	9. Properties of mechanical waves 10. Light as a wave
2. How are light and matter similar?	Provide evidence for the nature of light and matter, and analyse the data from experiments that support this evidence.	11. Behaviour of light as a particle 12. Light and matter
3. Practical investigation	Design and undertake a practical investigation related to waves, fields or motion, and present methodologies, findings and conclusions in a scientific poster.	13. Practical investigation

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9 Properties of mechanical waves

9.1 Overview

Numerous **videos** and **interactivities** are available just where you need them, at the point of learning, in your digital formats, learnON and eBookPLUS at www.jacplus.com.au.

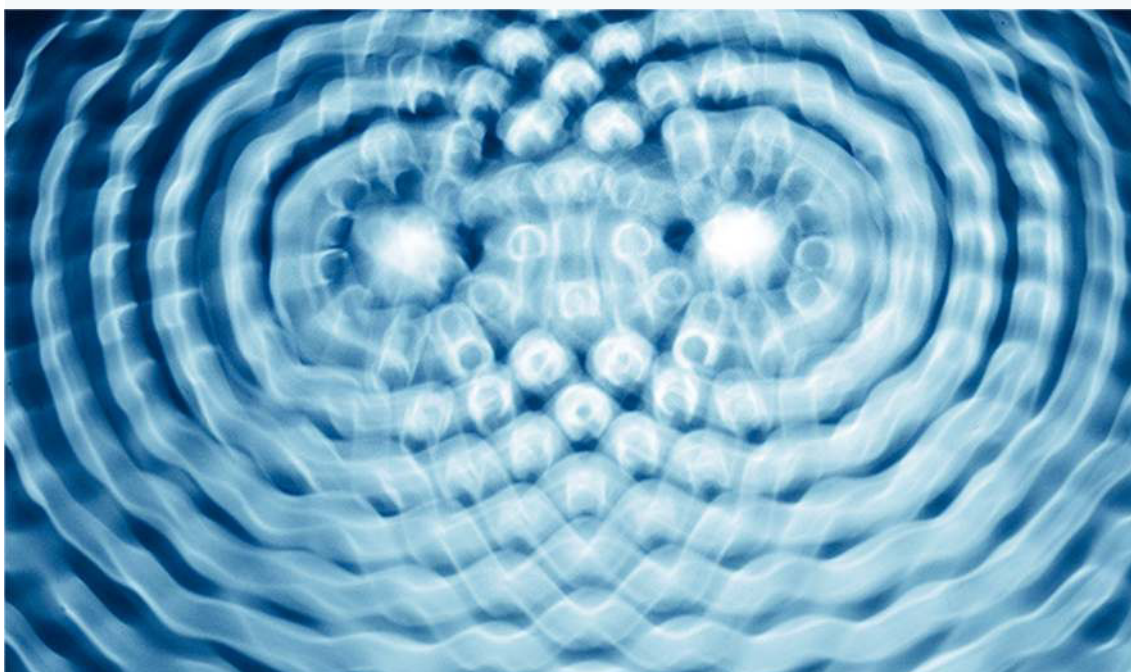
9.1.1 Introduction

In Unit 3 you learned that Newton's laws of motion and kinematics, with minor corrections described by Einstein's Theory of Special Relativity along with the theory of fields, explains a great deal of the natural world. Yet there is another common phenomenon — the behaviour of waves. Consider the ripple of waves on the surface of water, waves on a string such as a guitar, the propagation of sound through a medium, and the properties of light.

Waves can also transfer energy from one place to another. They seem to travel or propagate at a fixed speed in a medium regardless of the energy they contain. Waves have a tendency to spread out in all directions, unlike a beam of particles. Waves can pass through each other: they don't collide with each other in the same way particles collide; instead, they combine and interfere. In short, waves do things that particles can't, and particles do things that waves can't.

Waves can diffract, interfere, propagate through a medium, reflect and refract. They have a frequency, a wavelength and amplitude. You'll see in Unit 4 that both a wave and a particle model are needed to better understand natural phenomena.

FIGURE 9.1 The study of waves reveals many important concepts in physics.



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9.1.2 What you will learn

KEY KNOWLEDGE

After completing this topic, you will be able to:

- explain a wave as the transmission of energy through a medium without the net transfer of matter
- distinguish between transverse and longitudinal waves
- identify the amplitude, wavelength, period and frequency of waves
- calculate the wavelength, frequency, period and speed of travel of waves using: $v = f\lambda = \frac{\lambda}{T}$
- investigate and analyse theoretically and practically constructive and destructive interference from two sources with reference to coherent waves and path difference: $n\lambda$ and $(n - \frac{1}{2})\lambda$ respectively
- explain qualitatively the Doppler effect
- explain resonance as the superposition of a travelling wave and its reflection, and with reference to a forced oscillation matching the natural frequency of vibration
- analyse the formation of standing waves in strings fixed at one or both ends
- investigate and explain theoretically and practically diffraction as the directional spread of various frequencies with reference to different gap width or obstacle size, including the qualitative effect of changing the $\frac{\lambda}{w}$ ratio.

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PRACTICAL WORK AND INVESTIGATIONS

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



Resources



Digital documents Key science skills — VCE Physics Units 1–4 (doc-32112)

Key terms glossary (doc-32113)

Practical investigation logbook (doc-32111)



To access key concept summaries and past VCAA exam questions download and print the **studyON: Revision and past VCAA exam question booklet** (sonr-0058).

9.2 Explaining waves as the transmission of energy

KEY CONCEPTS

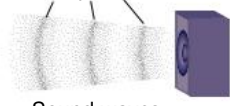
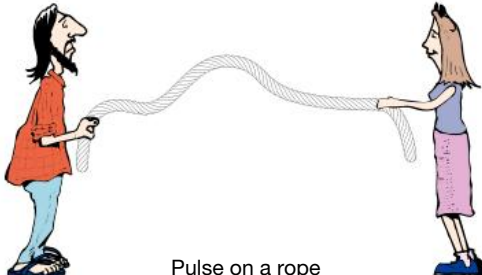
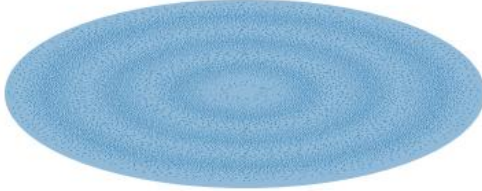
- Explain a wave as the transmission of energy through a medium without the net transfer of matter
- Distinguish between transverse and longitudinal waves

A **wave** is a disturbance that travels through a medium from the source to the detector without any movement of matter. Particles of the matter vibrate up and down or back and forth about their rest position, transferring energy from one place to another. Waves therefore transfer energy without any net movement of particles. **Periodic waves** are disturbances that repeat themselves at regular intervals. Periodic waves propagate by the disturbance in part of a medium being passed on to other parts of the medium. In this way, the disturbance travels but the medium stays where it is.

Looking at the examples in table 9.1, two different types of waves can be identified. For the pulse on the rope and the ripples on the water surface, the disturbance is at right angles to the direction the wave is travelling. These types of waves are called **transverse waves**.

In the examples of the sound wave travelling through air and the compression moving along the spring, the disturbance is parallel to the direction the wave is travelling. These types of waves are called **longitudinal waves**.

TABLE 9.1 Some examples of waves

Wave	Source	Medium	Detector	Disturbance	Type of wave
Sound	Push/pull of loudspeaker Compressions  Sound waves Speaker	Air	Ear	Increase and decrease in air pressure	Longitudinal wave
Rope	Upward flick of hand  Pulse on a rope	Rope	Person at other end	Section of rope moves up and then back down	Transverse wave
Stretched spring	Push of hand Compressions  Compressions moving along a stretched spring	Coils in the spring	Person at other end	Bunching of coils	Longitudinal wave
Water	Dropped stone  Ripples on water	Water	Bobbing cork placed in the water	Water surface at a point moves up then back down	Transverse wave

9.2 EXERCISE

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- How is a periodic wave different from a single pulse moving along a rope?
 - How is a periodic longitudinal wave different from a transverse wave?
- Ripples on a pond are caused when drops of water fall on the surface at the rate of 5 drops every 10 seconds. Calculate the following:
 - the time, in seconds, between consecutive ripples at a point on the surface of the pond

- (b) the type of wave generated when drops of water fall onto the surface of a pond.
3. What is the speed of sound in air if it travels a distance of 996 m in 3.00 s?

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9.3 Properties of waves

KEY CONCEPTS

- Identify the amplitude, wavelength, period and frequency of waves
- Calculate the wavelength, frequency, period and speed of travel of waves using: $v = f\lambda = \frac{\lambda}{T}$
- Explain qualitatively the Doppler effect

9.3.1 Wavelength, frequency and speed

The **frequency** of a periodic wave is the number of times that it repeats itself every second. Frequency is measured in hertz (Hz) and $1 \text{ Hz} = 1 \text{ s}^{-1}$. Frequency can be represented by the symbol f .

The **period** of a periodic wave is the time it takes a source to produce a complete wave. This is the same as the time taken for a complete wave to pass a given point. The period is measured in seconds and is represented by the symbol T .

The period of a wave is the reciprocal of its frequency. For example, if five complete waves pass every second, that is, $f = 5 \text{ Hz}$, then the period (the time for one complete wavelength to pass) is

$\frac{1}{5} = 0.2$ seconds. In other words,

$$f = \frac{1}{T} \Rightarrow T = \frac{1}{f}$$

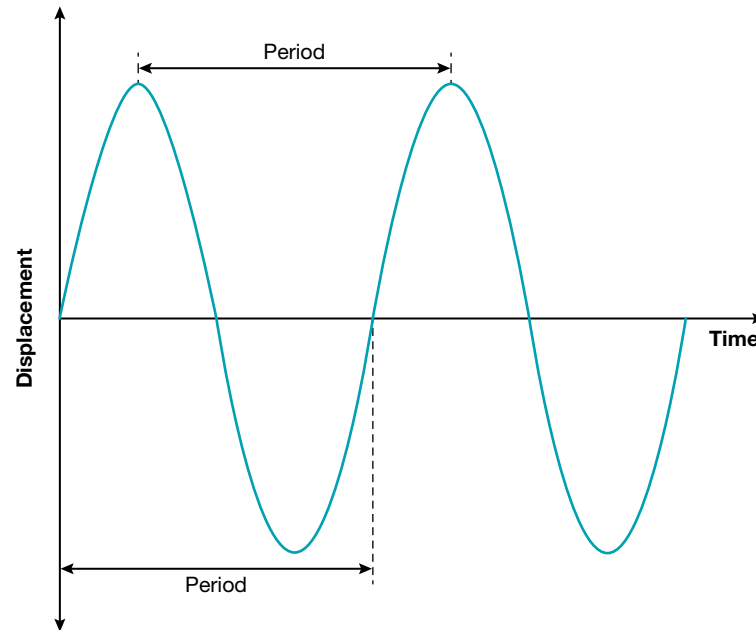
where: f is the frequency of the wave, in Hz

T is the period of the wave, in s

A displacement–time graph, as shown in figure 9.2, tracks the movement of a single point on a transverse wave over time as the wave moves through that point. In other words, it shows how the displacement of a single point on the wave varies over time. The period of the wave can be easily identified from this graph.

The **amplitude** of a wave is the size of the maximum disturbance of the medium from its normal state. The units of amplitude vary from wave type to wave type. For example, in sound waves the amplitude is measured in the units of pressure, whereas the amplitude of a water wave would normally be measured in centimetres or metres.

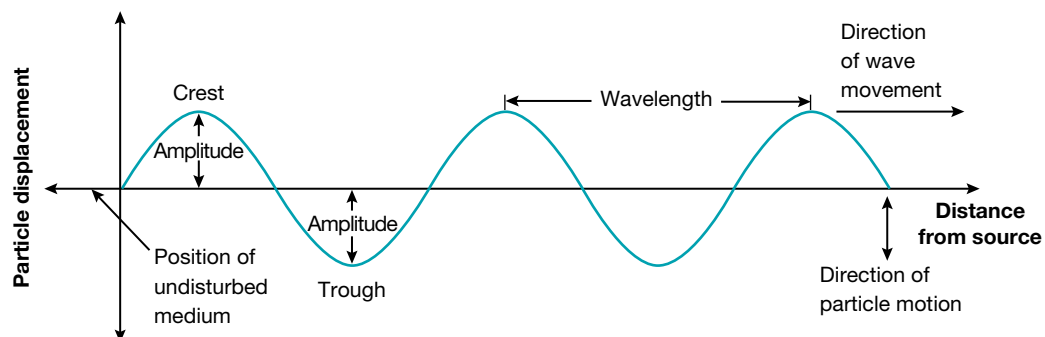
FIGURE 9.2 Displacement–time graphs: the movement of a single point on a transverse wave over time



The **wavelength** is the distance between successive corresponding parts of a periodic wave. The wavelength is also the distance travelled by a periodic wave during a time interval of one period. For transverse periodic waves, the wavelength is equal to the distance between successive crests (or troughs). For longitudinal periodic waves, the wavelength is equal to the distance between two successive compressions (regions where particles are closest together) or rarefactions (regions where particles are furthest apart). Wavelength is represented by the symbol λ (lambda).

The displacement of all particles along the length of a transverse wave can be represented in a displacement–distance graph as shown in figure 9.3. A displacement–distance graph is like a snapshot of the wave at an instant in time. The amplitude and wavelength of the wave can be easily identified from this graph.

FIGURE 9.3 Displacement–distance graphs: particle displacements along a transverse wave



The speed, v , of a periodic wave is related to the frequency and period. In a time interval of one period, T , the wave travels a distance of one wavelength, λ . Thus:

$$\text{speed} = \frac{\text{distance}}{\text{time}} = \frac{\lambda}{T} = \frac{\lambda}{\frac{1}{f}} = f\lambda$$

This relationship can be written as:

$$v = f\lambda = \frac{\lambda}{T}$$

where: v is the speed of the wave, in m s^{-1}

f is the frequency of the wave, in Hz

λ is the wavelength of the wave, in m

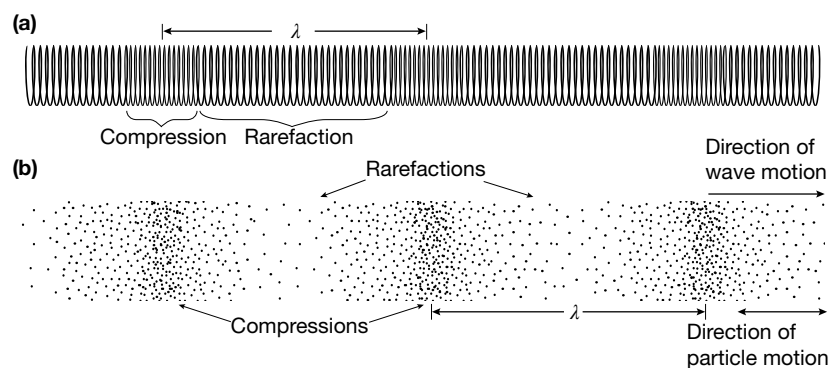
T is the period of the wave, in s

This relationship, $v = f\lambda$, is sometimes referred to as the universal wave equation.

The frequency of a periodic wave is determined by the source of the wave. The speed of a periodic wave is determined by the medium through which it is travelling. Because the wavelength is a measure of how far a wave travels during a period, if it can't be measured, it can be calculated using the formula $\lambda = \frac{v}{f}$.

In a longitudinal wave, as opposed to a transverse wave, the oscillations are parallel to the direction the wave is moving. Longitudinal waves can be set up in a slinky, as shown in figure 9.4a. Sound waves in air are also longitudinal waves, as shown in figure 9.4b. They are produced as a vibrating object (such as the arm of a tuning fork) first squashes the air, then pulls back to create a partial vacuum into which the air spreads.

FIGURE 9.4 Longitudinal waves in (a) a slinky (b) air



Longitudinal waves cause the medium to bunch up in places and to spread out in others. **Compressions** are regions in the medium where the particles are closer together. Referring to sound waves in air, compressions are regions where the air has a slightly increased pressure, as a result of the particles being closer together. **Rarefactions** are regions in the medium where the particles are spread out. This results in a slight decrease in air pressure in the case of sound waves.

The wavelength, λ , for longitudinal waves is the distance between the centres of adjacent compressions (or rarefactions). The amplitude of a sound wave in air is the maximum variation of air pressure from normal air pressure.

SAMPLE PROBLEM 1

What is the speed of a sound wave if it has a period of 2.0 ms and a wavelength of 68 cm?

THINK

1. Note down the known variables in their appropriate units. Time must be expressed in seconds and length in metres.
2. Choose the appropriate formula.
3. Substitute values for the wavelength and period and then solve for v .

WRITE

$$\begin{aligned}T &= 2.0 \text{ ms} \\&= 2.0 \times 10^{-3} \text{ s} \\\lambda &= 68 \text{ cm} \\&= 0.68 \text{ m} \\v &= f\lambda \\\Rightarrow v &= \frac{\lambda}{T} \\v &= \frac{0.68 \text{ m}}{2.0 \times 10^{-3} \text{ s}} \\&= 340 \text{ m s}^{-1}\end{aligned}$$

PRACTICE PROBLEM 1

What is the speed of a sound wave if it has a period of 1.5 ms and a wavelength of 51 cm?

SAMPLE PROBLEM 2

What is the wavelength of a sound of frequency 550 Hz if the speed of sound in air is 335 m s^{-1} ?

THINK

1. Note down the known variables in their appropriate units. Frequency must be expressed in hertz and speed in m s^{-1} .
2. Choose the appropriate formula.
3. Substitute values for the frequency and speed and then solve for the wavelength.

WRITE

$$\begin{aligned}f &= 550 \text{ Hz}, v = 335 \text{ m s}^{-1} \\v &= f\lambda \\\Rightarrow v &= \frac{\lambda}{f} \\&= \frac{335 \text{ m s}^{-1}}{550 \text{ Hz}} \\&= 0.609 \text{ m}\end{aligned}$$

PRACTICE PROBLEM 2

A siren produces a sound wave with a frequency of 587 Hz. Calculate the speed of sound if the wavelength of the sound is 0.571 m.



Resources



Digital document Investigation 9.1 Investigating waves from a slinky spring (doc-32625)

9.3.2 The Doppler effect

Everyone is familiar with the change in pitch of sound made by a car when it passes them. This is most pronounced when an emergency vehicle races by. Think of the sounds people make when mimicking passing racing cars. The sound always starts high but finishes low. This effect is called the Doppler effect, after Christian Andreas Doppler, who predicted it in 1842 before it had been observed. The Doppler effect is the result of a wave travelling at a constant speed through a medium while the source is in motion relative to the medium or if an observer is in motion relative to the medium. In either case, the frequency of the source will be different from the frequency as measured by an observer.

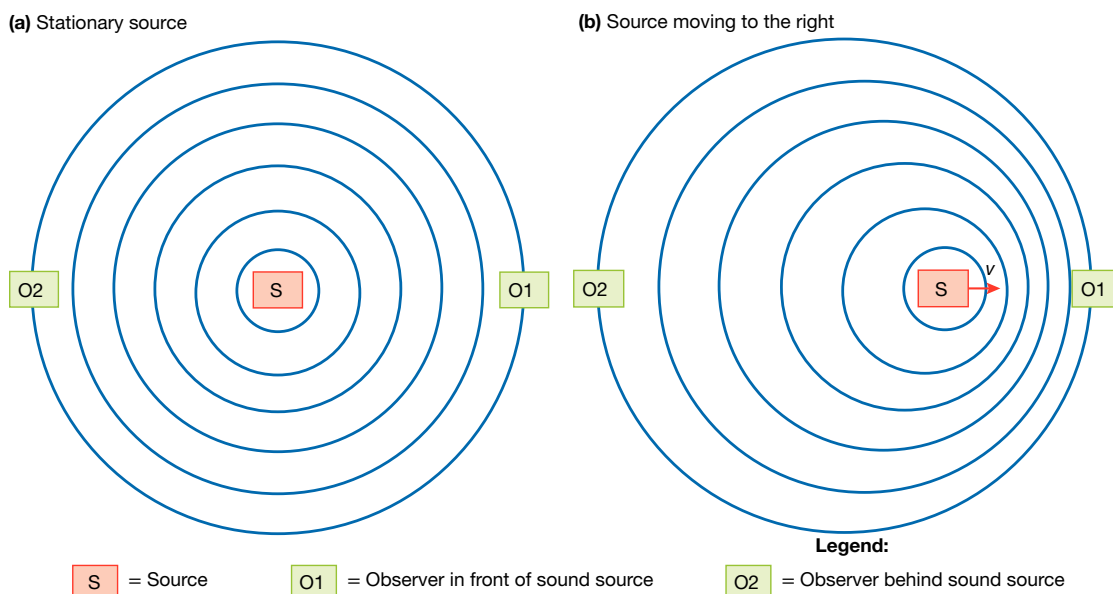
Consider a fire-engine racing to attend a fire. While it is stuck in traffic with its siren blaring, a physics student decides to measure the frequency and wavelength of the sound. The fire-engine's siren alternates between a high-pitched sound and a low-pitched sound. The student measures the high-pitched sound to have a frequency of 500 Hz and the low-pitched sound to have a frequency of 200 Hz. After determining the speed of sound to be 340 m s^{-1} , and noticing that there is no wind, the student calculates the wavelengths using $v = f\lambda$:

$$\begin{aligned}\lambda &= \frac{v}{f} \\ &= \frac{340 \text{ m s}^{-1}}{500 \text{ Hz}} \\ &= 0.680 \text{ m for the 500 Hz sound}\end{aligned}$$

$$\begin{aligned}\lambda &= \frac{v}{f} \\ &= \frac{340 \text{ m s}^{-1}}{200 \text{ Hz}} \\ &= 1.70 \text{ m for the 200 Hz sound}\end{aligned}$$

Later, the traffic jam has cleared and another fire-engine passes the physics student. The fire-engine travels at a velocity of 24 m s^{-1} relative to the road (and air). The speed of sound remains at 340 m s^{-1} through the air. The fire-engine is identical to the first one, but now the student measures the frequencies to be 538 Hz and 215 Hz as the fire-engine approaches, and 467 Hz and 187 Hz as the fire-engine moves away. The student's frequency-measuring equipment is not faulty — the student could clearly hear the pitch drop as the fire-engine passed. When the air is still, something approaching a listener will sound higher in pitch than when it is at rest relative to the listener, and will sound lower in pitch when it is moving away. Doppler cleverly predicted this result before the advent of fast fire-engines. His prediction was first confirmed experimentally by having a trumpeter play a note while passing on a 'relatively' fast-moving train.

FIGURE 9.5 The Doppler effect, (a) O1 and O2 both hear the same frequency sound. (b) O1 hears a higher frequency than O2.



The sound produced by the siren of the fire-engine is a series of pressure variations in the air. When the fire-engine produces a compression (region of higher than average air pressure) of the high-frequency sound, this compression moves forward at the speed of sound in air, 340 m s^{-1} . The next compression is produced T seconds later, where T is the period of the sound wave.

$$\begin{aligned} T &= \frac{1}{f} \\ &= \frac{1}{500 \text{ Hz}} = 0.00200 \text{ s} \end{aligned}$$

At 0.002 s, the first compression has travelled the following distance:

$$\begin{aligned} d &= vt \\ &= 340 \text{ m s}^{-1} \times 0.00200 \text{ s} = 0.680 \text{ m} \end{aligned}$$

In this time, the fire-engine has moved:

$$\begin{aligned} d &= vt \\ &= 24 \text{ m s}^{-1} \times 0.00200 \text{ s} = 0.0480 \text{ m} \end{aligned}$$

The distance between compressions is therefore:

$$\begin{aligned} \lambda &= 0.680 \text{ m} - 0.0480 \text{ m} \\ &= 0.632 \text{ m} \end{aligned}$$

For the fire-engine that was stationary, the wavelength was 0.68 m. As sound is travelling at 340 m s^{-1} relative to the student on the roadside, and $v = f\lambda$, the shorter wavelength from the approaching fire-engine will have a higher frequency than the stationary fire-engine. In this case, the detected frequency measured by the student for the 500 Hz sound as the fire-engine approached at 24 m s^{-1} would be:

$$\begin{aligned} f &= \frac{v}{\lambda} \\ &= \frac{340 \text{ m s}^{-1}}{0.632 \text{ m}} = 538 \text{ Hz} \end{aligned}$$

In summary, when a source of waves is approaching an observer, the frequency appears to be greater than the source frequency. When the source of waves is receding from the observer, the frequency appears to be smaller than the source frequency. Likewise, if an observer is approaching a stationary source, the frequency appears higher and, if the observer is receding from the stationary source, the frequency appears lower. The equations for calculating these changes in frequency due to motion of a source and observer relative to a medium are not examinable.



Resources



Digital document Investigation 9.2 The Doppler effect (doc-32321)



Weblink Doppler effect applet

9.3 EXERCISE

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1. How far does a periodic wave travel in one period? Give your answer in terms of the wavelength of the periodic wave.
2. Do loud sounds travel faster than soft sounds? Justify your answer.
3. A marching band on the other side of a sports oval appears to be 'out of step' with the music. Explain why this might happen.
4. You arrive late to an outdoor concert and have to sit 500 m from the stage. Will you hear high-frequency sounds at the same time as low-frequency sounds if they are played simultaneously? Explain your answer.
5. A loudspeaker is producing a note of 256 Hz. How long does it take for 200 wavelengths to interact with your ear?
6. What is the wavelength of a sound that has a speed of 340 m s^{-1} and a period of 3.00 ms ?
7. What is the speed of a sound if the wavelength is 1.32 m and the period is $4.00 \times 10^{-3} \text{ s}$?
8. The speed of sound in air is 340 m s^{-1} and a note is produced that has a frequency of 256 Hz.
 - (a) What is its wavelength?
 - (b) This same note is now produced in water where the speed of sound is $1.50 \times 10^3 \text{ m s}^{-1}$. What is the new wavelength of the note?
9. Copy and complete the following table by using the wave formula.

$v \text{ (m s}^{-1}\text{)}$	$f \text{ (Hz)}$	$\lambda \text{ (m)}$
	500	0.67
	12	25
1500		0.30
60		2.5
340	1000	
260	440	

10. A stationary siren is producing a sound. The siren vibrates at 100 Hz to make the sound. One observer measures the sound to have a frequency of 110 Hz. A second observer measures the sound to have a frequency of only 90 Hz. Explain why this is the case.

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9.4 Diffraction of waves

KEY CONCEPT

- Investigate and explain theoretically and practically diffraction as the directional spread of various frequencies with reference to different gap width or obstacle size, including the qualitative effect of changing the $\frac{\lambda}{w}$ ratio.

Waves spread out as they pass around objects or travel through gaps in barriers. This is readily observable in sound and water waves. For example, you can hear someone speaking in the next room if the door is open, even though there is not a direct straight line between the person and your ears.

Diffraction is the directional spread of waves as they pass through gaps or pass around objects. The amount of diffraction depends on two factors:

- the wavelength of the wave, λ
- the width of the gap or the size of the obstacle, for which w will be used as the variable.

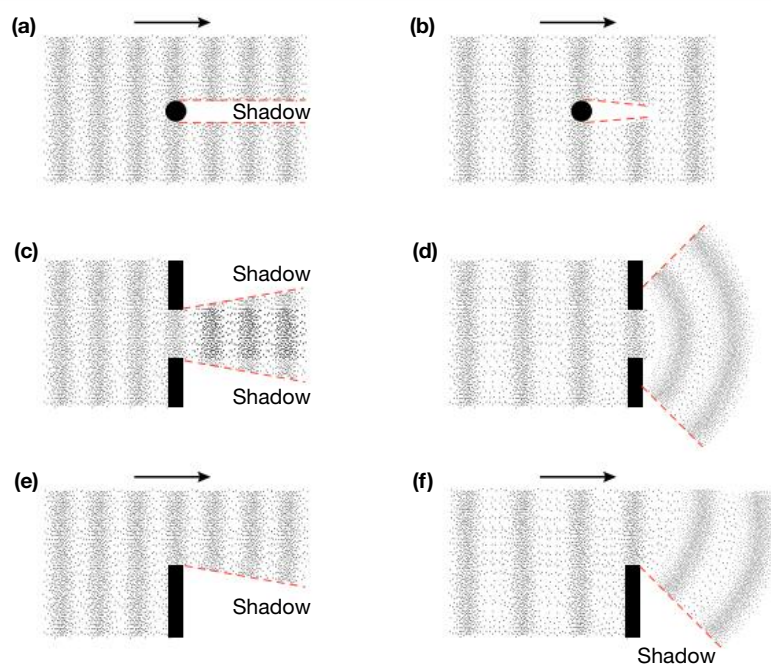
For example, the spreading out of sound from loudspeakers is the result of diffraction. The sound waves spread out as they are generated by the speaker cone of the loudspeaker. Without the effects of diffraction, hardly any sound would be heard other than from directly in front of the speaker cone. In this case, w is associated with the diameter of the speaker cone.

9.4.1 Varying the wavelength and gap width

The diffraction of sound, and indeed light, can be modelled with water waves in a ripple tank. Figure 9.6 shows the way that water waves diffract in various situations. The diagrams apply equally well to the diffraction of sound waves and light.

Importantly, the larger the wavelength λ (in figures 9.6b, d and f), the larger or more significant the amount of diffraction.

FIGURE 9.6 Diffraction of water waves: (a) short wavelength around an object, (b) long wavelength around the same object, (c) short wavelength through a gap, (d) long wavelength through the same gap, (e) short wavelength around the edge of a barrier and (f) long wavelength around the edge of the same barrier

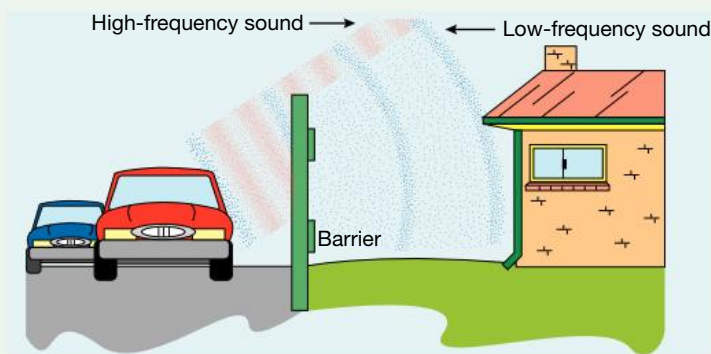


The region where waves don't travel is called a shadow. The amount of diffraction that occurs depends on the wavelength of the waves. The longer the wavelength, the more diffraction occurs. As a general rule, if the wavelength is less than the size of the object, there will be a significant shadow region.

When waves diffract through a gap of width w in a barrier, the ratio $\frac{\lambda}{w}$ is important. As the value of this ratio increases, so too does the amount of diffraction that occurs.

SOUND BARRIERS NEAR FREEWAYS

Barriers built next to freeways are effective in protecting nearby residents from high-frequency sounds as these have short wavelengths and undergo little diffraction. The low-frequency sounds from motors and tyres, however, diffract around the barriers because of their longer wavelengths.



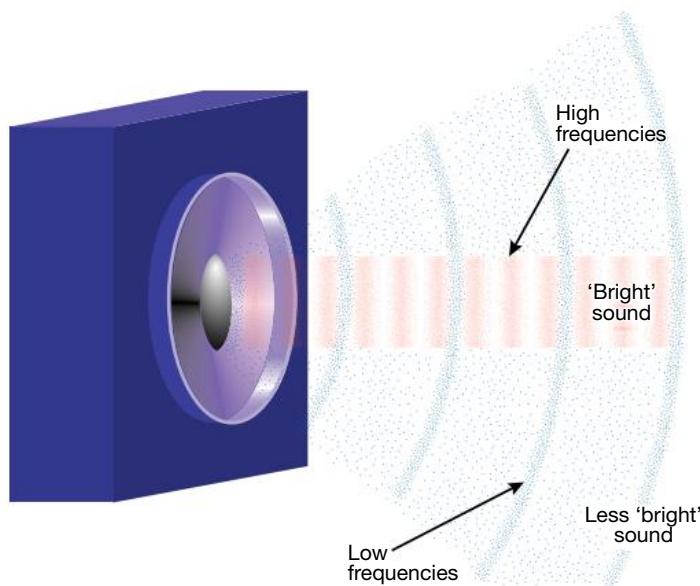
on Resources

-  **Digital documents** Investigation 9.3 Diffraction of waves in a ripple tank (doc-31609)
Investigation 9.4 Observing water waves (doc-31616)

9.4.2 Directional spread of different frequencies

The opening at the end of a wind instrument such as a trumpet, the size of someone's mouth and the size of a loudspeaker opening all affect the amount of diffraction that occurs in the sound produced. High-frequency sounds can best be heard directly in front of these devices.

FIGURE 9.7 The diffraction of high and low frequencies from a loudspeaker



When a loudspeaker plays music, it is reproducing more than one frequency at a time. Low-frequency sound waves from a bass instrument have a large wavelength; high-frequency sound waves from a trumpet have a short wavelength. Short-wavelength, high-frequency sounds do not diffract (spread out) very much when they emerge from the opening of a loudspeaker, but long wavelength sounds do. If a single loudspeaker is used, the best place to hear the sound is directly in front of the speaker.

SAMPLE PROBLEM 3

Two sirens are used to produce frequencies of 200 Hz and 10 000 Hz. Describe the spread of the two sounds as they pass through a window in a wall. The window has a width of 35 cm. Assume that the speed of sound in air is 330 m s^{-1} .

 **Teacher-led video:** SP3 (tlvd-0190)

THINK

1. First calculate the wavelengths of the sounds using the formula $v = f\lambda$.

WRITE

200 Hz siren:

$$v = f\lambda$$

$$\lambda = \frac{v}{f}$$

$$= \frac{330}{200}$$

$$= 1.65 \text{ m}$$

$$= 165 \text{ cm}$$

10 000 Hz siren:

$$v = f\lambda$$

$$\lambda = \frac{v}{f}$$

$$= \frac{330}{10\,000}$$

$$= 0.0330 \text{ m}$$

$$= 3.30 \text{ cm}$$

2. Diffraction is more significant when the wavelength λ is large compared to w , in this case the width of the window.

There will be a large diffraction spread for the sound of wavelength 165 cm (200 Hz) because the wavelength is large compared

with the opening: $\frac{\lambda}{w} = \frac{165 \text{ cm}}{35 \text{ cm}} = 4.7$

There will be a very small diffraction spread for the sound of wavelength 3.3 cm (10 000 Hz) because the wavelength is small compared with the opening:

$$\frac{\lambda}{w} = \frac{3.3 \text{ cm}}{35 \text{ cm}} = 0.094$$

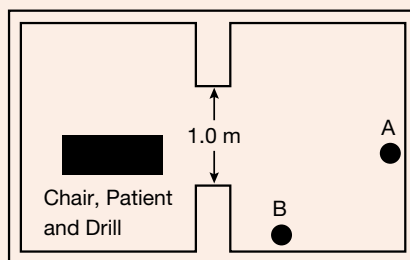
PRACTICE PROBLEM 3

Two sirens are used to produce frequencies of 150 Hz and 15 000 Hz. Describe the spread of the two sounds as they pass through a doorway. The doorway has a width of 80.0 cm. Assume that the speed of sound in air is 330 m s^{-1} .

9.4 EXERCISE

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- (a) What is diffraction?
(b) Why is diffraction an important concept to consider when designing loudspeakers?
- The following figure shows the design of a dentist's waiting room and surgery.



There are two people sitting in the waiting room at points A and B. The door to the surgery is open and it has a width of 1.0 m. A drill is operating and produces a sound of 5000 Hz frequency. The patient in the surgery groans at a frequency of 200 Hz. Assume the speed of sound is 340 m s^{-1} .

- What is the wavelength of the patient's groan?
 - What difference, if any, is there between the sound intensity levels produced by the patient's groan at points A and B? Justify your answer.
 - What difference, if any, is there between the sound intensity levels produced by the dentist's drill at points A and B? Justify your answer.
- A 1500 Hz sound and an 8500 Hz sound are emitted from a loudspeaker whose diameter is $w = 0.30 \text{ m}$. Assume the speed of sound in air is 340 m s^{-1} .
 - Calculate the wavelength of each sound.
 - A sound engineer wants to use a different speaker for the 8500 Hz sound so that it has the same amount of diffraction as the 1500 Hz sound has for the 0.30 m diameter speaker. Calculate the diameter of the new speaker if this is to occur.
 - A sound of wavelength λ passes through a gap of width w in a barrier. How will the following changes affect the amount of diffraction that occurs?
 - λ decreases
 - λ increases
 - w decreases
 - w increases

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9.5 Standing waves in strings

KEY CONCEPTS

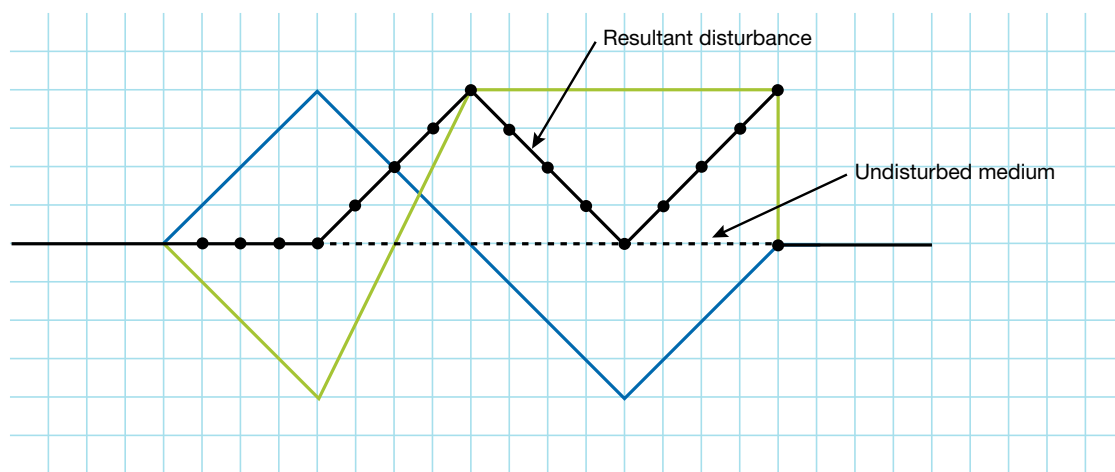
- Analyse the formation of standing waves in strings fixed at one or both ends
- Explain resonance as the superposition of a travelling wave and its reflection, and with reference to a forced oscillation matching the natural frequency of vibration

9.5.1 Superposition

Pulses (and periodic waves) pass through each other undisturbed. If this were not true, music and conversations would be distorted as the sound waves passed through each other. This can be observed when two pulses pass through each other on a spring. When the pulses are momentarily occupying the same part of the spring, the amplitudes of the individual pulses add together to give the amplitude of the total disturbance of the spring. This effect is known as **superposition** (positioning over).

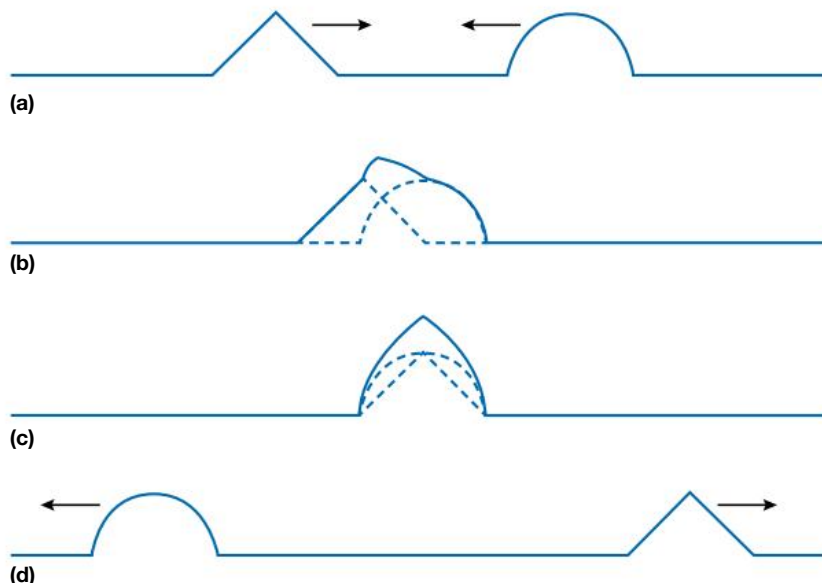
The resultant disturbance can be found by applying the superposition principle: ‘*The resultant wave is the sum of the individual waves*’. For convenience, you can add the individual displacements of the medium at regular intervals where the pulses overlap to get the approximate shape of the resultant wave. Displacements above the position of the undisturbed medium are considered to be positive and those below the position of the undisturbed medium are considered to be negative. This is illustrated in figure 9.8, in which two pulses have been drawn in green and blue with a background grid. The sum of the displacements on each vertical grid line is shown with a dot and the resultant disturbance, drawn in black, is obtained by drawing a line through the dots.

FIGURE 9.8 Determining the shape of a resultant disturbance



It is possible for a part or whole of a pulse to be ‘cancelled out’ by another pulse. When this effect occurs, destructive superposition, or **destructive interference**, is said to occur. When two pulses superimpose to give a maximum disturbance of a medium, constructive superposition, or **constructive interference**, is said to occur. This effect is shown in figure 9.9. However, when two pulses superimpose to cause a cancellation, destructive interference is said to occur. The superposition gives a small disturbance.

FIGURE 9.9 (a) Two pulses of different shapes approach each other on a spring. (b) The pulses begin to pass through each other. (c) As the pulses pass through each other, the amplitudes of the individual pulses add together to give a resultant disturbance. (d) After passing through each other, the pulses continue on undisturbed.



9.5.2 Reflection of waves

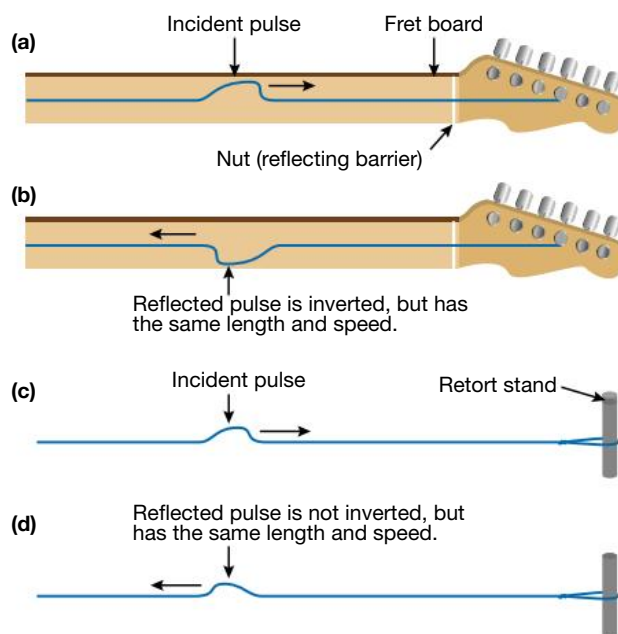
When waves arrive at a barrier, reflection occurs. Reflection is the returning of a wave into the medium in which it was originally travelling. When a wave strikes a barrier, or comes to the end of the medium in which it is travelling, at least a part of the wave is reflected.

A wave's speed depends only on the medium, so the speed of the reflected wave is the same as for the original (incident) wave. The wavelength and frequency of the reflected wave will also be the same as for the incident wave.

Reflection of transverse waves in strings

When a string has one end fixed so that it is unable to move (for example, when it is tied to a wall or is held tightly to the 'nut' at the end of a stringed instrument), the reflected wave will be inverted. This is called a change of phase. If the end is free to move, the wave is reflected upright and unchanged, so there is no change of phase. These situations are illustrated in figure 9.10.

FIGURE 9.10 Reflection of a transverse pulse on a string when (a) and (b) the end of the string is fixed (as in a guitar), and when (c) and (d) the end of the string is free to move (as with a loop supported by a retort stand)



on Resources

- Digital document** Investigation 9.5 Reflection of pulses in springs (doc-31610)
- Teacher-led video** Investigation 9.5 Reflection of pulses in springs (tlvd-0247)

9.5.3 Standing waves

Standing waves are an example of what happens when two waves pass through the same point in space. They can either interfere constructively or destructively. Interference is explained more in topic 10. The phenomenon of standing waves is an example of interference in a confined space. The restriction may be a guitar string tied down at both ends, or a trumpet closed at the mouthpiece and open at the other end, or even a drum skin stretched tightly and secured at its circumference.

A couple of questions need to be asked, though. How and where do the nodes and antinodes form? And, what does this imply about what you hear?

Transverse standing waves in strings or springs

When two symmetrical periodic waves of equal amplitude and frequency (and therefore wavelength), but travelling in opposite directions, are sent through an elastic one-dimensional medium like a string, spring or a rope, constructive interference and destructive interference occur. In fact, destructive interference occurs at evenly spaced points along the medium and it happens all the time at these points. The medium at these points never moves. Such points in a medium where waves cancel each other at all times are called **nodes**. In between the nodes are points where the waves reinforce each other to give a maximum amplitude of the resultant waveform. This is caused by constructive interference. Such points are called **antinodes**.

When this effect occurs, the individual waves are undetectable. All that is observed are points where the medium is stationary and others where the medium oscillates between two extreme positions. There seems to be a wave but it has no direction of propagation. When this occurs, it is said to be a stationary or standing wave.

Figure 9.11 shows how standing waves are formed in a string by two continuous periodic waves travelling in opposite directions. It is important to note that the wavelength of the waves involved in the standing wave is twice the distance between adjacent nodes (or adjacent antinodes).

FIGURE 9.11 The formation of a standing wave

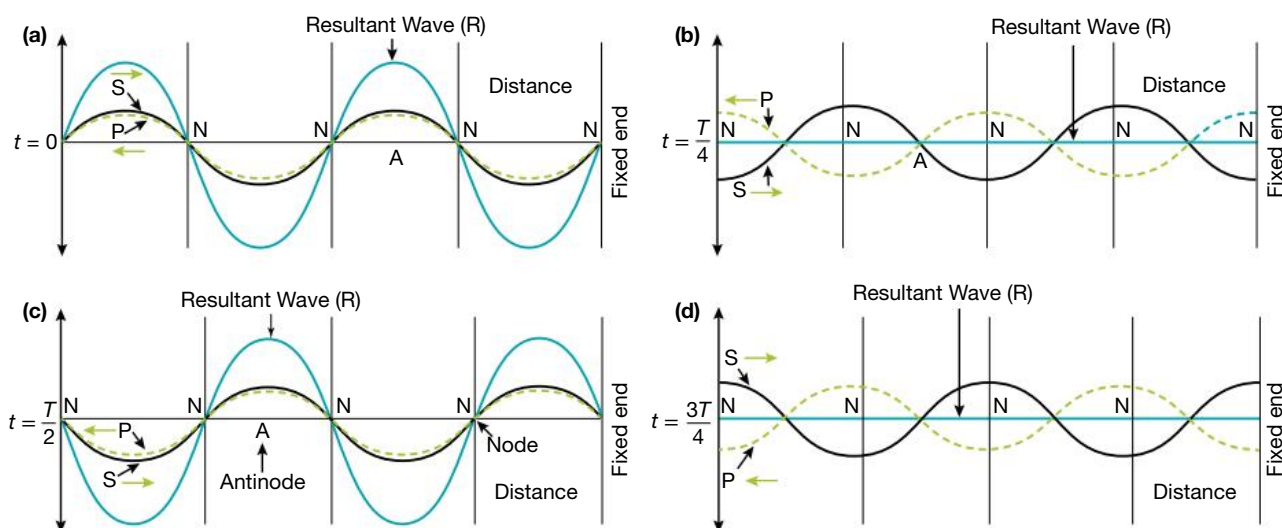
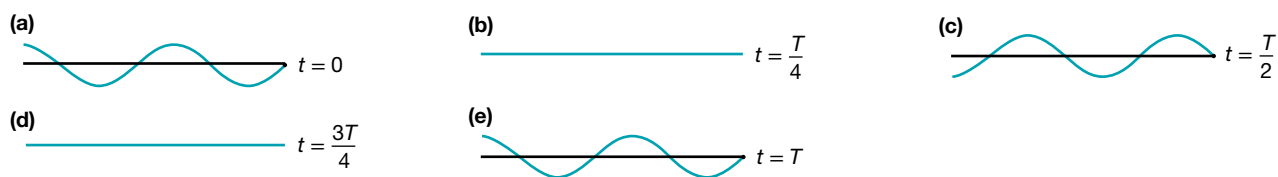


Figure 9.12 shows the motion of a spring as it carries a standing wave. It shows the shape of the spring as it completes one cycle. The time taken to do this is one period (T). Note that:

- at $t = \frac{T}{4}$ and at $t = \frac{3T}{4}$, the medium is momentarily undisturbed at all points
- adjacent antinodes are opposite in phase — when one antinode is a crest, those next to it are troughs.

FIGURE 9.12 A standing wave over one cycle



9.5.4 Harmonics associated with standing waves

One important application of standing wave theory is that standing waves are produced on a medium fixed at both ends. This can be applied to guitar and violin strings, for example, or to water waves reflecting off a barrier, even to suspension bridges with the road fixed to a pylon at both ends. The important physics here is that when waves are generated, in the case of a guitar by plucking, a violin by using a bow, or by air passing over a bridge, travelling waves in both directions are produced and will reflect off the fixed ends. The reflected waves interfere with each other, and standing waves will be created. In all cases, the medium will only resonate at fixed frequencies that are dependent on the speed of the travelling waves and the distance between the two ends of the medium.

Resonance is the vibration of an object caused when a forced oscillation matches the object's natural frequency of vibration. Every object has one or more natural frequencies of vibration. For example, when a crystal wine glass is struck with a spoon, a distinct pitch of sound is heard. If the resonant frequency is produced by a sound source near the glass, the glass will begin to vibrate.

Strings fixed at both ends

Now, consider a string under tension of length L fixed at both ends, and capable of resonating — that is, capable of supporting a variety of frequencies. What would be the values of the allowable frequencies? The answer lies in the fact that the ends of the string must be nodes. The longest wavelength occurs when half the wavelength can fit onto a string of length L , that is $L = \frac{\lambda}{2}$ or $\lambda = 2L$. The frequency and associated wavelength of this standing wave will be called the fundamental frequency and fundamental wavelength respectively, using the symbols f_1 and λ_1 . Using the wave equation $v = f\lambda$, it follows that if $\lambda_1 = 2L$ then $f_1 = \frac{v}{2L}$. This is the fundamental frequency for a standing wave on a medium of length L fixed at both ends. Importantly, this standing wave is known as the 1st harmonic.

The next possible standing wave that could be made occurs when two half-wavelengths, or one whole wavelength, fits onto a string of length L — that is $\lambda = L$ for this standing wave.

This standing wave will be called the second harmonic. Thus $\lambda_2 = L$ and $f_2 = \frac{2v}{2L} = \frac{v}{L} = 2f_1$. The second harmonic has a frequency that is exactly twice the frequency of the first harmonic.

FIGURE 9.13 The first harmonic

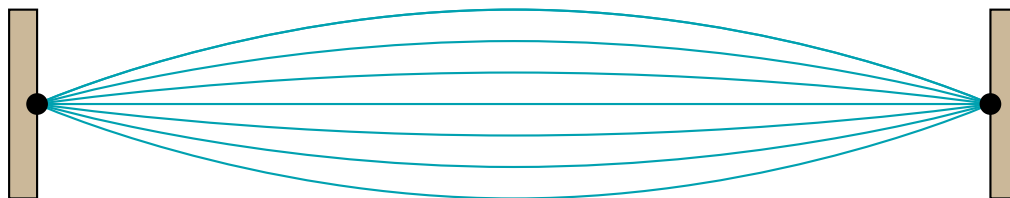


FIGURE 9.14 The second harmonic

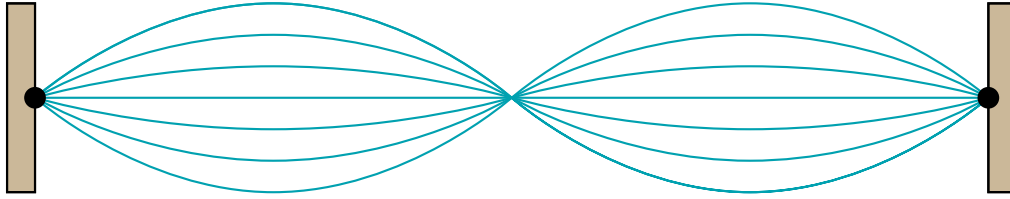
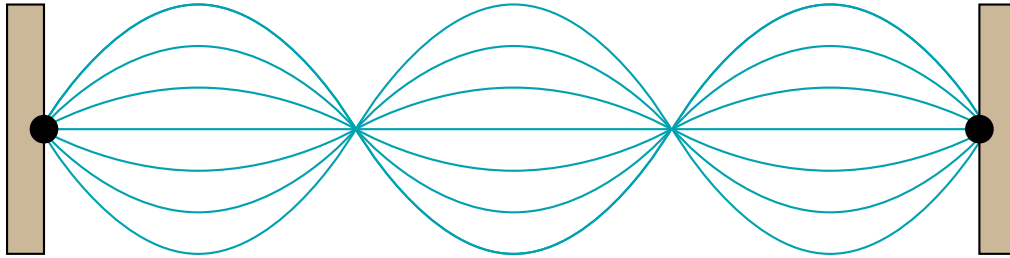


FIGURE 9.15 The third harmonic



The third harmonic will show that a number pattern emerges for all harmonics. The third harmonic will be again fixed at both ends where 1.5 wavelengths will fit onto a string of length L — that is $L = \frac{3}{2}\lambda$, so $\lambda_3 = \frac{2L}{3}$.

In general, the n th harmonic will have a wavelength given by:

$$\lambda_n = \frac{2L}{n}$$

where: λ_n is the wavelength, in m
 L is the length of the string, in m
 n is the number of the harmonic ($n = 1, 2, 3, 4, 5 \dots$)

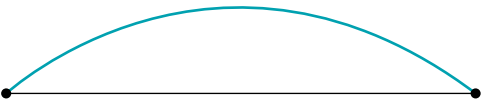
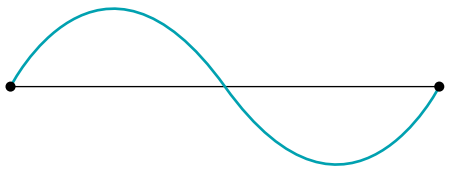
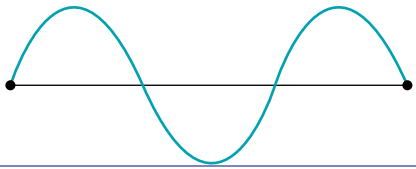
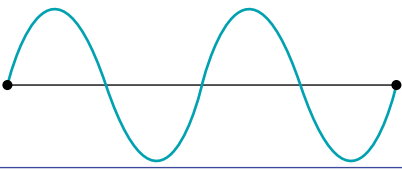
Since the n th harmonic has the wavelength $\frac{2L}{n}$, the frequency of the n th harmonic will be given by:

$$f_n = \frac{nv}{2L} = nf_1$$

where f_n is the frequency of the wave, in Hz
 L is the length of the string, in m
 n is the number of the harmonic ($n = 1, 2, 3, 4, 5 \dots$)
 v is the velocity of the wave, in m s^{-1}
 f_1 is the fundamental frequency, in Hz

Each of these standing waves or resonances can exist independently of each other and so they give rise to the rich diversity of sound made by musical instruments, even when they are playing the same note. Each instrument will make harmonics of different intensities to produce a spectrum of frequencies unique to that instrument. Nonetheless, the resonant frequencies are governed by simple rules that rely solely on the speed of the travelling wave for the medium, v , and the length of the medium, L , fixed at both ends. This concept applies equally well to pipes used in organs and explains how a musical note can be generated in an air column.

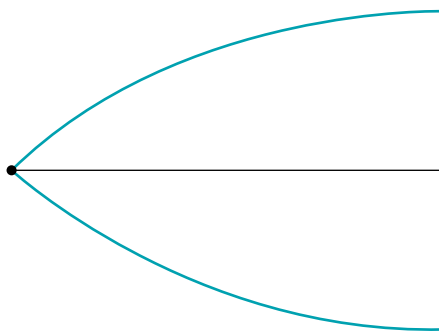
TABLE 9.2 Standing waves on a string fixed at both ends

Harmonic	Number of nodes	Number of antinodes	Pattern	Resonant frequency: $f = \frac{v}{\lambda}$
First	2	1		$L = \frac{\lambda_1}{2},$ $f_1 = \frac{v}{2L}$
Second	3	2		$L = \frac{2\lambda_2}{2} = \lambda_2$ $f_2 = \frac{v}{L} = 2f_1$
Third	4	3		$L = \frac{3\lambda_3}{2},$ $f_3 = \frac{3v}{2L} = 3f_1$
Fourth	5	4		$L = \frac{4\lambda_4}{2},$ $f_4 = \frac{4v}{2L} = 4f_1$
n th	$n+1$	n		$L = \frac{n\lambda_n}{2},$ $f_n = \frac{nv}{2L} = nf_1$ $n = 1, 2, 3, 4, 5...$

Strings fixed at one end

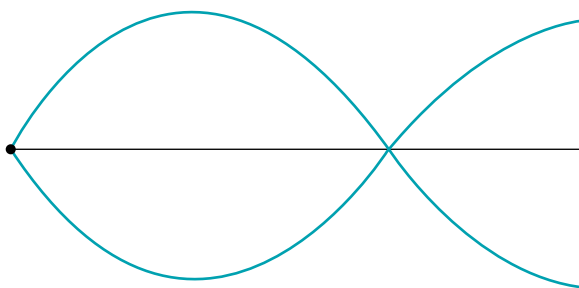
Resonances can also occur on strings fixed at one end (producing a node) but free at the other end (producing an antinode). The fundamental standing wave on such a string of length L will only be one quarter of a wavelength, $\frac{\lambda}{4}$. Here $\lambda_1 = 4L$ and hence the fundamental frequency $f_1 = \frac{v}{4L}$.

FIGURE 9.16 The first harmonic



The next possible frequency for a resonance to occur is when an additional half wavelength is added to the fundamental quarter-wavelength to make a standing wave such that $L = \frac{3\lambda}{4}$ or rearranging $\lambda_3 = \frac{4L}{3}$. In which case, the next lowest frequency $f_3 = \frac{3v}{4L}$.

FIGURE 9.17 The third harmonic

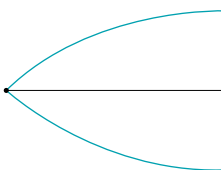
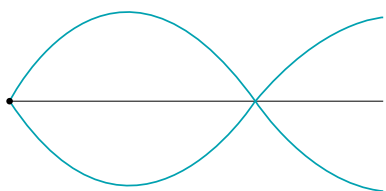
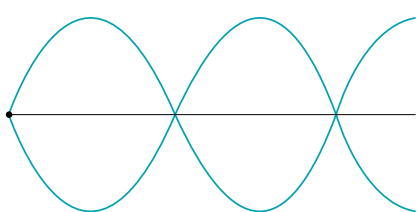
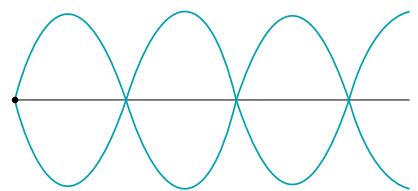


There is an important difference between resonances produced on strings fixed at both ends compared with those where the strings are fixed at one end only:

1. For a string fixed at only one end, the fundamental frequency is half the frequency of a string fixed at both ends.
2. For a string fixed at only one end, only odd harmonics are allowed; the 3rd harmonic is the second lowest frequency, the 5th harmonic is the third lowest frequency, and so on.

This is summarised in table 9.3.

TABLE 9.3 Standing waves on a string fixed at one end only

Harmonic	Number of nodes	Number of antinodes	Pattern	Resonant frequency: $f = \frac{v}{\lambda}$
First	1	1		$L = \frac{\lambda_1}{4},$ $f_1 = \frac{v}{4L}$
Third	2	2		$L = \frac{3\lambda_3}{4},$ $f_3 = \frac{3v}{4L}$ $= 3f_1$
Fifth	3	3		$L = \frac{5\lambda_5}{4},$ $f_5 = \frac{5v}{4L}$ $= 5f_1$
Seventh	4	4		$L = \frac{7\lambda_7}{4},$ $f_7 = \frac{7v}{4L}$ $= 7f_1$
odd n th	$2n - 1$	$2n - 1$		$L = \frac{n\lambda_n}{4},$ $f_n = \frac{nv}{4L}$ $= nf_1$ $n = 1, 3, 5, 7 \dots$

SAMPLE PROBLEM 4

Two students have created a standing wave using wire under tension attached to two ends as part of an extended investigation. The distance between the two ends is 1.50 m. At one instant when the amplitude of the standing wave is a maximum, the wave looks like this:



- a. How many nodes are there in this standing wave (including the two fixed ends)?
- b. How many antinodes are there?
- c. Which harmonic of all the possible standing waves does this standing wave represent?
- d. What is the wavelength of the standing wave?

The students measure the frequency of the standing wave to be 4.2 Hz.

- e. What is the period of the standing wave?
- f. What is the speed of the travelling waves on this wire that superimpose to produce this standing wave?
- g. What would be the fundamental frequency f_1 and wavelength λ_1 for a standing wave on this wire?

 **Teacher-led video:** SP4 (tlvd-0191)

THINK

- a. A node can be identified as any point where the amplitude of the wave is a minimum. Count the number of nodal points, including both ends.
- b. An antinode can be identified as any point where the amplitude of the wave is a maximum. Count the number of antinodes.
- c. The number of antinodes is equal to the harmonic number. There are three antinodes.

- d. The length of the wire, 1.5 m is $\frac{3}{2}$ wavelengths.

- e. The period for the 3rd harmonic is $T = \frac{1}{f_3}$

- f. Use the equation $v = f_3 \lambda_3$ and solve for v .

- g. 1. The n th harmonic is given by the expression $f_n = \frac{nv}{2L} = nf_1$ where $f_3 = 4.2$ Hz.

- 2. The fundamental wavelength can be found using the rule $\lambda_n = \frac{2L}{n}$

WRITE

- a. There are four nodes for this standing wave.

- b. There are three antinodes for this standing wave.

- c. The wave is the 3rd harmonic for this wire.

- d. $L = \frac{3}{2}\lambda$ for the 3rd harmonic.

$$\begin{aligned}\text{Thus: } 1.5 &= 1.5\lambda \\ \Rightarrow \lambda &= 1.0 \text{ m}\end{aligned}$$

- e. $T = \frac{1}{f_3}$
 $= \frac{1}{4.2}$
 $= 0.2381 \approx 0.24 \text{ s}$

- f. $v = f_3 \lambda_3$
 $= 4.2 \times 1.0$
 $= 4.2 \text{ m s}^{-1}$

- g. 1. $f_3 = 4.2 = 3 \times f_1$
 $f_1 = \frac{4.2}{3} = 1.4 \text{ Hz}$

The fundamental frequency for the wire is 1.4 Hz.

- 2. $\lambda_1 = 2L = 2 \times 1.5 = 3.0 \text{ m}$
The fundamental wavelength is 3.0 m.

PRACTICE PROBLEM 4

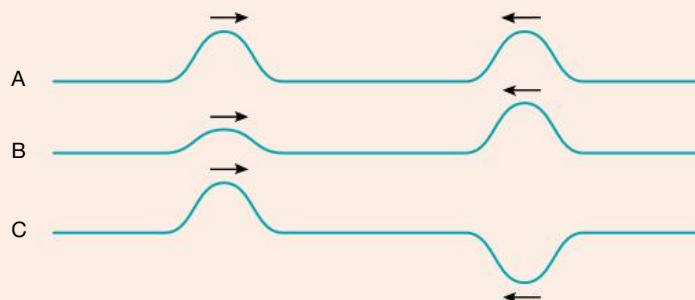
The tension in the wire is now increased so that the speed of the travelling waves is 6.0 m s^{-1} .

- What will be the respective frequencies f_1, f_2 and f_3 of the first, second and third harmonic standing waves now?
- For each of the first three harmonics, what will be the wavelengths λ_1, λ_2 and λ_3 ?

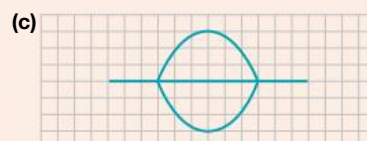
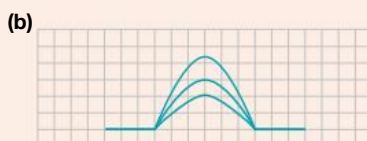
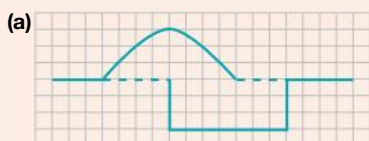
9.5 EXERCISE

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

- In each of the following diagrams, two waves move towards each other. Identify the diagram (or diagrams) showing waves that, as they pass through each other, could experience:
 - only destructive interference
 - only constructive interference.



- What is superposition and when does it occur?
- What is constructive interference and when does it occur?
- The following diagrams show the positions of three sets of two pulses as they pass through each other. Copy the diagrams and sketch the shape of the resultant disturbances.



- What is the wavelength of a standing wave if the nodes are separated by a distance of 0.75 m ?
- The following figure shows a standing wave in a string. At that instant ($t = 0$) all points of the string are at their maximum displacement from their rest positions.



If the period of the standing wave is 0.40 s , sketch diagrams to show the shape of the string at the following times:

- $t = 0.05 \text{ s}$
- $t = 0.1 \text{ s}$
- $t = 0.2 \text{ s}$
- $t = 0.4 \text{ s}$.

7. Kim and Jasmine set up two loudspeakers in the following arrangements:
- The speakers face each other.
 - They are 10 m apart.
 - The speakers are in phase and produce a sound of 330 Hz.
- Jasmine uses a microphone connected to a CRO and detects a series of points between the speakers where the sound intensity is a maximum. These points are at distances of 3.5 m, 4.0 m and 4.5 m from one of the speakers.
- What causes the maximum sound intensities at these points?
 - What is the wavelength of the sound being used?
 - What is the speed of sound on this occasion?
8. A standing wave is set up by sending continuous waves from opposite ends of a string. The frequency of the waves is 4.0 Hz, the wavelength is 1.2 m and the amplitude is 10 cm.
- What is the speed of the waves in the string?
 - What is the distance between the nodes of the standing wave?
 - What is the maximum displacement of the string from its rest position?
 - How many times per second is the string straight?
9. A standing wave is set up by sending continuous waves from opposite ends of a string. The frequency of the waves is 2.5 Hz, the wavelength is 2.4 m and the amplitude is 0.04 m.
- What is the speed of the waves in the string?
 - What is the distance between the nodes of the standing wave?
 - What is the maximum displacement of the string from its rest position?
 - How many times per second is the string straight?
10. A guitar string is capable of supporting many discrete frequencies when plucked. The length of the guitar string is 0.80 m, and travelling waves on the string have speed 650 m s^{-1} . Determine the frequency of the first three harmonics.
11. In a classroom demonstration, a teacher vibrates a string that is fixed at one end and connected to a vibrating device at the other end. The vibrating device has a frequency of 200 Hz. The fixed end (right-hand end) can be considered as a node while the other end can be modelled as an antinode. In the demonstration, the pattern looks like the following diagram.



- Which harmonic does this pattern represent for the string?
- How many nodes are there in this pattern?
- The length of the string is 1.5 m. What is the wavelength of the standing wave?
- What is the speed of travelling waves on this string?
- What frequency would the teacher need to set the vibrating device at to produce the fundamental or first harmonic standing wave using this apparatus?

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9.6 Interference of waves

KEY CONCEPT

- Investigate and analyse theoretically and practically constructive and destructive interference from two sources with reference to coherent waves and path difference: $n\lambda$ and $\left(n - \frac{1}{2}\right)\lambda$ respectively.

9.6.1 Interference of waves in two dimensions

Interference of waves is best observed in a ripple tank. When two point sources emit continuous waves with the same frequency and amplitude, the waves from each source interfere as they travel away from their respective sources. If the two sources are in phase (producing crests and troughs at the same time as each other), an interference pattern similar to that shown in figure 9.18 is obtained.

Lines are seen on the surface of the water where there is no displacement of the water surface. These lines are called **nodal lines**. They are caused by destructive interference between the two sets of waves. At any point on a nodal line, a crest from one source arrives at the same time as a trough from the other source, and vice versa. Any point on a nodal line is sometimes called a local minimum, because of the minimum disturbance that occurs there.

Between the nodal lines are regions where constructive interference occurs. The centres of these regions are called **antinodal lines**. At any point on an antinodal line, a crest from one source arrives at the same time as a crest from the other source, or a trough from one source arrives at the same time as a trough from the other source, and so on. Any point on an antinodal line is sometimes called a local maximum, because of the maximum disturbance that occurs there.

When the two sources are in phase, as shown in figure 9.18, the interference pattern produced is symmetrical with a central antinodal line. Note that any point on the central antinodal line is an equal distance from each source. Since the sources produce crests at the same time, crests from the two sources will arrive at any point on the central antinodal line at the same time.

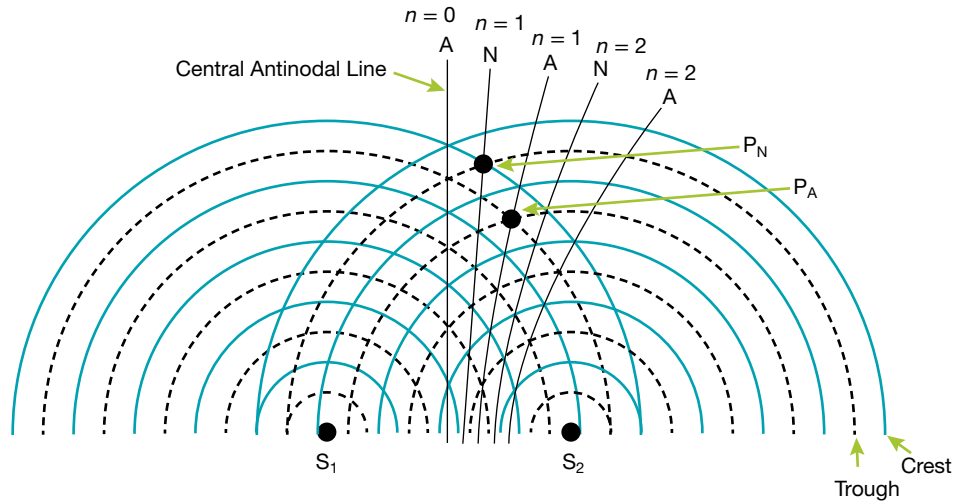
Similar analysis will show that, for any point on the first antinodal line on either side of the centre of the pattern, waves from one source have travelled exactly one wavelength further from one source than from the other. This means that crests from one source still coincide with crests from the other, although they were not produced at the same time. Point P_A in figure 9.19 is on the first antinodal line from the centre of the pattern. It can be seen that point P_A is 4.5 wavelengths from S_1 and 3.5 wavelengths from S_2 .

A way to establish whether a point is a local maximum is to look at the distance it is from both sources. If the distance that the point is from one source is zero or a whole number multiple of the wavelength further than the distance it is from the other source, then that point is a local maximum. This 'rule' can be re-expressed as: *'If the path difference at a point is $n\lambda$, the point is a local maximum'*.

FIGURE 9.18 An interference pattern obtained in water by using two point sources that are in phase



FIGURE 9.19 Interference pattern produced by two sources in phase



Therefore,

For a point to be an antinode:

$$d(PS_1) - d(PS_2) = n\lambda \quad n = 0, 1, 2, 3, 4, \dots$$

where:

n is the number of the antinodal line from the centre of the pattern

λ is the wavelength, in m

P is the point in question

S_1 and S_2 are the sources of the waves

$d(PS_1)$ is the distance from P to S_1 , in m

$d(PS_2)$ is the distance from P to S_2 , in m

Similar analysis shows that, for a point on a nodal line, the difference in distance from the point to the two sources is $\frac{1}{2}\lambda$ or $1\frac{1}{2}\lambda$ or $2\frac{1}{2}\lambda$ and so on. This means that a crest from one source will coincide with a trough from the other source, and vice versa. Point P_N in figure 9.19 is 5 wavelengths from S_1 and 4.5 wavelengths from S_2 .

For a point to be a node:

$$d(PS_1) - d(PS_2) = \left(n - \frac{1}{2}\right)\lambda \quad n = 0, 1, 2, 3, 4, \dots$$

where:

n is the number of the nodal line obtained by counting outwards from the central antinodal line

λ is the wavelength, in m

P is the point in question

S_1 and S_2 are the sources of the waves

$d(PS_1)$ is the distance from P to S_1 , in m

$d(PS_2)$ is the distance from P to S_2 , in m

SAMPLE PROBLEM 5

Two point sources S_1 and S_2 emit waves in phase in a swimming pool. The wavelength of the waves is 1.00 m. P is a point that is 10.00 m from S_1 , and P is closer to S_2 than to S_1 . How far is P from S_2 if:

a. P is on the first antinodal line from the central antinodal line

b. P is on the first nodal line from the central antinodal line?

THINK

a. 1. $d(PS_1)$ is greater than $d(PS_2)$;

If P is on the first antinodal line from the central antinodal line, then:

$$d(PS_1) - d(PS_2) = \lambda$$

2. $d(PS_1) = 10.00$ m, $\lambda = 1.00$ m

b. 1. $d(PS_1)$ is greater than $d(PS_2)$;

If P is on the first nodal line from the central antinodal line, then:

$$d(PS_1) - d(PS_2) = \frac{1}{2}\lambda$$

2. $d(PS_1) = 10.00$ m, $\lambda = 1.00$ m

WRITE

a. $d(PS_1) - d(PS_2) = \lambda$

$$\begin{aligned}d(PS_2) &= d(PS_1) - \lambda \\&= 10.00 \text{ m} - 1.00 \text{ m} \\&= 9.00 \text{ m}\end{aligned}$$

b. $d(PS_1) - d(PS_2) = \frac{1}{2}\lambda$

$$\begin{aligned}d(PS_2) &= d(PS_1) - \frac{1}{2}\lambda \\&= 10.00 \text{ m} - 0.50 \text{ m} \\&= 9.50 \text{ m}\end{aligned}$$

PRACTICE PROBLEM 5

Two point sources S_1 and S_2 emit waves in phase in a swimming pool. The wavelength of the waves is 1.00 m. P is a point that is 10.00 m from S_1 , and P is closer to S_2 than to S_1 . How far is P from S_2 if:

a. P is on the second antinodal line from the central antinodal line

b. P is on the second nodal line from the central antinodal line?

9.6.2 Interference with sound

When two sources emit sound with the same frequency in phase, an interference pattern is produced. The pattern is three-dimensional, but its features are the same as for interference patterns produced in water.

A local antinode, or maximum, is a point where constructive interference produces a sound of greater intensity than that produced by one source alone. As the pattern is three-dimensional, there is a central antinodal plane (as opposed to a line) where all points are an equal distance from each source. In this plane, a compression from one source coincides with a compression from the other source. This is followed by a progression of coincidental rarefactions and compressions. As the waves pass through such a point, there is a maximum variation in the air pressure, resulting in a louder sound.

A local node, or minimum, is a point where destructive interference produces a sound of much less intensity than that produced by one source alone. At a point in a nodal region, compressions from one source coincide with rarefactions from the other source and vice versa. As the waves pass through such a point, there is very little variation in the air pressure, resulting in a very soft sound.

COMPLETE DESTRUCTIVE INTERFERENCE

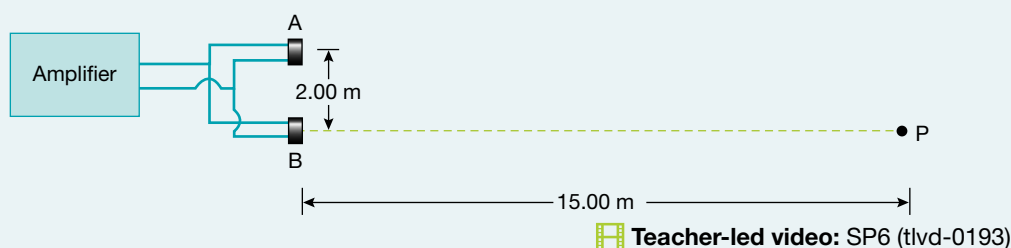
Complete destructive interference rarely occurs, as the sounds produced from each source are usually not of equal intensity, due to the different distances travelled by the individual waves and the inverse square law that describes this variation in intensity with distance from the source.

The same formulae that were used for water waves can be used to determine whether a point is part of a nodal or antinodal region.

SAMPLE PROBLEM 6

A student arranges two loudspeakers, A and B, so that they are connected in phase to an audio amplifier. The speakers are then placed 2.00 m apart and they emit sound that has a wavelength of 0.26 m.

Another student stands at a point P, which is 15.00 m directly in front of speaker B. The situation representing this arrangement is shown in the following figure. Describe what the student standing at point P will hear from this position.



THINK

1. In this type of question, it is important to determine whether the point is a node or antinode. This is done by determining the path difference and then comparing this to the wavelength.
 $\lambda = 0.26 \text{ m}$, $d(\text{PB}) = 15.00 \text{ m}$, $d(\text{AB}) = 2.00 \text{ m}$
2. $d(\text{PA})$ can be found by applying Pythagoras's theorem.
3. Calculate the path difference.
4. Compare the path difference to the wavelength.
5. Describe what the student standing at P will hear.

WRITE

$$\begin{aligned}d(\text{PA})^2 &= 15.00^2 + 2.00^2 \\&= 229 \\ \text{so, } d(\text{PA}) &= 15.13 \text{ m} \\d(\text{PA}) - d(\text{PB}) &= 15.13 \text{ m} - 15.00 \text{ m} \\&= 0.13 \text{ m} \\0.13 \text{ m} &= \frac{1}{2}\lambda \\0.13 &= \frac{1}{2} \times 0.26 \text{ m} = \frac{1}{2}\lambda \\ \text{Therefore, this is part of a node.} \\ \text{The student is at a local minimum and} \\ \text{will hear only a very soft sound.}\end{aligned}$$

PRACTICE PROBLEM 6

Consider the scenario from sample problem 6.

A third student stands at a point Q, which is 3.60 m directly in front of speaker B. Describe what the student standing at point Q will hear from this position.

9.6.3 Colour effects of interference

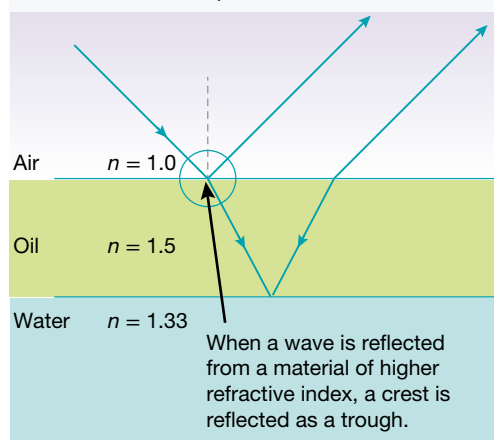
In the case of light, when two waves of red light meet, constructive interference would result in bright red light. Destructive interference would result in an absence of light, that is, darkness.

When light of a mixture of colours shines on a film of oil in a puddle on the road, light is reflected from the top surface of the oil, as well as from the bottom surface. However, the light from the bottom surface has further to travel, that is, twice the thickness of the oil film. Depending on how this extra distance compares with the wavelength of a particular colour, the two waves may undergo constructive or destructive interference. For example, when you look at an oil film (see figures 9.20 and 9.21), the section that looks yellow is where the thickness is just right for yellow light to undergo maximum constructive interference. Yet at the same place, other colours (which have different wavelengths) undergo destructive interference or less than maximum constructive interference. At other places on the oil film, the thickness will be just right for maximum constructive interference for another colour. The different colours on the oil film indicate the different thicknesses of the oil as the film spreads out.

FIGURE 9.20 The colours on this oil film are the result of the interference of light.



FIGURE 9.21 The light waves reflecting from the bottom surface interfere with those from the top surface.



The colours that flash at you when you move the shiny surface of a CD in sunlight also appear as a result of interference (see figure 9.22). The light from adjacent ridges in the surface follows paths of ever so slightly different lengths. The waves interfere with each other. The difference between the lengths of the paths changes because the distance between adjacent ridges changes. Different colours undergo constructive and destructive interference, depending on the path difference.

FIGURE 9.22 These colours are the result of interference.



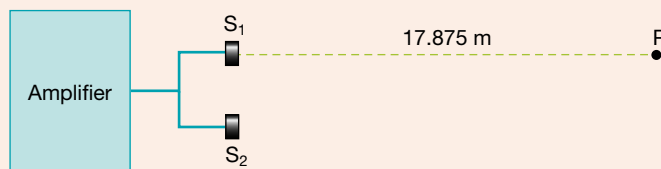
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 **Digital document** Investigation 9.6 Thin soap films (doc-31611)

9.6 EXERCISE

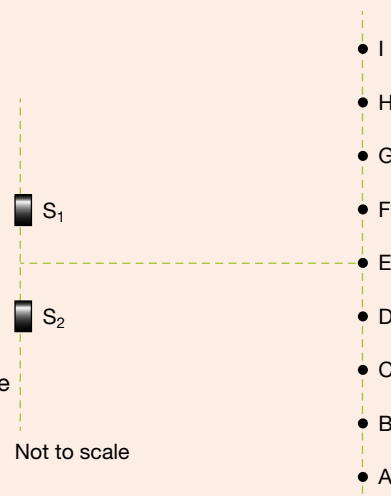
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- Describe the interference pattern produced when two sound sources produce sounds of equal frequency in phase. How can you determine whether a point on the interference pattern is a local maximum or local minimum?
- Explain what is meant by the expression 'interference pattern' when applied to two sound sources that are in phase.
- Two sources in phase emit sound with a wavelength of 0.90 m. Describe the loudness (louder or softer when compared to that produced by a single source) at the following positions:
 - at an equal distance from both sources
 - at a distance of 15.45 m from one source and 14.55 m from the other
 - at a distance of 15.75 m from one source and 16.20 m from the other.
 Justify your answers.
- Two loudspeakers are set up on an open-air stage as shown in the following diagram.



A sound engineer tests the arrangement by feeding a tone of 660 Hz through both speakers. For the following questions, assume that:

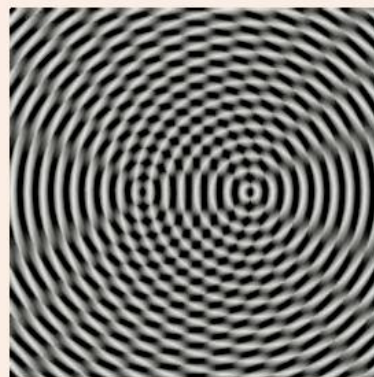
- the speakers are producing sound in phase
 - the speed of sound in air is 330 m s^{-1} .
- What is the wavelength of the sound that is produced by each speaker?
 - The engineer walks directly away from one of the speakers until he notices that the sound has a minimum value at point P. He accurately measures the distance from this point to the nearest speaker (S_1) and finds that it is 17.875 m. How far is he from speaker S_2 ? (In calculating this distance, assume that P is on the first nodal line.)
 - How far apart are the speakers?
5. Two loudspeakers in phase produce an interference pattern on a sports field. The set-up of the apparatus is shown in the diagram to the right.
- The speakers produce sound with a wavelength of 80.00 cm. Suroor walks from point A to point I and detects either a loud or very soft sound at the points labelled in the diagram.
- What causes the variations in the loudness of the sound?
 - Describe the sound (loud or soft) detected at point E. Explain your answer.
 - Describe the sound (loud or soft) detected at point D. Explain your answer.
 - If point D is 20.00 m from speaker S_2 , how far is it from speaker S_1 ?
 - Suroor stands at point D as her assistant, Susie, slowly increases the frequency while keeping the power of the speakers constant. Describe the loudness of the sound that Suroor detects as the frequency increases. Justify your answer.



6. Consider an interference pattern resulting from two in-phase sources in a large swimming pool where the wavelength of the waves is 0.80 m.

An overview image of the pattern is shown in the diagram at the right.

- (a) On the diagram, label a point A where the path difference is 0.
- (b) On the diagram, label a point B where the path difference is 1.2 m.
- (c) On the diagram, label a point C where the path difference is 2.4 m.
- (d) If the source frequency was increased, the wavelength of the travelling waves would decrease. Describe what changes in the pattern would occur.



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9.7 Review

9.7.1 Summary

- Waves provide a means of energy transfer from one place to another place without matter transfer. There are many examples of waves and they can be transverse or longitudinal.
- Properties of waves that can be measured include speed, wavelength and frequency. These quantities are connected by the universal wave equation:

$$\text{speed} = \text{frequency} \times \text{wavelength, or } v = f\lambda.$$

- As a transverse wave moves through a medium, the particles vibrate perpendicularly to the direction of propagation. Surface waves on water or vibrations of a string are examples of transverse waves.
- As longitudinal waves move through a medium, the particles of the medium vibrate back and forth parallel to the direction of propagation. Sound is an example of a longitudinal wave.
- Light is a form of electromagnetic radiation that can be modelled as a type of transverse wave with different colours differing in frequency and wavelength.
- The Doppler effect is the result of a wave source moving through the medium. The waves move at constant speed relative to the medium away from the moving source, resulting in a higher frequency in front of the moving source and a lower frequency behind it.
- An observer moving towards a stationary source will measure a frequency greater than the source frequency. An observer moving away from a stationary source will measure a frequency smaller than the source frequency.
- All waves when passing through a narrow opening or around an obstacle will diffract. Diffraction is the spreading of waves. The amount of diffraction is increased when the wavelength λ is increased. The amount of diffraction is also increased when the size of the opening w is decreased or the obstacle is made smaller. The ratio $\frac{\lambda}{w}$ is useful in deciding the amount of diffraction that will occur in a given situation.
- All waves, including light, have the capacity to interfere with each other, producing constructive interference or destructive interference when and where two waves meet.
- Standing waves are caused by the superposition of two wave trains of the same frequency and amplitude travelling in opposite directions. Points of no disturbance are called nodal points or nodes, and points of maximum disturbance are called antinodes.

- Standing waves on strings fixed at both ends are capable of supporting many discrete frequencies called harmonics. The first harmonic is given by: $f_1 = \frac{v}{2L}$ where v is the speed of the travelling wave and L is the length of the string, assuming both ends to be nodes. The n th harmonic is given by the expression $f_n = nf_1$ where f_1 is the fundamental frequency or first harmonic.
- For a string of length L fixed at both ends only, the wavelength of the n th harmonic standing wave is $\lambda_n = \frac{\lambda_1}{n}$ where $\lambda_1 = 2L$.
- Standing waves on strings that are fixed at one end and free at the other end are capable of supporting many discrete frequencies called harmonics. The first harmonic is given by $f_1 = \frac{v}{4L}$ where v is the speed of the travelling wave and L is the length of the string. The n th harmonic is given by the expression $f_n = nf_1$ where f_1 is the fundamental frequency or first harmonic frequency and only odd numbered harmonics, $n = 3, 5, 7$ and so on, are allowed.
- For a string of length L fixed at one end only, the wavelength of the n th harmonic standing wave is $\lambda_n = \frac{\lambda_1}{n}$ where $\lambda_1 = 4L$ and $n = 3, 5, 7 \dots$
- When waves that are in phase pass through a pair of openings, an interference pattern is produced due to constructive and destructive interference of the two waves emerging from the opening. This pattern is called a double-slit interference pattern.
- The pattern can be explained using the concept of path difference such that regions of constructive interference occur at X when the path difference is $0, \pm 1\lambda, \pm 2\lambda, \pm 3\lambda \dots$ or, alternatively, $|S_1X - S_2X| = n\lambda$, where $n = 0, 1, 2, 3, \dots$
- Regions of destructive interference occur at Y when the path difference is $\pm \frac{1}{2}\lambda, \pm \frac{3}{2}\lambda, \pm \frac{5}{2}\lambda \dots$ or, alternatively, $|S_1Y - S_2Y| = \left(n - \frac{1}{2}\right)\lambda$, where $n = 1, 2, 3 \dots$

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9.7.2 Key terms

The **amplitude** of a wave is the size of the maximum disturbance of the medium from its normal state.

An **antinodal line** is a line where constructive interference occurs on a surface.

An **antinode** is a point at which constructive interference takes place.

A **compression** is a region of increased pressure in a medium during the transmission of a sound wave.

Constructive interference describes the addition of two wave disturbances to give an amplitude that is greater than either of the two waves.

Destructive interference is the addition of two wave disturbances to give an amplitude that is less than either of the two waves.

Diffraction is the spreading out, or bending of, waves as they pass through a small opening or move past the edge of an object.

The **frequency**, f , of a periodic wave is the number of times the wave repeats itself every second.

A **longitudinal wave** is a wave for which the disturbance is parallel to the direction of propagation.

A **nodal line** is a line where destructive interference occurs on a surface, resulting in no displacement of the surface.

A **node** is a point at which destructive interference takes place.

The **period**, T , of a periodic wave is the time it takes a source to produce one complete wave. This is the same as the time taken for a complete wave to pass a given point.

A **periodic wave** is a disturbance that repeats itself at regular intervals.

A **rarefaction** is a region of reduced pressure in a medium during the transmission of a sound wave.

Resonance is the condition where a medium responds to a periodic external force by vibrating with the same frequency as the force.

A **standing wave** is the superposition of two wave trains at the same frequency and amplitude travelling in opposite directions. Standing waves are also known as stationary waves because they do not appear to move through the medium. The nodes and antinodes remain in a fixed position.

Superposition is the adding together of amplitudes of two or more waves passing through the same point.

A **transverse wave** is a wave for which the disturbance is at right angles to the direction of propagation.

A **wave** is a transfer of energy through a medium without any net movement of matter.

The **wavelength** is the distance between successive corresponding parts of a periodic wave.

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 **Digital document** Key terms glossary (doc-32113)

9.7.3 Practical work and investigations

Investigation 9.1

Investigating waves from a slinky spring

Aim: To observe and investigate the behaviour of waves (or pulses) travelling along a slinky spring

Digital document: doc-32625

Investigation 9.2

The Doppler effect

Aim: To observe the effects of wind on the frequency of sound

Digital document: doc-32321

Investigation 9.3

Diffraction of waves in a ripple tank

Aim: To investigate the effect of wavelength and width of the gap on the amount of diffraction that occurs when waves travel around the edge of a barrier or through a gap

Digital document: doc-31609

Investigation 9.4

Observing water waves

Aim: To observe a wave motion travelling in two dimensions

Digital document: doc-31616

Investigation 9.5

Reflection of pulses in springs

Aim: To investigate the reflection of pulses in a long slinky spring

Digital document: doc-31610

Teacher-led video: tlvd-0247

Investigation 9.6

Thin soap films

Aim: To examine the interference effect of light on soap films

Digital document: doc-31611





9.7 Exercises

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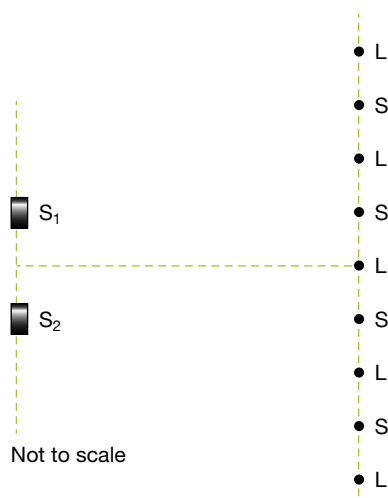
9.7 Exercise 1: Multiple choice questions

- Which statement is correct?
 - Sound is a type of transverse wave whereas surface waves on a ripple tank are a type of longitudinal wave.
 - Sound is a type of longitudinal wave whereas surface waves on a ripple tank are a type of transverse wave.
 - Both sound and surface waves on a ripple tank are types of longitudinal waves.
 - Both sound and surface waves on a ripple tank are types of transverse waves.
- The musical note A has a frequency of 440 Hz. Orchestras often use this note to tune up. Calculate the wavelength of this note in air and identify the value in the following list. The speed of sound in air is 340 m s^{-1} .
 - 0.770 m
 - 1.29 m
 - 0.640 m
 - 1.54 m
- Consider a periodic sound wave produced by a speaker in air where the frequency is slowly increased from 440 Hz to 880 Hz. Which one of the following statements is correct?
 - The wavelength will remain constant and the speed of the sound wave will slowly increase.
 - The wavelength will slowly increase and the speed of the sound wave will remain constant.
 - The wavelength will slowly decrease and the speed of the sound wave will slowly increase.
 - The wavelength will slowly decrease and the speed of the sound wave will remain constant.
- A group of students produces periodic waves in a ripple tank with a wavelength λ that pass through a narrow opening of width w to demonstrate diffraction. In which situation will diffraction be most significant?
 - $\lambda = 20 \text{ mm}$ and $w = 10 \text{ mm}$
 - $\lambda = 40 \text{ mm}$ and $w = 10 \text{ mm}$
 - $\lambda = 40 \text{ mm}$ and $w = 5.0 \text{ mm}$
 - $\lambda = 20 \text{ mm}$ and $w = 5.0 \text{ mm}$
- A guitar string is tuned so that the first harmonic is 440 Hz. Which of the following are possible harmonics for that string when vibrated?
 - 110, 220, 330 Hz
 - 220, 660, 880 Hz
 - 660, 880, 1320 Hz
 - 880, 1320, 1760 Hz
- A teacher uses a vibrating string to demonstrate standing waves to a group of students. The distance between two adjacent nodes on the string is measured to be 36.0 cm when the frequency of the wave generator attached to the string is 120 Hz. The speed of the travelling waves on the string is:
 - 43.2 m s^{-1}
 - 86.4 m s^{-1}
 - 57.6 m s^{-1}
 - 173 m s^{-1}

7. A teacher uses a skipping rope to demonstrate standing waves to a group of students. One end of the rope is fixed while the other end, held by the teacher, can be considered to be an antinode. The rope has a length of 2.4 m. The teacher produces the 3rd harmonic on the rope. The distance from the fixed end to the nearest node on this standing wave is closest to:
- 1.8 m
 - 3.2 m
 - 1.2 m
 - 1.6 m
8. When waves are passed through two closely spaced openings, an interference pattern results on the far side. In a student investigation into interference, periodic waves of wavelength 1.5 cm are used to study double-slit interference using a ripple tank. A region of destructive interference is observed. A possible path difference for this region is:
- 1.5 cm
 - 0 cm
 - 3.0 cm
 - 0.75 cm

Use the following information to answer Questions 9 and 10.

A double-slit interference pattern may be made with in-phase sound waves of a single frequency being produced by two speakers S_1 and S_2 . This is shown in the following diagram. Regions of loud and soft sounds are shown by labels L and S respectively.



9. Which of the following is correct?
- A region of loud sound is due to constructive interference of waves from S_1 and S_2 .
 - A region of loud sound is due to destructive interference of waves from S_1 and S_2 .
 - A region of soft sound is due to constructive interference of waves from S_1 and S_2 .
 - A region of soft sound is due to destructive interference of waves from S_1 and S_2 .
10. The frequency of the sound waves is now increased. Which one of the following statements is correct?
- The regions of loud sounds, L, will be louder than before.
 - The distance between adjacent loud regions and soft regions will be greater than before.
 - The regions where the sound is loud will be quieter than before.
 - The distance between adjacent loud regions and soft regions will be less than before.

9.7 Exercise 2: Short answer questions

1. Waves are capable of transferring energy from one place to another. Explain why waves require a medium to achieve this.
2. A student is studying surface waves using water at a local swimming pool. She makes waves at a rate of two every second and the ripples radiate away from the source.
 - a. What is the period of the waves?
 - b. The waves radiate away from the source at a speed of 2.5 m s^{-1} . What is the distance between two adjacent peaks, that is, the wavelength of the waves?
 - c. If she increases the rate at which she makes waves, what will happen to the wavelength of the waves? What will happen to the speed of the waves?
3. Sound produced by an opera singer has a frequency of 926 Hz.
 - a. What is the period of the sound wave?
 - b. Taking the speed of sound to be 340 m s^{-1} , what is the wavelength of this sound in air?
4. Humans can hear sounds ranging from approximately 20 Hz to 20 000 Hz. What is the wavelength associated with these frequencies in air?
5. Consider an ambulance with its siren blaring at a fixed frequency as it travels along a road. Discuss the frequencies heard by the following three groups of people:
 - a. those behind the ambulance, having been passed by it
 - b. the driver of the ambulance
 - c. those in front of the ambulance as it moves towards them.
6. Describe what diffraction is and state changes in a diffraction pattern when:
 - a. the wavelength of the waves used is decreased, keeping the width of the opening constant
 - b. the width of the opening is decreased, keeping the wavelength constant.
7. On a guitar, the bottom string is called the E-string. When tuned correctly, the fundamental or first harmonic note has a frequency of 82.41 Hz.
 - a. When the E-string is plucked, a series of different frequencies or harmonics is produced. Determine the frequencies of the first four harmonics.

The length of the E-string on a typical acoustic guitar is 0.750 m and the string can be considered to be fixed at both ends.

 - b. Calculate the wavelength of the fundamental tone on the string.
 - c. Use your result to part b to determine the speed of the travelling waves on the string.
 - d. Are the waves on the string transverse or longitudinal? Explain.
 - e. Consider the 3rd harmonic for this string. What is the distance between two adjacent nodes on the string?
8. A student plays a note on a violin. The 4th harmonic associated with the note is 2460 Hz.
 - a. Determine the frequency of the fundamental associated with this note.
 - b. Draw the standing wave for this 4th harmonic to illustrate the location of nodes and antinodes on the violin string.

The distance between the bridge of the violin and the position of the student's finger on the string is 0.580 m.

 - c. Use your answer to part a to determine the speed of the travelling waves on the string.
 - d. Determine the distance between two adjacent antinodes on the string for the 4th harmonic.

9. A two-source interference pattern is produced in a school pool with two sources S_1 and S_2 , each making periodic surface waves with wavelength 0.80 m. This is shown in the following diagram with the horizontal dotted line representing where the path difference is zero for the two sources.



- The distance $S_1A = 12.0$ m. What is the distance S_2A ?
 - The point B lies on the first nodal line away from the dotted line. What is the path difference $|S_1B - S_2B|$ equal to?
 - The path difference $|S_1C - S_2C|$ is 1.6 m. At point C, are the waves from S_1 and S_2 constructively or destructively interfering? Explain your answer.
 - The path difference $|S_1D - S_2D|$ is 3.0 m and $S_1D = 14.8$ m. Calculate the distance S_2D .
10. A two-source interference experiment is produced in a ripple tank. A student locates a point of no disturbance X along the first nodal line of the pattern, as shown in the following diagram.



- In terms of the wavelength λ , what is the path difference $|S_1X - S_2X|$?
- The student measures the distances $S_1X = 14.8$ cm and $S_2X = 15.8$ cm. What is the wavelength of the surface waves generated in the ripple tank?
- Waves are generated with frequency 8.0 Hz. Calculate the speed of the surface waves in the ripple tank.

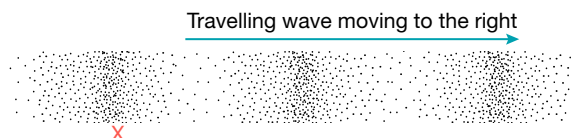
9.7 Exercise 3: Exam practice questions

Question 1 (6 marks)

- In what way are longitudinal waves different from transverse waves? Give an example of each type of wave in your answer. **2 marks**
- Jenny states that longitudinal and transverse waves have similarities. Discuss three ways in which both types of waves are similar. **3 marks**
- Sarah claims that a transverse wave will diffract when passing through a narrow opening but that a longitudinal wave will not. Her friend Tony claims that both transverse and longitudinal waves will diffract. Discuss each person's claim and determine who is correct. **1 mark**

Question 2 (3 marks)

Consider the wave pattern shown in the following diagram, which illustrates compressions and rarefactions of a sound wave at one instant progressing to the right.



- If the distance between a compression and adjacent rarefaction is measured to be 2.25 cm, determine the wavelength of the sound wave. **1 mark**
- If the speed of the wave to the right is 38 cm s^{-1} , calculate the frequency of the source of the waves. **1 mark**
- Consider the compression labelled X on the diagram. Describe where the point X would be found 0.10 s later. **1 mark**

Question 3 (2 marks)

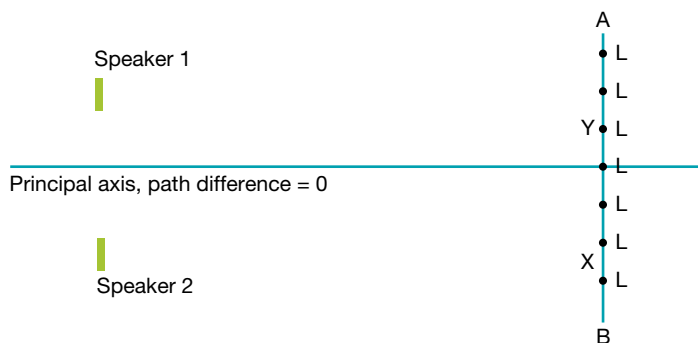
Jimmy plucks one of the strings on his guitar. It vibrates with a fundamental frequency of 530 Hz. The length of the string is 85 cm and it is fixed at both ends.

- Calculate the speed of the travelling wave on the string. **1 mark**
- Determine the first three overtones (2nd, 3rd and 4th harmonics) that could be produced when Jimmy plucks the string. **1 mark**

Question 4 (6 marks)

A group of students investigating the wave nature of sound set up a pair of speakers separated by 2.80 m. Each speaker produces in-phase sound with frequency 720 Hz from a single audio amplifier. The following diagram gives an overhead view of the arrangement. A student walks along the line AB and detects a series of evenly spaced loud (L) and soft sounds.

Assume the speed of sound = 340 m s^{-1} .



- Explain why the sound intensity varies from loud to soft at regular intervals as the student walks from A to B at a steady pace. **2 marks**
- Determine the wavelength of the sound waves produced by both speakers. **1 mark**
- A student positions himself at point Y, where the sound is loud. Calculate the path difference from the two speakers to this point. **1 mark**
- When the student is at point X, she notes that the sound is soft and assumes she is on a nodal line. She measures the distance to speaker 2 and finds it to be 7.2 m. How far is she from speaker 1? **2 marks**

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10 Light as a wave

10.1 Overview

Numerous **videos** and **interactivities** are available just where you need them, at the point of learning, in your digital formats, learnON and eBookPLUS at www.jacplus.com.au.

10.1.1 Introduction

Understanding waves will add to your knowledge of physics and complement your knowledge of the motion of particles. Light has always been considered a mystery from ancient times to the present. Could light be a type of wave or does it propagate and transfer energy more like a particle? In this topic, you will investigate light as a wave as considered by Huygens (though it was considered, by Newton, to consist of particles). The refraction of light and its ability to both diffract and interfere clearly indicates that light can be modelled as a type of wave propagating at a constant speed through a variety of media. Maxwell took advantage of new knowledge in the fields of magnetism and electricity, particularly electromagnetic induction, to propose that light was in fact a self-propelled transverse wave consisting of dual electric and magnetic fields perpendicular to each other. This mathematical model of light as a wave, combined with the mathematical model of matter as a particle, seemed to make physics complete as a subject area near the end of the nineteenth century.

FIGURE 10.1 Understanding light as a wave helps to explain many physical phenomena.



10.1.2 What you will learn

KEY KNOWLEDGE

After completing this topic, you will be able to:

- describe light as an electromagnetic wave, which is produced by the acceleration of charges, which in turn produces changing electric fields and associated changing magnetic fields
- identify that all electromagnetic waves travel at the same speed, c , in a vacuum
- compare the wavelength and frequencies of different regions of the electromagnetic spectrum, including radio, microwave, infra-red, visible, ultraviolet, X-ray and gamma, and identify the distinct uses each has in society
- explain polarisation of visible light and its relation to a transverse wave model
- investigate and analyse theoretically and practically the behaviour of waves including:
 - refraction using Snell's Law: $n_1 \sin(\theta_1) = n_2 \sin(\theta_2)$ and $n_1 v_1 = n_2 v_2$
 - total internal reflection and critical angle including applications: $n_1 \sin(\theta_c) = n_2 \sin(90^\circ)$.
- investigate and explain theoretically and practically colour dispersion in prisms and lenses with reference to refraction of the components of white light as they pass from one medium to another
- investigate and explain theoretically and practically diffraction as the directional spread of various frequencies with reference to different gap width or obstacle size, including the qualitative effect of changing the $\frac{\lambda}{w}$ ratio
- investigate and describe theoretically and practically the effects of varying the width of a gap or diameter of an obstacle on the diffraction pattern produced by light and apply this to the limitations of imaging using light
- explain the results of Young's double-slit experiment with reference to:
 - evidence for the wavelike nature of light
 - constructive and destructive interference of coherent waves in terms of path differences: $n\lambda$ and $(n - \frac{1}{2})\lambda$ respectively
 - effect of wavelength, distance of screen and slit separation on interference patterns: $\Delta x = \frac{\lambda L}{d}$.

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PRACTICAL WORK AND INVESTIGATIONS

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



Resources



Digital documents Key science skills — VCE Units 1–4 (doc-32112)

Key terms glossary (doc-32259)

Practical investigation logbook (doc-32260)



To access key concept summaries and past VCAA exam questions download and print the **studyON: Revision and past VCAA exam question booklet** (sonr-0059).

10.2 BACKGROUND KNOWLEDGE Light and its properties

BACKGROUND KNOWLEDGE

- Distinguish that sources of light can be luminous or non-luminous, and that luminous light can be incandescent
- Understand the propagation of light and how it travels
- Investigate the reflection of light, and observe that the angle of incidence equals the angle of reflection
- Identify that colour is both a property of light and an aspect of human perception.

Sight is the sense by which humans and most other mammals get most of their information about the world. This sense responds to light. Questions about light naturally arise. Where does light come from? What can it do? How can its properties be explained?

Some obvious observations concerning light include the following:

- Sources of light are needed for a person to be able to see.
- Light travels very fast and appears to travel in a straight line.
- Light produces shadows.
- Light is sensed by people as exhibiting different colours.

10.2.1 Sources of light

When you experience darkness at night or in an enclosed room, you know that a source of light, such as the Sun or a lamp, is needed to light up the darkness. Once a lamp is turned on, you can see features in the room because the light from the lamp shines on them and is then reflected into your eyes.

This means that objects can be classified into two groups. Objects seen because they give off their own light are called **luminous** objects; those seen because they reflect light are called non-luminous objects. The Sun, torches and candles are luminous objects. Tables, chairs, cats and dogs are non-luminous objects.

Some luminous objects produce light because they are hot. The Sun is one example. The higher the temperature, the brighter the light. This also causes a change in colour. These objects are called **incandescent**.

Other objects are cold and produce light in another way. This involves changes in the energy of electrons in the material brought about by either chemical or electrical processes.

10.2.2 Propagation of light

The gap experienced between seeing lightning and hearing thunder shows that sound travels relatively slowly. Light seems to travel so fast that its speed seems infinite; that is, events seem to be observed at the instant they happen.

Galileo Galilei (1564–1642) was not convinced of this. He attempted to determine the speed of light by measuring the time delay between the flash of his lamp to an assistant on a distant mountain and the return flash from his assistant's lamp (see figure 10.3). No detectable delay was observed and Galileo concluded that the speed of light was very high. A longer distance was needed to investigate such a high speed.

FIGURE 10.2 The Pleiades open star cluster in the constellation Taurus. All stars are incandescent sources of light.



FIGURE 10.3 Galileo used this method to measure the speed of light. He attempted to time, with his pulse, the delay between uncovering his lantern and seeing the light from his partner's lantern, which his partner uncovered at the moment when he saw the light from Galileo's lantern.

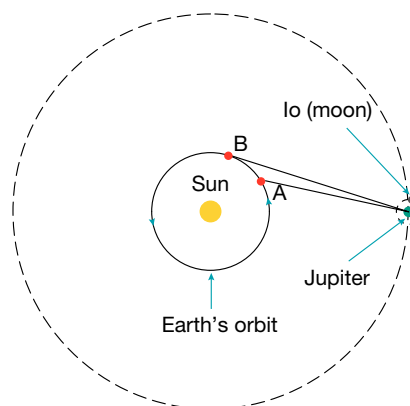


Olaus Roemer was a Danish astronomer born two years after Galileo died. He observed that the time between eclipses of Jupiter's moons by Jupiter decreased as the Earth moved closer to Jupiter and increased as the Earth moved away. Roemer reasoned that this was because the distance the light travelled from Jupiter to Earth became greater as the Earth's orbit took it further from Jupiter, as shown in figure 10.4. Roemer used this time and the known diameter of the Earth's orbit about the Sun to estimate the speed of light. The value he obtained was $2.7 \times 10^8 \text{ m s}^{-1}$.

Eventually, in the nineteenth century, with stronger light sources and more precise timing devices, Galileo's method could be used, but the assistant was replaced by a mirror. The values obtained then were about $3.0 \times 10^8 \text{ m s}^{-1}$.

Early in the twentieth century, the American scientist Albert A. Michelson (1852–1931) used a rapidly rotating eight-sided mirror, as shown in figure 10.5. The light was reflected to a distant mirror about 35 kilometres away, then reflected back to the rotating mirror.

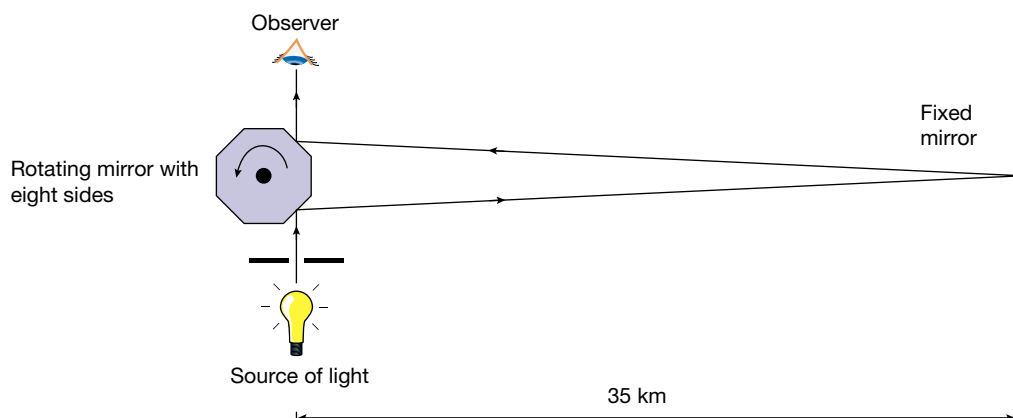
FIGURE 10.4 The time, as seen from the Earth, for Jupiter's moon Io to orbit Jupiter increases as the Earth moves from A to B. (The diagram is not to scale.)



For some particular rotation rates, this light is reflected by one of the sides of the rotating mirror directly to the observer. The rotation rate can be used to calculate the speed of light.

The value Michelson obtained was $2.997\,96 \times 10^8 \text{ m s}^{-1}$. He actually measured the distance of 35 km to an accuracy of 2.5 cm. The speed of light is currently measured at $2.997\,924\,58 \times 10^8 \text{ m s}^{-1}$. It is rounded off to $3.0 \times 10^8 \text{ m s}^{-1}$ for calculation purposes.

FIGURE 10.5 Light from the source reflects off one of the sides of the rotating mirror towards a mirror 35 kilometres away. The returning beam hits the rotating mirror. If one of the sides of the mirror is in the correct position, the light enters the eyepiece and can be seen by the observer. By measuring the speed of rotation when the beam enters the eyepiece, the speed of light can be calculated.



SAMPLE PROBLEM 1

How long does light take to travel from the Sun to the Earth, given that the speed of light is $3.0 \times 10^8 \text{ m s}^{-1}$ and the distance to the Sun is $1.50 \times 10^{11} \text{ m}$?

THINK

- To calculate the time taken for light to travel from the Sun to the Earth, the speed of light and the distance from the Sun to Earth need to be known.
- Substitute the values for the speed of light and the distance between the Sun and Earth into the following equation and solve for time:

$$\text{average speed} = \frac{\text{distance travelled}}{\text{time taken}}$$

WRITE

$$\begin{aligned}\text{Speed of light} &= 3.0 \times 10^8 \text{ m s}^{-1} \\ \text{Distance from Sun to Earth} &= 1.50 \times 10^{11} \text{ m}\end{aligned}$$

$$\text{average speed} = \frac{\text{distance travelled}}{\text{time taken}}$$

$$\Rightarrow \text{time taken} = \frac{\text{distance travelled}}{\text{average speed}}$$

$$\begin{aligned}\text{time} &= \frac{1.50 \times 10^{11} \text{ m}}{3.0 \times 10^8 \text{ m s}^{-1}} \\ &= 0.50 \times 10^3 \text{ s} \\ &= 500 \text{ s} \\ &= 8 \text{ minutes } 20 \text{ seconds}\end{aligned}$$

PRACTICE PROBLEM 1

The Moon is approximately 380 000 km from the Earth. How long would it take light to travel from a laser based on the Earth to reflect off a mirror positioned on the Moon and then return back to Earth?

SAMPLE PROBLEM 2

How far does light travel in one year (one light-year)?

THINK

1. To calculate the distance that light travels in one year, the speed of light and the number of seconds in a year need to be known.
2. Substitute the values for the speed of light and the time taken into the following equation and solve for distance:

$$\text{distance travelled} = \text{average speed} \times \text{time}$$

WRITE

$$\begin{aligned}\text{Speed of light} &= 3.0 \times 10^8 \text{ m s}^{-1} \\ \text{Seconds in a year} &= 365.25 \times 24 \times 3600 \\ &= 31\,557\,600 \text{ seconds}\end{aligned}$$

$$\begin{aligned}\text{distance travelled} &= \text{average speed} \times \text{time} \\ &= 3.0 \times 10^8 \times (31\,557\,600) \\ &= 9.5 \times 10^{15} \text{ m} \\ &= 9.5 \times 10^{12} \text{ km}\end{aligned}$$

PRACTICE PROBLEM 2

In an optic fibre made from glass, it takes light $1.0 \mu\text{s}$ to travel a distance of 200 m. What is the speed of light in glass? Is it greater or less than the speed of light in a vacuum?

on Resources



Digital documents Investigation 10.1 Luminous or not? (doc-31612)

Investigation 10.2 Luminosity and temperature (doc-31613)

10.2.3 Ray model for light

The need for sources of light, the great speed of light and the existence of sharp shadows can be described by a ray model. The model assumes that light travels in a straight-line path called a **light ray**. A light ray can be considered as an infinitely narrow beam of light and can be represented as a straight line, as shown in figure 10.6.

The bright Sun produces sharp shadows on the ground. The shape of the shadow is the same shape as the object blocking the light. This could happen only if light travels in a straight line.

FIGURE 10.6 Light rays leave a point on this pencil and travel in straight lines in all directions. The pencil is seen because of the 'bundle' of rays that enter the eye.

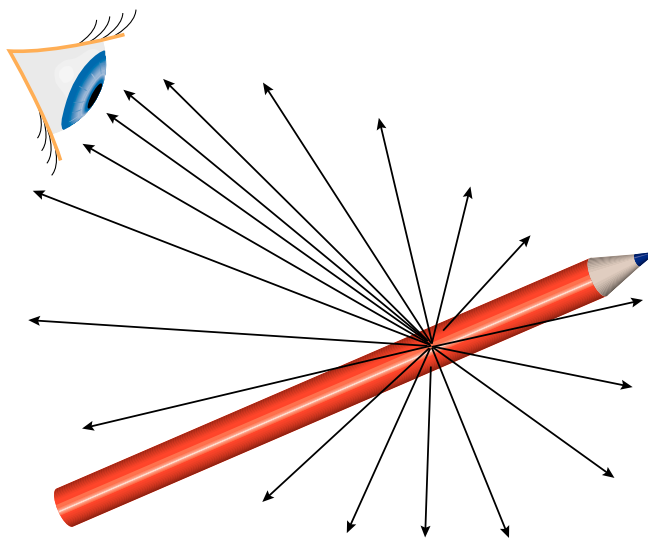


FIGURE 10.7 The straight rays passing the edge of a bird leave a sharp shadow on the ground.



10.2.4 Reflection: regular and diffuse

When you look at yourself in a plane mirror, some of the light rays from your nose, for example, travel in the direction of the mirror and reflect off in the direction of your eye (as seen in figure 10.8). What is happening at the surface of the mirror to produce such a perfect image?

To investigate the reflection of light, the angles made by the rays need to be measured. Measurements of these angles show that, like a ball bouncing off a flat wall, the **angle of incidence** equals the **angle of reflection** (as observed in figure 10.9). The ray approaching the mirror is called the incident ray. The ray leaving the mirror is called the reflected ray. The **normal** is a line at right angles to the mirror. The angles are measured between each ray and the normal. It can be observed that the incident ray, the normal and the reflected ray all lie in the same plane.

FIGURE 10.8 Light rays from the tip of the nose reflect off the mirror and enter the eye.

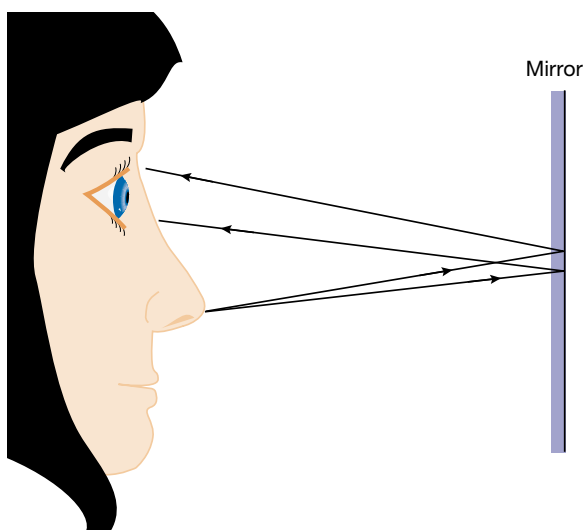
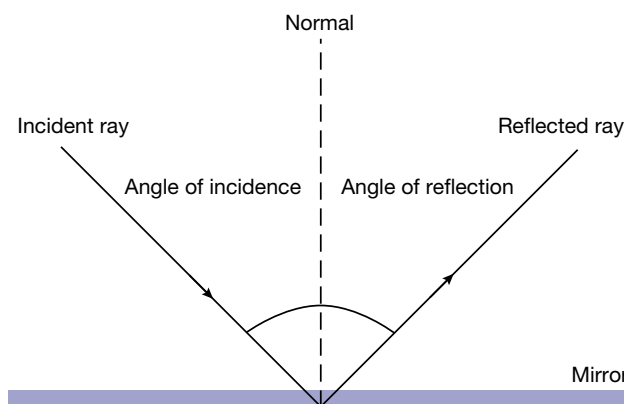


FIGURE 10.9 The angle of incidence always equals the angle of reflection.



Reflection from a smooth surface is called **regular** or **specular reflection**. But what happens with an irregular surface, such as a page in a book? A page is not smooth like a mirror. At the microscopic level, ‘hills and valleys’ exist. As the light rays come down into these hills and valleys, they still reflect with the two angles the same but, because the surface is irregular, the reflected rays emerge in all directions. This is called **diffuse reflection**. Light rays from diffuse reflections — from the ground, trees and other objects — enter the eye and enable the brain to make sense of the world. Therefore, observers in all directions receive light from the surface.

FIGURE 10.10 The incident ray, the ‘normal’ to the surface of the mirror and the reflected ray all lie in the same plane, which is at right angles to the plane of the mirror.

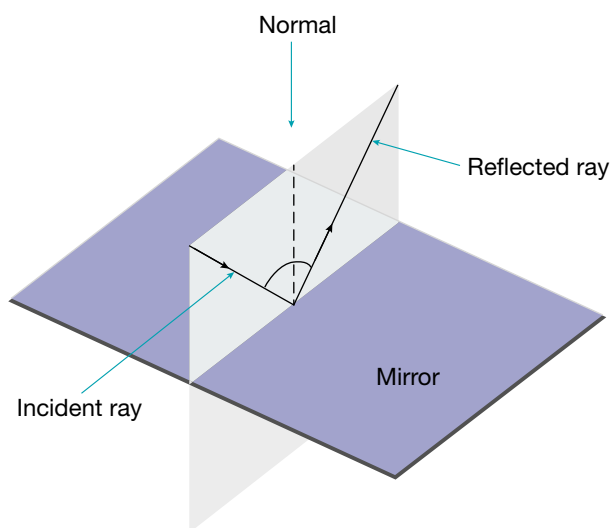
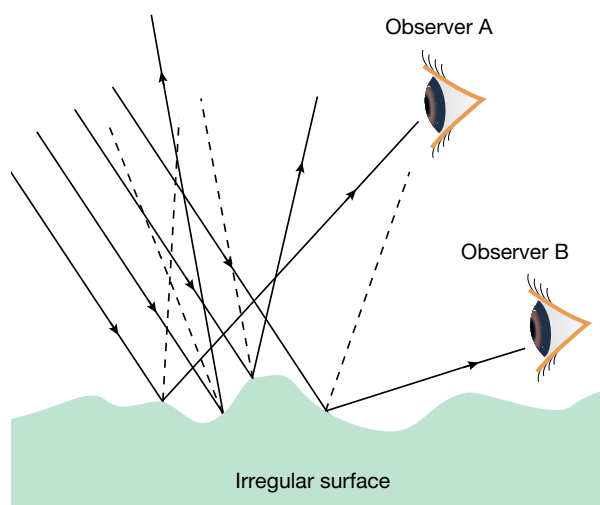


FIGURE 10.11 In diffuse reflection, each of the incoming parallel rays meets the irregular surface at a different angle of incidence. The reflected rays will therefore go off in different directions.



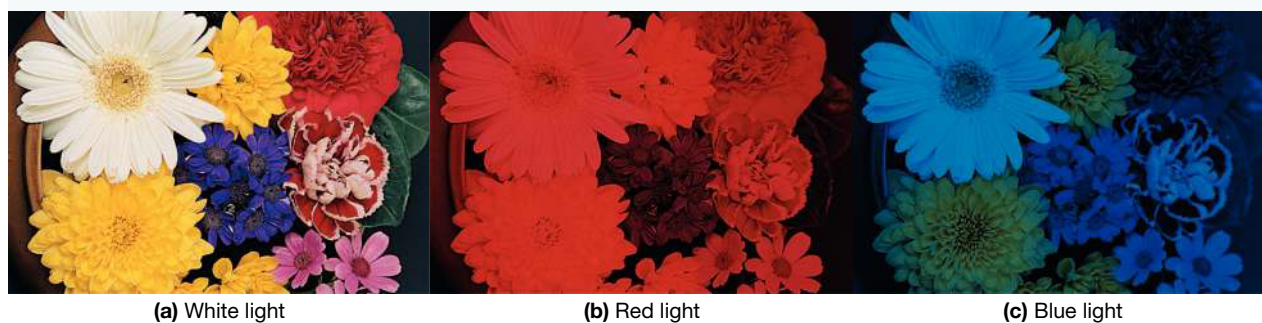
10.2.5 What is colour?

Colours are an important part of humanity’s language and environment. Colours can be peaceful to the eye or very stimulating. Colours are used in language to convey feelings and emotions (for example, *fiery red*, *warm orange* and *icy blue*).

At first, colour may seem to be a defining part of an object, like size, shape and texture. For example, you can say *green leaves*, *red earth* and *blue eyes*. It is only when experiments are done with light that you can observe that the colour or appearance of an object changes with the light that is shining on it.

But what about rainbows? And the blue sky? Here it seems that colour, pure colour, is separate from any solid object. So what really is colour? It is both a property of light and an aspect of human perception. A wave model of light will assign the human perception of colour to the frequency of the light.

FIGURE 10.12 Changing the colour of the light on these flowers from white to red to blue changes one’s perception of their colour.



Source: The Picture Source

10.2 EXERCISE

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

1. Calculate the longest and shortest time for a radio signal travelling at the speed of light ($3.0 \times 10^8 \text{ m s}^{-1}$) to go from the Earth (the radius of Earth's orbit around the Sun is $1.50 \times 10^{11} \text{ m}$) to a space probe when the space probe is:
 - (a) near Mars (the radius of Mars's orbit around the Sun is $2.28 \times 10^{11} \text{ m}$)
 - (b) near Neptune (the radius of Neptune's orbit around the Sun is $4.50 \times 10^{12} \text{ m}$).
2. A ray of light strikes a planar mirror with an angle of incidence of 25° and regular reflection takes place.
 - (a) What angle does the light ray make with the mirror surface?
 - (b) What is the angle of reflection?
3. A student arranges a beam of light from a laser to strike a plane mirror such that the incident beam and the reflected beam form a right angle. What is the angle of incidence that the light from the laser makes with the mirror?

Fully worked solutions and sample responses are available in your digital formats.

10.3 Bending of light

KEY CONCEPTS

- Investigate and analyse theoretically and practically the behaviour of waves including:
 - refraction using Snell's Law: $n_1 \sin(\theta_1) = n_2 \sin(\theta_2)$ and $n_1 v_1 = n_2 v_2$.
- Investigate and explain theoretically and practically colour dispersion in prisms and lenses with reference to refraction of the components of white light as they pass from one medium to another.

Experience shows that when you are spearing for fish in the shallows you must aim the spear below where the fish appears to be in the water. At the beach or in a pool, people standing in the shallows appear to have shorter legs. Perception is distorted, but the reason is not apparent.

When a special situation is set up, such as in figure 10.13, where a straight rod is placed in a beaker of liquids that do not mix, the idea of the change of direction of the light is apparent. This change in direction is called **refraction**. Refraction occurs when light travels from one medium to another, such as when travelling through air and into water.

FIGURE 10.13 An example of refraction

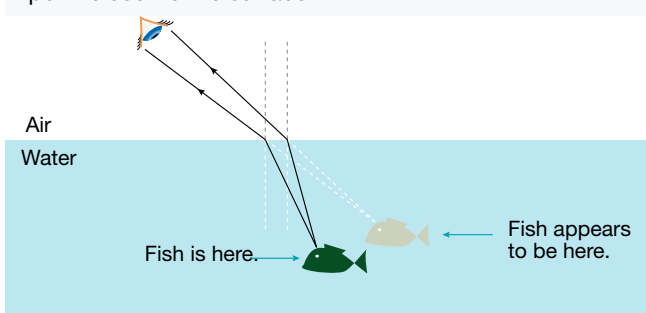


Source: © John Wiley & Sons Australia / Photo by Ron Ryan

The ray model can help explain observations of light. If a fish seems closer to the surface of the water, the ray of light from the fish must have bent. To your eye, the ray seems to be coming from another direction. Given that light can travel both ways along a light path, the fish will see the spear thrower further towards the vertical.

The ray model not only provides a way of describing your observations of the bending of light, but also of taking measurements. The angle that a ray of light makes with the normal — the angle of incidence and **angle of refraction** — can be measured and investigated.

FIGURE 10.14 The rays from the fish bend when they enter the air. To the eye, the rays appear to come from a point closer to the surface.



on Resources

 **Digital document** Investigation 10.3 Seeing is believing (doc-31614)

10.3.1 Snell's Law

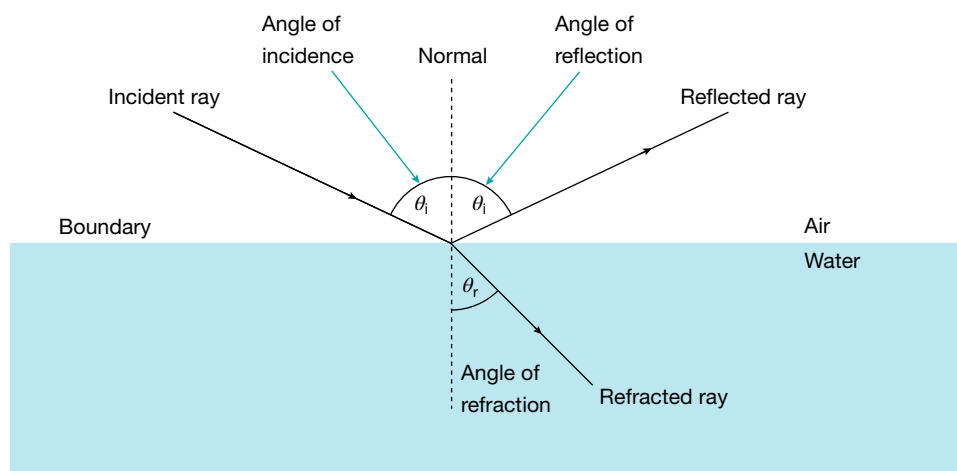
In 1621, the Dutch physicist Willebrord Snellius (1580–1626), known in the English-speaking world as Willebrand Snell, investigated the refraction of light and found that the ratio of the sines of the angles of incidence and refraction was constant for all angles of incidence.

$$\frac{\sin \theta_i}{\sin \theta_r} = \text{constant}$$

where: θ_i is the angle of incidence
 θ_r is the angle of refraction

Figure 10.15 shows how an incident ray is affected when it meets the boundary between air and water. The normal is a line at right angles to the boundary, and all angles are measured from the normal. Some of the light from the incident ray is reflected back into air while the rest is transmitted into the water. The ratio shown in figure 10.15 is a constant for all angles of light travelling from air to water.

FIGURE 10.15 The ratio $\frac{\sin \theta_i}{\sin \theta_r}$ is constant for all angles for light travelling from air to water.



EARLY HISTORY OF REFRACTION

Snell's Law was first discovered by Abu Sa'd Ibn Sahl (c. 940 – c. 1000), a Muslim physicist in the court in Baghdad, in 984. He reported his findings in his book on burning mirrors and lenses. Ibn Sahl used the relationship to design a shape for lenses that overcame the problem of spherical aberration. Ptolemy (c. 100 – c. 170), a Greco-Egyptian mathematician, had investigated refraction much earlier, compiling a table of angles for light travelling from air into water.

Snell repeated his experiments with different substances and found that the ratio between the sines of the angle of incidence was constant for a given substance. However, he found that each substance had a different value for this constant. This suggested that different substances bend light by different amounts. (Remember that some light is always reflected.)

In fact, there is a different ratio for each pair of substances (for example: air and glass, air and water). A different ratio is obtained for light travelling from water into glass. The value of the ratio is called the **relative refractive index** because it depends on the properties of two different substances.

The bending of light always involves light travelling from one substance to another. It is not possible to find the effect of a particular substance on the deflection of light without adopting one substance as a reference standard. Once you have a standard, every substance can be compared with it. A natural standard is a vacuum — the absence of any substance. The **absolute refractive index** of a vacuum is given the value of one. From this, the absolute refractive index of all other substances can be determined. Some examples are given in table 10.1. (The word 'absolute' is commonly omitted and the term 'refractive index' usually refers to the absolute refractive index.)

The refractive index is given the symbol n because it is a pure number without any units. This enables a more useful restatement of Snell's Law, for example:

$$n_{\text{air}} \sin \theta_{\text{air}} = n_{\text{water}} \sin \theta_{\text{water}}$$

More generally this would be expressed as follows:

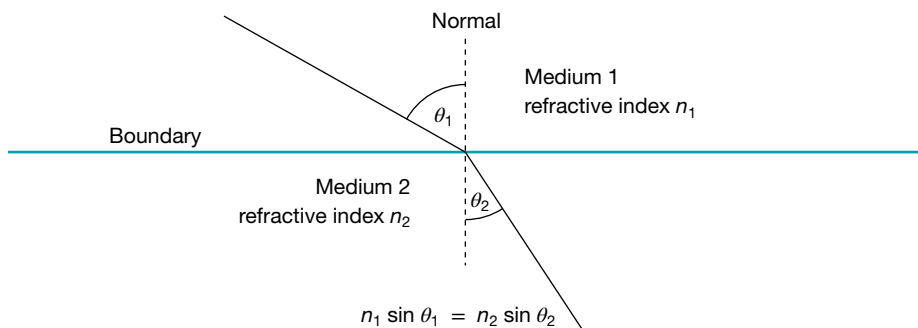
$$n_1 \sin \theta_1 = n_2 \sin \theta_2$$

where: n_1 is the refractive index of the first medium
 n_2 is the refractive index of the second medium
 θ_1 is the angle of incidence
 θ_2 is the angle of refraction

TABLE 10.1 Values for absolute refractive index

Material	Value
Vacuum	1.000 00
Air at 20 °C and normal atmospheric pressure	1.000 28
Water	1.33
Perspex	1.49
Quartz	1.46
Crown glass	1.52
Flint glass	1.65
Carbon disulfide	1.63
Diamond	2.42

FIGURE 10.16 A graphical depiction of Snell's Law for any two substances. Note that the light ray has no arrow, because the relationship is true for the ray travelling in either direction, and reflected light rays have been omitted for clarity.



SAMPLE PROBLEM 3

A ray of light moving through air strikes a glass block of refractive index 1.45 at an angle of incidence of 30° . What is the angle of refraction?

Teacher-led video: SP3 (tlvd-0196)

THINK

1. List the known information.
2. Use Snell's Law, $n_1 \sin \theta_1 = n_2 \sin \theta_2$, to determine the angle of refraction.

WRITE

$$n_{\text{air}} = 1.0; \theta_{\text{air}} = 30^\circ; n_{\text{glass}} = 1.45; \theta_{\text{glass}} = ?$$

$$1.0 \times \sin 30^\circ = 1.45 \times \sin \theta_{\text{glass}}$$

$$\sin \theta_{\text{glass}} = \frac{\sin 30^\circ}{1.45}$$

$$= 0.3448$$

$$\Rightarrow \theta_{\text{glass}} = \sin^{-1}(0.3448)$$

$$\Rightarrow \theta_{\text{glass}} = 20.17^\circ$$

$$\Rightarrow \theta_{\text{glass}} = 20^\circ$$

PRACTICE PROBLEM 3

A ray of light moving through air enters a plastic block at an angle of incidence of 40° . The angle of refraction is 30° . What is the refractive index of the plastic?

GRAVITATIONAL FIELDS AND BENDING LIGHT

Light can be bent by a strong gravitational field, such as that near the Sun. The gravitational field can act like a convex lens. Light from a distant star that is behind and blocked by the Sun bends around the Sun so that astronomers on Earth see an image of the star to the side of the Sun. This is quite different to how refraction occurs.

Resources

- Digital document** Investigation 10.4 Snell's Law (doc-32090)
- Teacher-led video** Investigation 10.4 Snell's Law (tlvd-0251)
- Video eLesson** Refraction of light and Snell's Law (eles-0037)
- Interactivity** Refraction of light and Snell's Law (int-0056)

10.3.2 Dispersion: producing colour from white light

White light can be separated into colours using a narrow beam of light and a glass triangular prism. This phenomenon is called **dispersion**. It was first analysed in this way by Isaac Newton in 1666, although René Descartes had sought an explanation for rainbows in 1637 by working with a spherical glass flask filled with water.

As light enters a triangular glass prism, it is refracted towards the normal. It then travels through the prism to the other side where it is refracted away from the normal, because the light is re-emerging into the air.

The colours spread as they enter the glass and travel on different paths through the triangular prism. They are spread even more as they leave the glass. Violet is bent the most and red the least. The order of the colours, from the colour that bends least to the colour that bends most, is red, orange, yellow, green, blue, indigo, and violet.

FIGURE 10.17 The colours in white light separate as they enter the glass and separate even more when they leave. At each edge, the violet is deflected more than the red.

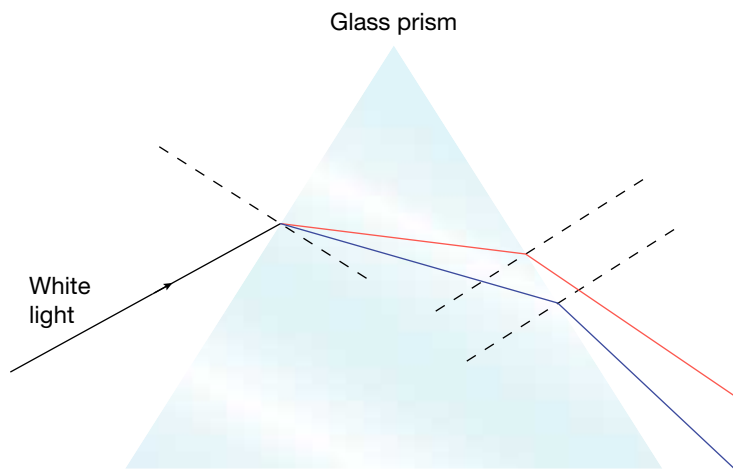
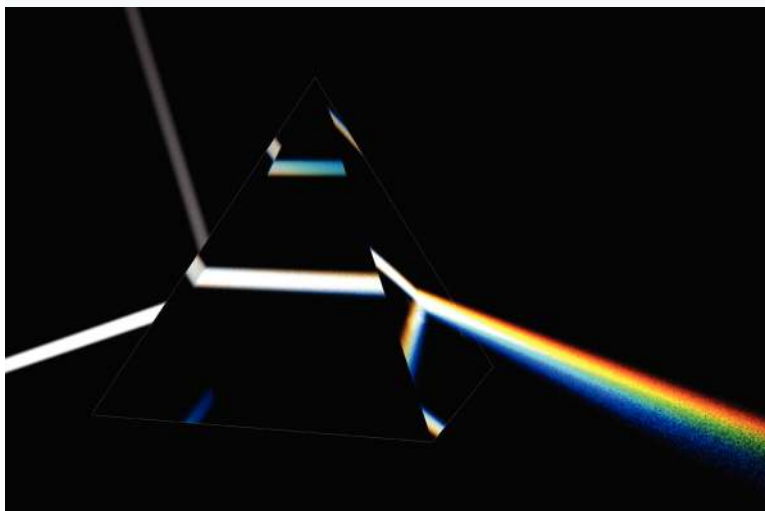


FIGURE 10.18 A spectrum of colours is produced when white light is passed through a prism. The red light is deflected the least and each colour in the spectrum is deflected progressively more.



Each colour has a different angle of refraction. This means that the glass has a different refractive index for each colour. This can be expressed as a statement of Snell's Law, as follows:

$$n_{\text{air}} \sin \theta_i = n_{\text{gl (red)}} \sin \theta_{\text{red}} = n_{\text{gl (violet)}} \sin \theta_{\text{violet}}$$

For example, as shown in figure 10.19, violet light is bent more than red, so θ_{violet} is smaller than θ_{red} . This means that the refractive index of glass for violet light is greater than that for red light. This is also true for other materials (see table 10.2).

FIGURE 10.19 The angle of refraction for violet light is smaller than that for red light. This means that the refractive index of the glass is different for different colours. For violet it must be greater than that for red.

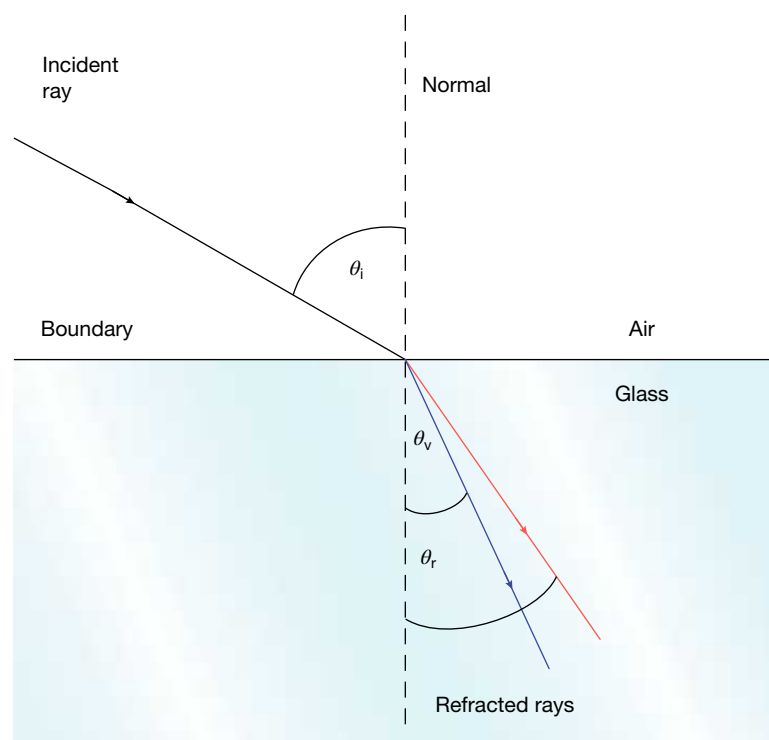


TABLE 10.2 Refractive index values vary for different coloured light

Colour	Index of refraction			Water
	Crown glass	Flint glass	Diamond	
Red	1.514	1.571	2.410	1.331
Yellow	1.517	1.575	2.418	1.333
Deep blue	1.528	1.594	2.450	1.340



Resources



Digital documents

eModelling Using a spreadsheet to explore refraction through a prism (doc-0058)

Investigation 10.5 Separating colours (doc-31615)



Interactivity

Spreading the spectrum (int-6609)

10.3.3 Limitations of the ray model

So far in this topic, the ray model has been used to describe how light is refracted. Ray diagrams illustrate Snell's Law and have allowed the visualisation of a range of optical phenomena such as mirages, and the development of technologies such as optical fibres. However, the ray model, which views light as a pencil-thin beam, does not offer an explanation of *why* light refracts. More sophisticated models are needed to provide an explanation for refraction and, in doing so, they suggest further experiments to investigate the properties of light more deeply, and to develop new technologies.

Two very different models of light were developed in the seventeenth century — one by Sir Isaac Newton (1642–1727) in England and the other by Christiaan Huygens (1627–1695) in Holland.

Newton's model was described as a 'particle model'. In his model, light consists of a stream of tiny, mass-less particles that he called corpuscles. The particles stream from a light source, like water from a sprinkler.

Huygens proposed a wave model of light, where light travels in a similar way to sound and water waves. Light leaves a source in the same way that water ripples move out from a dropped stone. The disturbance of the water surface travels outwards from the source.

FIGURE 10.20 Huygens proposed that light travelled outwards from a source like circular ripples on a pond.



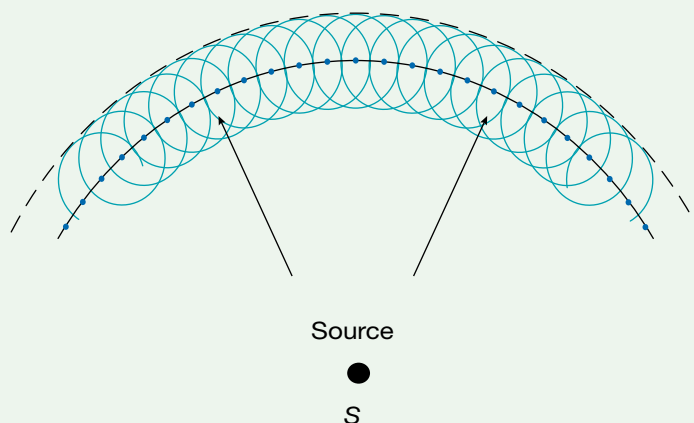
HOW DO THE TWO MODELS EXPLAIN THE PROPERTIES OF LIGHT?

How light travels

Newton's particle model: Once ejected from a light source, the particles continue in a straight line until they hit a surface.

Huygens's wave model: Huygens proposed the basic principle that 'Every point in the wavefront is a source of a small wavelet. The new wavefront is the envelope of all the wavelets.'

FIGURE 10.21 Every point in the wavefront is a source of a small wavelet. The new wavefront is the envelope of all the wavelets.



Reflection of light

Newton's particle model: As particles approach a surface, they are repelled by a force at the surface that slows down and reverses the normal component of the particle's velocity but does not change its tangential component. The particle is then reflected from the surface at an angle equal to its angle of approach. The same process happens when a billiard ball hits a cushion.

Huygens's wave model: As each part of the wavefront arrives at the surface, it produces a reflected wavelet. The new wavelets overlap to produce the next wavefront, which is travelling away from the surface at an angle equal to its angle of approach. As seen in figure 10.23, rays C and D are parallel incoming rays, and AB is the wavefront. When ray C hits the mirror at A, a circular wavelet is produced. By the time B has reached the mirror at E, the reflected wavelet has travelled out to F. The line EF is the reflected wavefront.

FIGURE 10.22 Newton's particle model of reflection

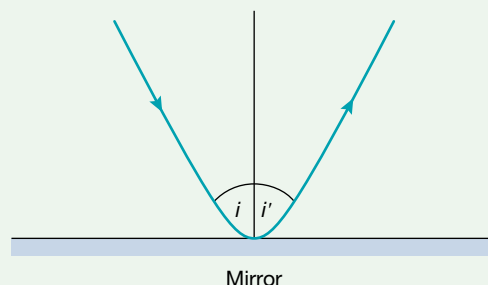
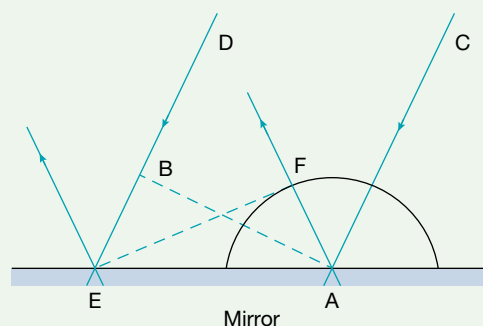


FIGURE 10.23 Huygens's wave model of reflection



Refraction of light

Newton's particle model: In approaching a denser medium, the particles experience an attractive force that increases the normal component of the particle's velocity but does not affect the tangential component. This has the effect of changing the direction of the particles, bending them towards the normal where they are now travelling faster in the denser medium. Snell's Law can be explained by this model. As seen in figure 10.24, the particles are pulled towards the denser medium, resulting in a change in direction.

Huygens's wave model: When the wavefront meets a heavier medium, the wavelets do not travel as fast as before. This causes the wavefront to change direction. In this case, the wavefront bends towards the normal when it enters a medium where the wave is slowed down. Snell's Law can be explained by this model. As seen in figure 10.25, rays C and D are parallel incoming rays, and AB is the wavefront. When ray C hits the surface at A, a circular wavelet of slower speed, and so smaller radius, is produced. By the time B has reached the surface at E, the refracted wavelet has only gone as far as F. The line EF is the refracted wavefront, heading in a direction bent towards the normal compared to the incoming wavefront, AB.

FIGURE 10.24 The particle model of refraction

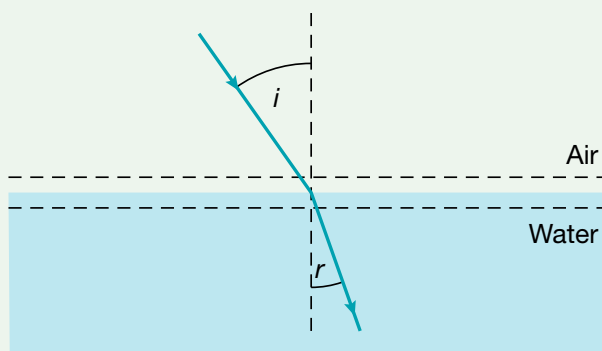
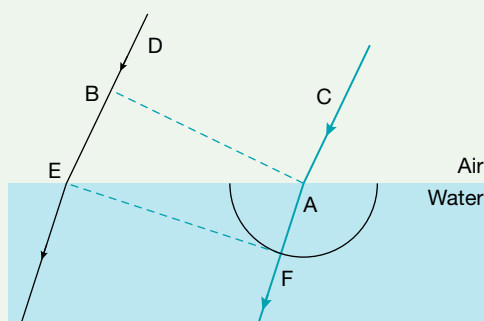


FIGURE 10.25 The wave model of refraction



A point of difference

Now, with these two explanations of refraction, there is a clear distinction between the two models. When light bends towards the normal as it enters water (a denser medium), the particle model says it is because light travels faster in water (the denser medium), whereas the wave model says it is because the light is travelling slower.

In the seventeenth century, scientists did not have the technology to measure the speed of light in water. However, the particle model became the accepted explanation, partly because of Newton's status and partly because Huygens's principle suggested that light should bend around corners like sound, and there was no evidence of this at the time. (Newton himself actually thought that the particles in his model needed to have some wavelike characteristics to explain some of his other observations of light and colour.)

New evidence emerges

In 1802, Thomas Young (1773–1829) showed that, in fact, light could bend around an edge. This is covered in some detail in subtopic 10.6. This was convincing evidence for the wave model, as the particle model had no mechanism to explain how particles could bend around a corner. However, the status of Newton was such that not all were convinced by Young's results. It was suggested that conclusive evidence would be to measure the speed of light in water and see if it was faster or slower than that in air. Jean Bernard Leon Foucault (1819–1868) and Hippolyte Fizeau (1819–1896) competed to measure the speed of light in water; in 1850, both showed that light was slower in water, though Foucault won by seven weeks.



Resources



Digital documents Investigation 10.6 Refraction of particles (doc-32086)

Investigation 10.7 Refraction of waves (doc-31617)



Weblink

Huygens's principle applet

10.3.4 Speed of light in glass

Foucault and Fizeau's results, along with the work of Augustin-Jean Fresnel (1788–1827) (pronounced 'fray-NEL'), showed that the speed of light in water was less than the speed of light in air. This allowed scientists to determine the physical meaning of the refractive index:

$$\text{absolute refractive index of water} = \frac{\text{speed of light in a vacuum}}{\text{speed of light in water}}$$

In general:

The refractive index of a material is the ratio of the speed of light in a vacuum to the speed of light in the medium:

$$n = \frac{c}{v}$$

where: n is the refractive index of the medium

c is the speed of light in a vacuum ($3.0 \times 10^8 \text{ m s}^{-1}$)

v is the speed of light in the medium

The formula can be rearranged to give:

$$n_{\text{water}} \times v_{\text{water}} = c$$

where c = the speed of light in a vacuum

v_{water} = the speed of light in water.

Similarly, for glass, $n_{\text{glass}} \times v_{\text{glass}} = c$, which means $n_{\text{glass}} \times v_{\text{glass}} = n_{\text{water}} \times v_{\text{water}}$, or, as a general relationship for any two materials:

$$n_1 v_1 = n_2 v_2$$

SAMPLE PROBLEM 4

- a. The refractive index of glass is 1.5. How fast does light travel in glass?
b. Use the answer to (a) to determine the speed of light in water ($n_{\text{water}} = 1.33$).
 **Teacher-led video:** SP4 (tlvd-0197)

THINK

- a. Use the relationship $n_{\text{glass}} = \frac{c}{v_{\text{glass}}}$ to calculate the speed of light in glass.

WRITE

$$\begin{aligned} \text{a. } 1.5 &= \frac{3.0 \times 10^8}{(\text{speed of light in glass})} \\ \Rightarrow \text{speed of light in glass} &= \frac{3.0 \times 10^8}{1.5} \\ &= 2.0 \times 10^8 \text{ m s}^{-1} \end{aligned}$$

- b. Use the relationship $n_{\text{glass}} \times v_{\text{glass}} = n_{\text{water}} \times v_{\text{water}}$ to determine the speed of light in water.

$$\begin{aligned} \text{b. } n_{\text{glass}} \times v_{\text{glass}} &= n_{\text{water}} \times v_{\text{water}} \\ 1.5 \times 2.0 \times 10^8 &= 1.33 \times v_{\text{water}} \\ \Rightarrow v_{\text{water}} &= \frac{1.5 \times 2.0 \times 10^8}{1.33} \\ &= 2.3 \times 10^8 \text{ m s}^{-1} \end{aligned}$$

PRACTICE PROBLEM 4

- a. How fast does light travel in diamond ($n_{\text{diamond}} = 2.42$)?
b. Use the answer to (a) to determine the speed of light in carbon disulfide ($n_{\text{carbon disulfide}} = 1.63$).

on Resources



Digital document Investigation 10.8 Using apparent depth to determine the refractive index (doc-32333)



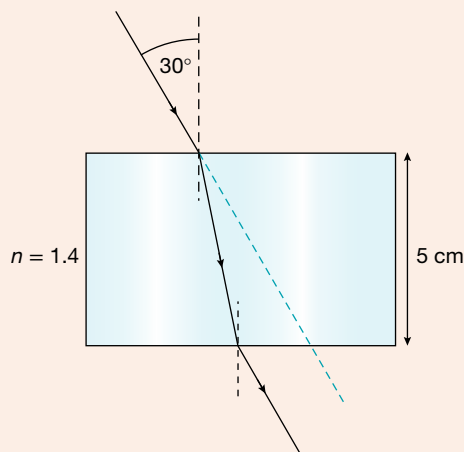
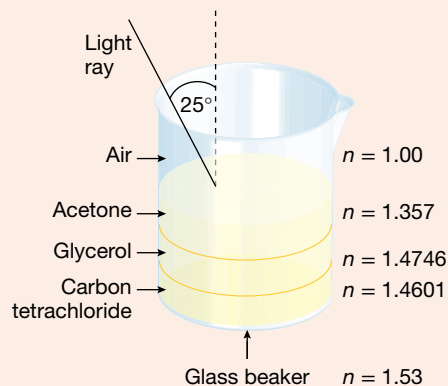
Teacher-led video Investigation 10.8 Using apparent depth to determine the refractive index (tlvd-0849)

10.3 EXERCISE

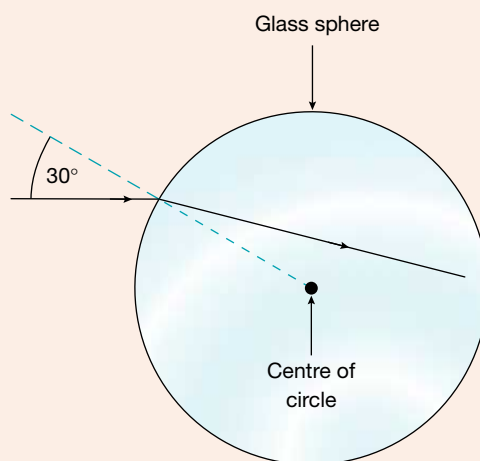
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1. A ray of light in air ($n_{\text{air}} = 1.00$) strikes water in a pond. What is the angle of refraction in water ($n_{\text{water}} = 1.33$) for an angle of incidence of 40° ? If the angle of incidence is increased by 10° , by how much does the angle of refraction increase?
2. A ray of light enters a plastic block at an angle of incidence of 55° with an angle of refraction of 33° . What is the refractive index of the plastic?
3. A ray of light passes from air through a rectangular glass block ($n_{\text{glass}} = 1.55$). The angle of incidence as the ray enters the block is 65° .
 - (a) Calculate the angle of refraction at the first face of the block.
 - (b) Calculate the angle of refraction as the ray emerges on the other side of the rectangular block.Comment on your answers.

4. A glass block ($n_{\text{glass}} = 1.55$) is immersed in a container of water ($n_{\text{water}} = 1.33$). A light ray passes from the water into the glass block at an angle of incidence of 28.0° . Determine the angle of refraction in the glass block.
5. Determine the speed of light in the following materials:
- water ($n_{\text{water}} = 1.33$)
 - glass ($n_{\text{glass}} = 1.50$)
 - diamond ($n_{\text{diamond}} = 2.42$).
6. Immiscible liquids are liquids that do not mix. Immiscible liquids will settle on top of one another, in the order of their density, with the densest liquid at the bottom. Some immiscible liquids are also transparent.
- Calculate the angles of refraction as a ray passes down through immiscible layers as shown in the diagram at right.
 - If a plane mirror was placed at the bottom of the beaker, calculate the angles of refraction as the ray reflects back to the surface. Comment on your answers.
7. Calculate the sideways deflection as a ray of light goes through a parallel-sided plastic block ($n_{\text{plastic}} = 1.4$) with sides 5.0 cm apart, as in the following figure.

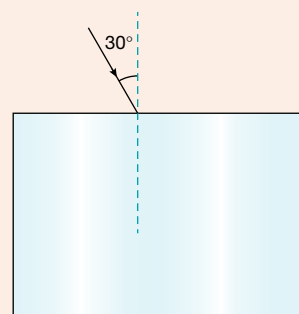


8. A ray of light enters a glass sphere ($n = 1.5$), as in the following figure. What happens to the ray?



9. Give the meaning of the following terms: refraction, reflection, dispersion, spectrum, refractive index.
10. (a) White light enters a crown glass rectangular prism. Sketch the path of red and deep blue light through the glass and back into air. How does the direction of the emerging coloured rays compare with that of the incoming white ray?
- (b) Suggest why a glass triangle is used to observe the visible spectrum, rather than a glass rectangle.

11. Which travels faster through crown glass — red light or violet light? What is the speed difference?
12. Green and violet light enter a triangular prism. Which is bent more?
13. A ray of white light in air strikes a rectangular glass block with an angle of incidence of 30° , as shown in the diagram on the right. For the glass block, the refractive index of red light is 1.514 and, for purple light, it is 1.530.
 - (a) On a copy of the diagram, carefully show the path taken by red light and by purple light.
 - (b) Use Snell's Law to find the angle of refraction for both the red light and the purple light.
 - (c) Determine the angle between the red light ray and the purple light ray in the rectangular glass



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10.4 Total internal reflection

KEY CONCEPTS

- Investigate and analyse theoretically and practically the behaviour of waves including:
 - total internal reflection and critical angle including applications: $n_1 \sin(\theta_c) = n_2 \sin(90^\circ)$.

10.4.1 The critical angle

Light can play some strange tricks. Many of these involve refraction away from the normal and the effect on light of a large increase in the angle of incidence.

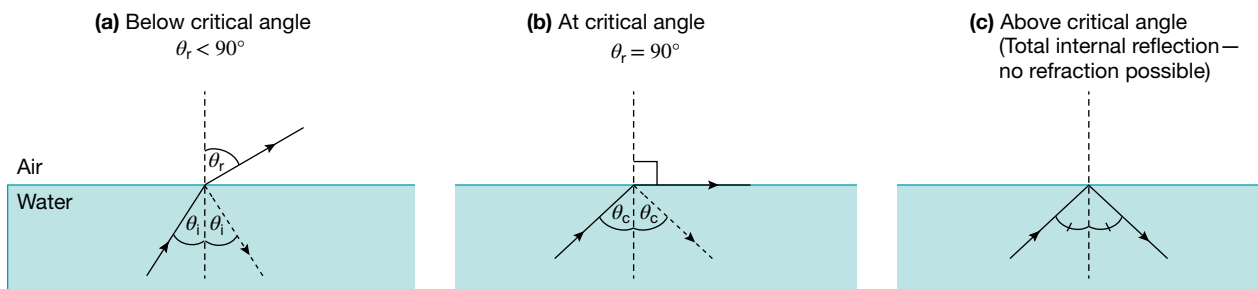
It has already been mentioned that some light is reflected off a transparent surface while the rest is transmitted into the next medium. This applies whether the refracted ray is bent towards or away from the normal.

However, a special situation applies when the refracted ray is bent away from the normal. This is illustrated in figure 10.27. As the angle of incidence increases, the angle of refraction also increases. Eventually the refracted ray becomes parallel to the surface and the angle of refraction reaches a maximum value of 90° (see figure 10.27b). When this condition is met, the corresponding angle of incidence is called the **critical angle**. If the angle of incidence is increased beyond the critical angle, all the light is reflected back into the water, with the angles being the same. This phenomenon is called **total internal reflection** (see figure 10.27c).

FIGURE 10.26 There are no mirrors in a fish tank but strange reflections can be seen. It appears that light is being reflected off the side of the fish tank and the water surface.



FIGURE 10.27 Three stages of refraction leading to total internal reflection



The critical angle can be calculated using Snell's Law:

$$n_1 \times \sin \theta_c = n_2 \times \sin 90^\circ$$

where: n_1 is the refractive index of medium 1
 n_2 is the refractive index of medium 2
 θ_c is the critical angle for medium 1

SAMPLE PROBLEM 5

What is the critical angle for water given that the refractive index of water is 1.3 and the refractive index of air is 1.0?

Teacher-led video: SP5 (tlvd-0198)

THINK

1. List the known information.
2. Use the relationship $n_{\text{water}} \times \sin \theta_c = n_{\text{air}} \times \sin 90^\circ$ to determine the critical angle for water.

WRITE

$$n_{\text{air}} = 1.0; \theta_{\text{air}} = 90^\circ; n_{\text{water}} = 1.3; \theta_{\text{water}} = ?$$

$$n_{\text{water}} \times \sin \theta_c = n_{\text{air}} \times \sin 90^\circ$$

$$1.3 \times \sin \theta_c = 1.0 \times \sin 90^\circ$$

$$\Rightarrow \sin \theta_c = \frac{\sin 90^\circ}{1.3}$$

$$= 0.7692$$

$$\Rightarrow \theta_c = \sin^{-1}(0.7692)$$

$$= 50.28^\circ$$

$$\theta_c = 50^\circ$$

The critical angle is 50° .

PRACTICE PROBLEM 5

Diamond has a refractive index of 2.42.

- a. What is the value of the critical angle for a diamond–air interface?
- b. The diamond is now placed in water ($n = 1.33$). Would the critical angle increase, decrease or stay the same?
- c. Determine the critical angle for a diamond–water interface.

Total internal reflection is a relatively common atmospheric phenomenon (as in mirages) and it has technological uses (for example, in optical fibres).

SPARKLING PHYSICS

Diamonds are cut by a gem-maker so that, when light enters the diamond, it strikes a few faces at angles greater than the critical angle. This maximises the light path and increases the separation of the colours that occurred when the light first entered the diamond.

The appearance of white paint as white is actually due to the large amount of refraction and dispersion created by the titanium dioxide particles it contains. A large percentage of the light that hits a white surface is reflected back — the colours go in all directions and hence the surface appears white.

10.4.2 Mirages

There are several types of mirages that can be seen when certain atmospheric conditions enable total internal reflection to occur. These mirages appear because the refractive index of air decreases with temperature.

A common type of mirage occurs in the desert or above a road on a sunny day. At ground level the air is hot with a refractive index close to 1. As height increases, the temperature of the air decreases and its refractive index increases.

FIGURE 10.28 A mirage on a country road.

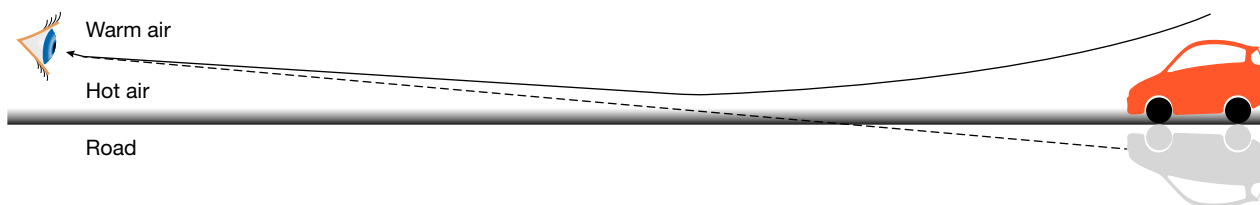


FIGURE 10.29 Mirages such as this are common on hot, sunny days.



Rays of light from a car, for example, go in all directions. The air above the ground can be considered as layers of air. The closer to the ground, the higher the temperature and the lower the refractive index. As a ray moves into hotter air, it bends away from the normal. After successive deflections, the angle of incidence exceeds the critical angle for air at that temperature and the ray is totally internally reflected. As the ray emerges, it follows a similar path, refracting towards the normal as it enters cooler air. An image of the car can be seen below street level, as shown in figure 10.30. The mirage is upside down because light from the car has been totally internally reflected by the hot air close to the road surface.

FIGURE 10.30 The mirage of the car appears upside down due to total internal reflection in the hot air close to the ground.



Another mirage that depends on layers of air at different temperatures is known as the ‘Fata Morgana’, in which vertical streaks, like towers or walls, appear. This occurs where there is a temperature inversion — very cold at ground level and warmer above — and very stable weather conditions.

The phenomenon is named after Morgan le Fay (Fata Morgana in Italian), who was a fairy and half-sister to King Arthur of the Celtic legend. She used mirages to show her powers and, in the Italian version of the legend, lived in a crystal palace under the sea. The mirage is often seen in the Strait of Messina and over arctic ice. As shown in figure 10.31, the light rays from a distant point are each refracted by the different layers of air, arriving at different angles to the eye. The effect is that the point source (P) becomes a vertically extended source, like a tower or wall. An example of the Fata Morgana, over an ice field in the Arctic Ocean off the coast of Svalbard, is shown in figure 10.32.

FIGURE 10.31 Ray paths for the Fata Morgana

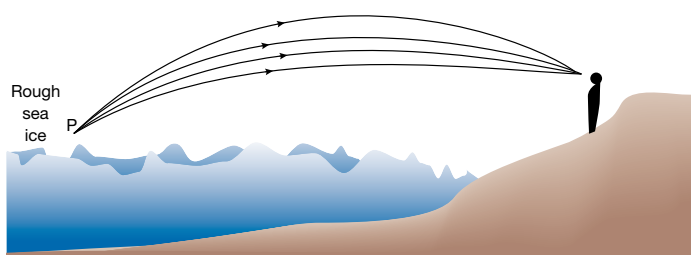


FIGURE 10.32 The Fata Morgana of Svalbard



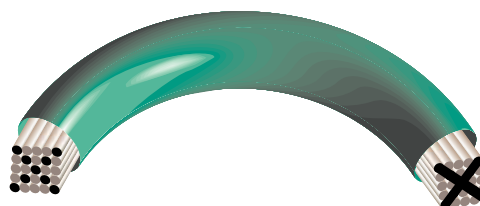
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 **Weblink** Mirages and more

10.4.3 Optical fibres

Another example of total internal reflection is in the important technological application of **optical fibres**. Optical fibres have become a feature of modern life. A thin, flexible cable containing an optical fibre can be placed inside a person’s body to transmit pictures of the condition of organs and arteries, without the need for invasive surgery. The same can be done in industry when there is a problem with complex machinery. Optical fibres are also the basis of the important telecommunications industry. They allow high-quality transmission of many channels of information in a small cable over very long distances and with negligible signal loss.

FIGURE 10.33 A bundle of optical fibres. Each fibre in the bundle carries its signal along its length. If the individual fibres remain in the same arrangement, the bundle will emit an image of the original object.



An optical fibre is like a pipe with a light shone in one end that comes out the other end. An optical fibre is made of glass that is approximately 10 micrometres (10×10^{-6} m) thick. Light travels along it, as glass is transparent, but the fibre needs to be able to turn and bend around corners. The optical fibre is designed so that any ray meeting the outer surface of the glass fibre is totally internally reflected back into the glass. As shown in figure 10.34, the light ray meets the edge of the fibre at an angle of incidence greater than the critical angle and is reflected back into the fibre. In this way, nearly all the light that enters the fibre emerges at the other end.

FIGURE 10.34 A light ray travels along an optical fibre through total internal reflection.

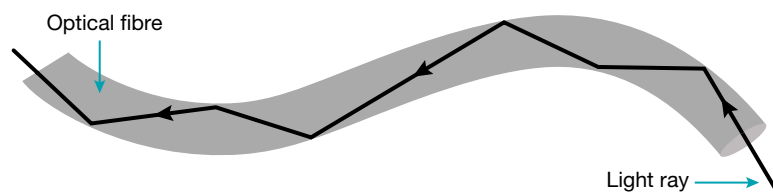
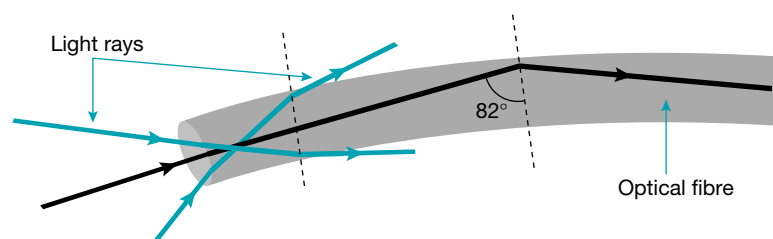


FIGURE 10.35 Light rays entering the fibre at too sharp of an angle are refracted out of the fibre.



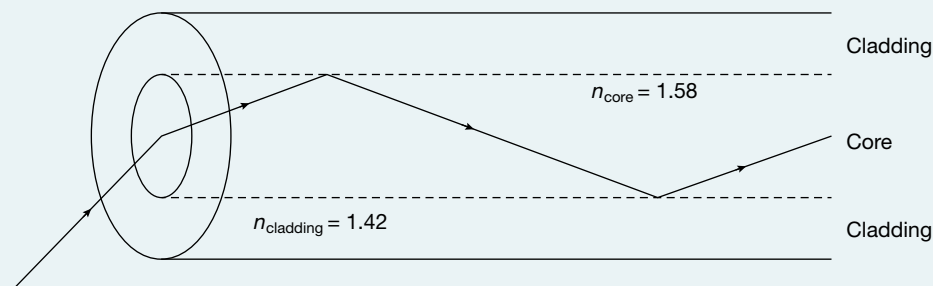
If the glass fibre is exposed to the air, the critical angle for light travelling from glass to air is 42° , which is quite small. Any angle of incidence greater than this angle will produce total internal reflection. If the fibre is very narrow, this angle is easily achieved.

However, in both medical and telecommunications uses, fibres are joined in bundles with edges touching. The touching would enable light rays to pass from fibre to fibre, confusing the signal. To overcome this, a plastic coating or cladding is put around the glass to separate the glass fibres. The total internal reflection occurs between the glass and the plastic. The critical angle for light travelling from glass to plastic is 82° . This value presents a problem because light meeting the edge of the glass at any angle less than 82° will pass out of the fibre.

This has implications for the design of the optical fibre and the beam of light that enters the fibre. The fibre needs to be very narrow and the light entering the fibre has to be a thin beam with all the rays parallel.

SAMPLE PROBLEM 6

Optical fibres transport data using light. They are constructed using transparent materials with different refractive indices. The following diagram shows a typical fibre with a cylindrical core and surrounding cladding. Laser light is shone from air in the optical fibre.



- Explain why it is necessary for the refractive index of the cladding to be smaller than the refractive index of the core.
- Calculate the critical angle for the laser light at the core–cladding boundary.
- Determine the speed of the laser light in the core of the optical fibre.

 **Teacher-led video:** SP6 (tlvd-0199)

THINK

- Explain why it is necessary for the refractive index of the cladding to be smaller than the refractive index of the core.

- Use the relationship

$$n_{\text{core}} \times \sin \theta_c = n_{\text{cladding}} \times \sin 90^\circ$$
to determine the critical angle.

- Analyse the refraction of the light at the entrance of the optical fibre, the air–core boundary. Use the relationship

$$n_{\text{air}} v_{\text{air}} = n_{\text{core}} v_{\text{core}}$$

WRITE

- If the refractive index of the cladding was larger than the refractive index of the core, the light would be refracted *towards the normal* and internal reflection would not be possible. When the refractive index of the cladding is less than that of the core, the light is refracted *away from the normal* so that total internal reflection is possible if the angle of incidence is larger than the critical angle.

$$\text{b. } n_{\text{core}} \times \sin \theta_c = n_{\text{cladding}} \times \sin 90^\circ$$

$$1.58 \times \sin \theta_c = 1.42 \times \sin 90^\circ$$

$$\Rightarrow \sin \theta_c = \frac{1.42 \sin 90^\circ}{1.58}$$

$$= \frac{1.42}{1.58}$$

$$\Rightarrow \theta_c = \sin^{-1} \left(\frac{1.42}{1.58} \right)$$

$$\theta_c = 64.0^\circ$$

The critical angle is 64.0° .

$$\text{c. } n_{\text{air}} v_{\text{air}} = n_{\text{core}} v_{\text{core}}$$

$$1.00 \times (3.00 \times 10^8) = 1.58 \times v_{\text{core}}$$

$$v_{\text{core}} = \frac{3.0 \times 10^8}{1.58}$$

$$= 1.90 \times 10^8 \text{ m s}^{-1}$$

The speed of the laser light in the core is $1.90 \times 10^8 \text{ m s}^{-1}$.

PRACTICE PROBLEM 6

A different optical fibre is used with the same cladding ($n_{\text{cladding}} = 1.42$) as in sample problem 6 but with a core of refractive index 1.56.

- Would the critical angle of this new optical fibre be larger or smaller than the previous fibre?
- Calculate the critical angle for this new optical fibre.
- Determine the speed of the laser light in the core of this new optical fibre. Is it larger or smaller than the speed of laser light in the previous fibre?

10.4.4 Rainbows

Rainbows are a common example of the dispersion of light. However, they are not only seen in the sky. You can also see a rainbow when you use a garden hose. Three conditions are necessary for a rainbow to be visible:

- The Sun needs to be visible.
- Some water droplets need to be airborne.
- An observer needs to be present.

For a rainbow to be seen, the usual arrangement of these three elements is to have the Sun oriented behind the observer and the airborne water to be present in front of the observer. The water drops separate the colours in a similar way to that which occurs with the glass prism. The big difference is that, before the colours emerge from the water droplet, they are reflected from the opposite surface of the droplet.

FIGURE 10.36 Each droplet of water in the air spreads the colours. Person A sees a rainbow between droplet 2 and droplet 3. Person B sees a rainbow between droplet 1 and droplet 2.

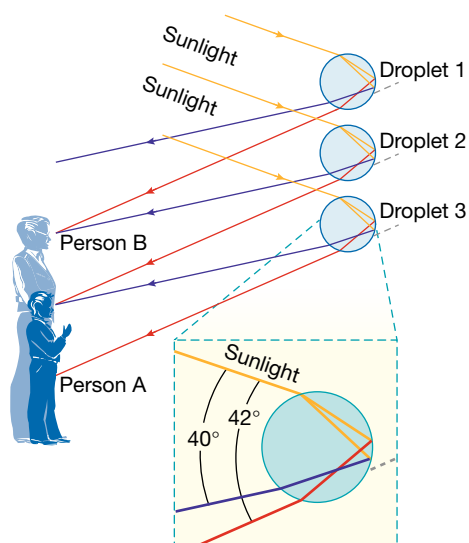
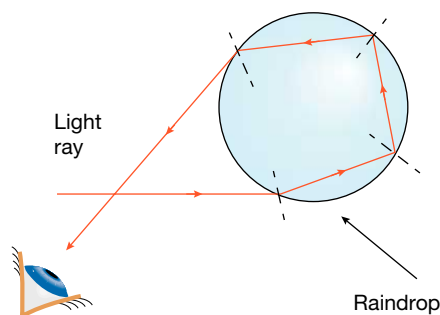


FIGURE 10.37 A light ray enters the bottom of the raindrop, is reflected twice off the wall of the raindrop, then emerges.



When you see a rainbow, each colour comes from a separate raindrop in the sky. If the red light from a raindrop enters your eye, then the violet light from that raindrop goes over your head to someone else. Each person sees his or her own personal rainbow. Your rainbow depends on raindrops in the sky being at a particular point so that the angle between you, the Sun and the raindrops is approximately 42° . The rainbow is not an image in the sky that everyone can see. In figure 10.37, the ray enters the eye at a higher angle than the primary rainbow. The colours are spread as they enter the raindrop and grow further apart the longer they are in the raindrop.

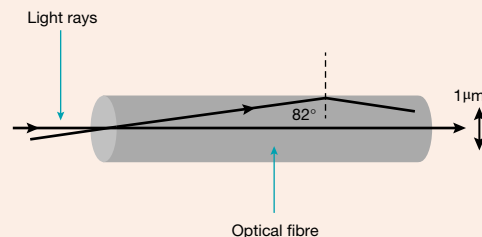
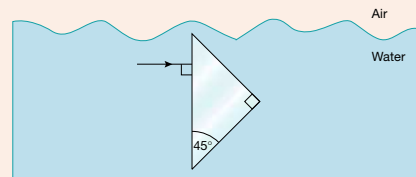
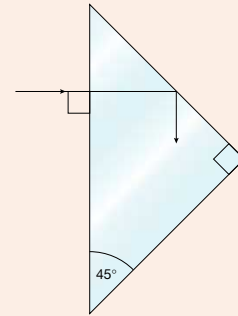
When the sky is very dark, a second, fainter rainbow may be visible on the outside of the bright one. This is due to the sunlight entering higher raindrops at the bottom and reflecting off the inside of the drop twice before emerging into the air.

10.4 EXERCISE

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- People enjoy the look of diamonds because they disperse white light.
 - Calculate the critical angle for light travelling through a diamond ($n_{\text{diamond}} = 2.50$) towards its surface. You may assume that the diamond is in air ($n_{\text{air}} = 1.00$).
 - The diamond is now placed in water ($n_{\text{water}} = 1.33$). Determine the critical angle now for light at a diamond–water
- Consider the triangular prism shown in the diagram to the right.
 - Calculate the refractive index of the glass triangular prism so that the light ray meets the faces at the critical angle. Is this value of the refractive index the minimum or maximum value for such a reflection?
 - One ray enters the prism as shown (2 cm from the top of the prism). Another ray, parallel to the one shown, also enters the prism, 2 cm from the bottom of the prism. Describe the positions of the rays after refraction.
 - Would the rays of light emerge at the same or different times?
- Calculate the refractive index of the plastic coating surrounding an optical fibre if the critical angle for glass to plastic is 82.0° and the refractive index of glass is 1.50.
- Describe what a submerged diver would see when looking directly up at the still water surface.
- A right-angled glass prism ($n = 1.55$) is placed under water ($n = 1.33$), as shown in the figure at the right:

A ray of light enters the longest side along the normal. What happens to the ray of light?
- A fish looking up at the surface of the water sees a circle, inside which it sees the ‘air world’. Outside the circle it sees the reflection of the ‘water world’. If the fish is 40 cm below the surface, calculate the radius of the circle ($n_{\text{water}} = 1.33$).
- Light enters an optical fibre $1.0 \mu\text{m}$ in diameter, as shown in the figure at the right. Some light goes straight down the centre of the fibre. Another ray is angled, leaving the central line and meeting the outside edge at slightly more than the critical angle of 82° , then reflects back to the central line.
 - How much further did this second ray travel compared to the ray that travelled down the centre of the fibre?
 - Calculate the speed of light in the glass and hence determine the time delay between the two rays after one internal reflection. Do you think this could be a problem when transmitting data in an optical fibre? If so, when? How could the problem be overcome?



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10.5 Diffraction of light

KEY CONCEPTS

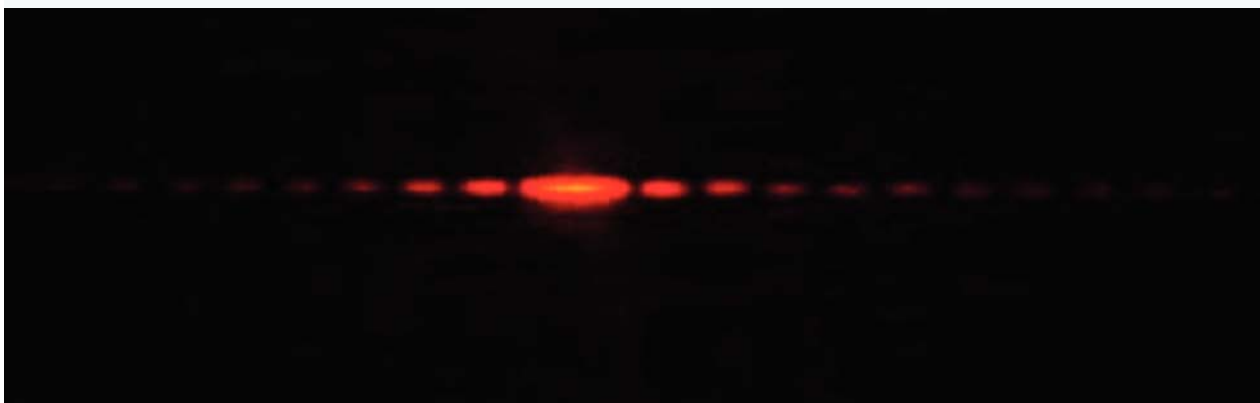
- Investigate and explain theoretically and practically diffraction as the directional spread of various frequencies with reference to different gap width or obstacle size, including the qualitative effect of changing the $\frac{\lambda}{w}$ ratio
- Investigate and describe theoretically and practically the effects of varying the width of a gap or diameter of an obstacle on the diffraction pattern produced by light and apply this to the limitations of imaging using light.

10.5.1 Light also diffracts

Topic 9 describes diffraction as one of the defining properties of waves. However, the word ‘diffraction’ was coined by Francesco Grimaldi (1618–1663) to describe a specific observation he made of light. He observed that, when sunlight entered a darkened room through a small hole, the spot was larger than would be expected from straight rays of light. He also noted that the border of the spot was fuzzy and included coloured fringes. He observed a similar effect when light passed a thin wire or a strand of hair. There is also some evidence that he repeated the experiment with two adjacent holes and observed evidence of cancellation: ‘That a body actually enlightened may become obscure by adding new light to that which it has already received.’ Grimaldi did not give an explanation for these observations in terms of waves or particles.

Newton was aware of Grimaldi’s observation of ‘diffraction’. He interpreted it using his particle model, arguing that the observed effect was due to light particles interacting with the edges of the hole as a refraction effect. He argued that if light was a wave, the bending would be much greater. Newton’s conclusions on the particle model were enough for scientists even a hundred years later, in Young’s time, to doubt any experimental evidence supporting the wave model.

FIGURE 10.38 Diffraction of red light through a slit



Source: University of Cambridge

However, with improving technology, the investigation of the diffraction of light revealed more than just the observation of spreading:

- The pattern had a central bright region with narrower and less bright regions either side.
- There was a dark gap between the bright regions.
- The central region was twice as wide as the other regions, which were all about the same size.
- The pattern for red light is more spread out than that for blue light.

FIGURE 10.39 Relative intensity and diffraction patterns through an identical slit for (a) blue light and (b) red light

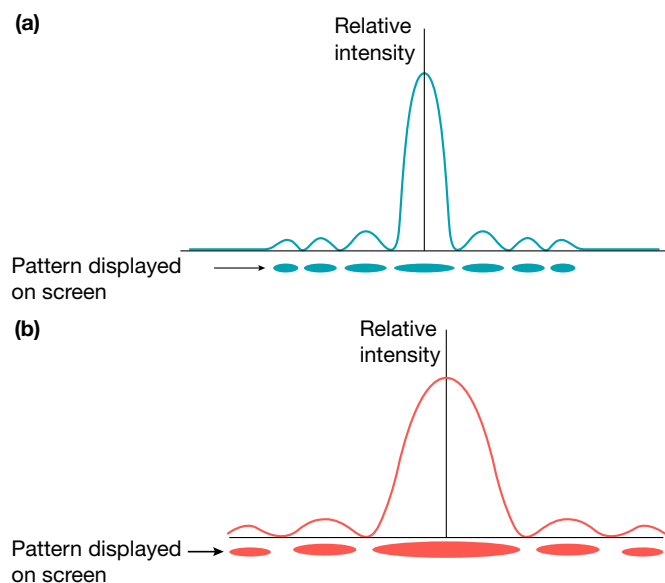
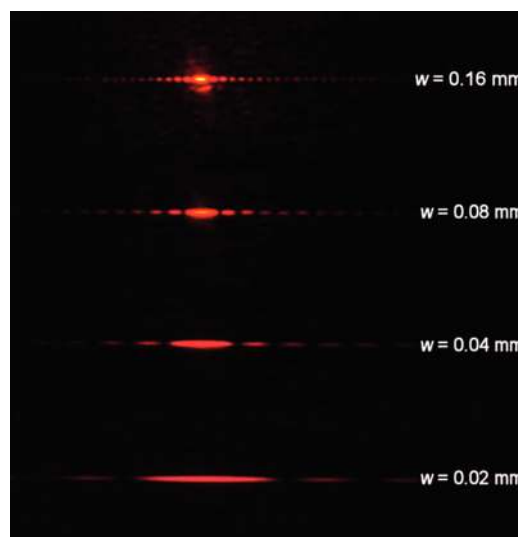


FIGURE 10.40 Diffraction patterns change with gap width. As the gap width gets smaller, the pattern spreads out more.



Source: University of Cambridge

Figure 10.39 and figure 10.40 confirm that light satisfies the same relationships as other waves, that is:

- the amount of spreading is proportional to the wavelength, λ
- the amount of spreading is proportional to the inverse of the gap width, $\frac{1}{w}$.

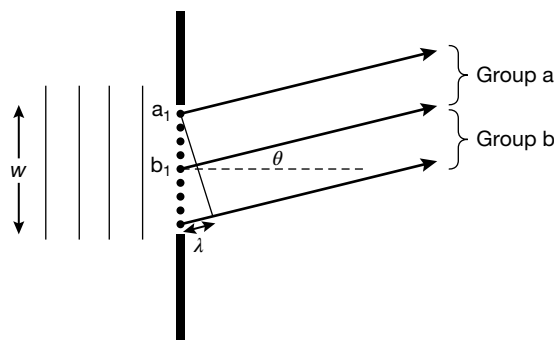
The dark gap between the bright bands is worthy of closer examination. These patterns will also be explored further and linked to interference in subtopic 10.6, using Young's experiment to help interpret and understand the bright and dark bands. According to Huygens's wave model, each point on a wavefront produces circular waves that overlap to produce the next wavefront. When a straight wavefront meets a small gap, each point in the gap produces circular waves, which means the next wavefront spreads out to be wider than the gap.

Now, what happens off to the side? Consider the rays travelling at an angle θ such that:

$$\sin \theta = \frac{\lambda}{w}$$

Divide the point sources in the gap into two groups, a and b. Pairing up the top point source of group a (a_1) with the top point source of group b (b_1) shows there is a path difference of $\frac{\lambda}{2}$. Therefore, waves from a_1 and b_1 will cancel in the direction of θ . Similarly, waves from a_2 and b_2 will cancel, and so on, due to destructive interference. So for the angle θ , waves from half of the point sources in the gap will cancel with waves from the other half. This means there will be a dark band, or as it is called a first minimum, at an angle that satisfies the relationship $\sin \theta = \frac{\lambda}{w}$.

FIGURE 10.41 Point sources in a diffraction gap



This relationship provides an explanation for the observations of the diffraction of light:

- A longer wavelength $\Rightarrow$ the angle of the first minimum is greater $\Rightarrow$ the pattern is wider.
- A larger gap width $\Rightarrow$ the angle of the first minimum is smaller $\Rightarrow$ the pattern is narrower.

10.5.2 Diffraction and optical instruments

Diffraction limits the usefulness of any optical instrument, whether it be your eye, a microscope or a telescope. It even affects radio telescopes.

The pupil of your eye is the circle through which light enters the eye. The objective lens of a microscope or a telescope determines how much light the instrument captures. These all have a width, so a diffraction effect is unavoidable. Diffraction limits the instrument's capacity to distinguish two objects that are very close to each other.

In the images in figure 10.42, light from two close sources passes an optical device and produces image (a), showing two distinct spots. When the two sources are moved closer together, image (b) is produced, and the spots begin to merge. Moving the two sources even closer together produces image (c); the two spots are now one broad spot. At the separation that produces image (b), the diffraction patterns produced by the optical device begin to overlap so that the central maximum of one pattern sits on the minimum of the other. This separation is the limit of the device to resolve the detail in an image; it is called the diffraction limit or resolution of the device.

The diffraction limit of a device depends on the ratio $\frac{\lambda}{w}$. Thus, a shorter wavelength gives a better resolution, as does a larger aperture for the optical device, such as in the use of electron microscopes.

FIGURE 10.42 Images produced by two point light sources as they get closer, from (a) to (c)

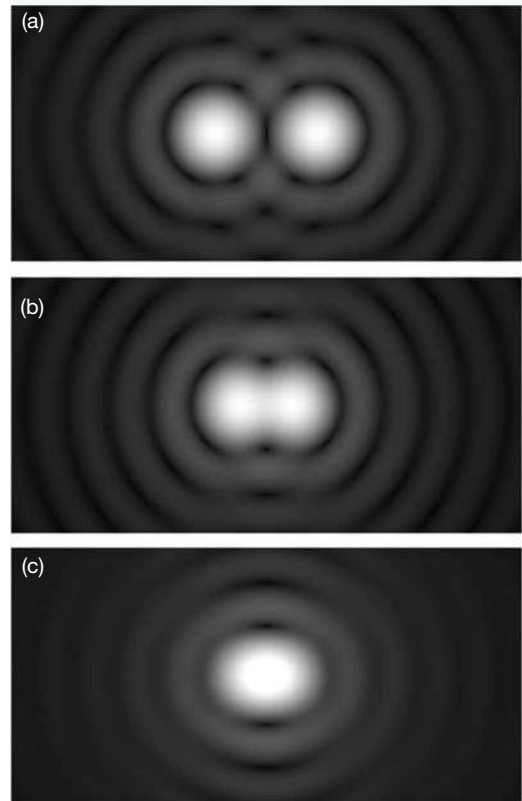
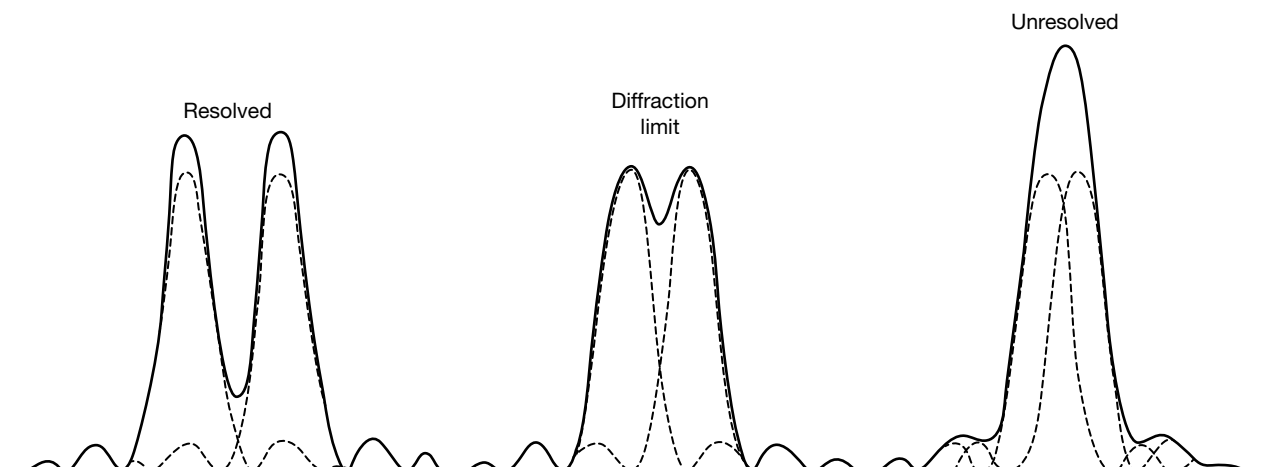


FIGURE 10.43 The diffraction patterns of two point sources overlap as the sources move closer together.



10.5 EXERCISE

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1. Light diffracts when it passes through a sufficiently narrow opening. Is this evidence for light being a type of wave or a stream of particles?
2. Consider the diffraction pattern produced when light passes through a narrow opening.
 - (a) Explain how the first minimum from the principal axis in the pattern occurs in terms of the interference of waves passing through the narrow opening.
 - (b) Sketch, on the same axes, the diffraction pattern produced by blue light and red light passing through the same narrow opening.
 - (c) Repeat (b) but this time for light passing through an opening that is narrower.
3. White light consisting of all colours passes through a narrow slit and projects onto a distant screen, which shows bright and dark bands with coloured fringes.
 - (a) Explain how the coloured fringes arise.
 - (b) Red fringes are observed at the furthestmost extent from the central white maximum. Why?
4. A beam of green light is directed at a small obstacle and a shadow is cast onto a distant screen. The shadow is not as sharp as one would expect using a ray model for light or even a particle model for light to predict the characteristics of the shadow.
 - (a) Comment on why this blurred edge shadow is evidence for the wave nature of light.
The light source is changed from green to red light and a shadow is produced on the screen.
 - (b) Would the shadow appear less or more sharp? Explain using your understanding of the wave nature of light.
 - (c) The beam of green light is restored and, this time, a smaller object is placed in it. Again a shadow is cast onto a distant screen. Would the shadow cast appear less or more sharp than that cast by the larger object?

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10.6 Interference using light

KEY CONCEPTS

- Explain the results of Young's double-slit experiment with reference to:
 - evidence for the wavelike nature of light
 - constructive and destructive interference of coherent waves in terms of path differences: $n\lambda$ and $\left(n - \frac{1}{2}\right)\lambda$ respectively
- effect of wavelength, distance of screen and slit separation on interference patterns: $\Delta x = \frac{\lambda L}{d}$.

10.6.1 Young's double-slit experiment

Thomas Young (1773–1829) was keenly interested in many things. He has been called 'the last man who knew everything'. He was a practising surgeon as well as a very active scientist. He analysed the dynamics of blood flow, explained the accommodation mechanism for the human eye and proposed the three-receptor model for colour vision. He also made significant contributions to the study of elasticity and surface tension. His other interests included deciphering ancient Egyptian hieroglyphics, comparing the grammar

and vocabulary of over 400 languages, and developing tunings for the twelve notes of the musical octave. Despite these many interests, the wave explanation of the nature of light was of continuing interest to him.

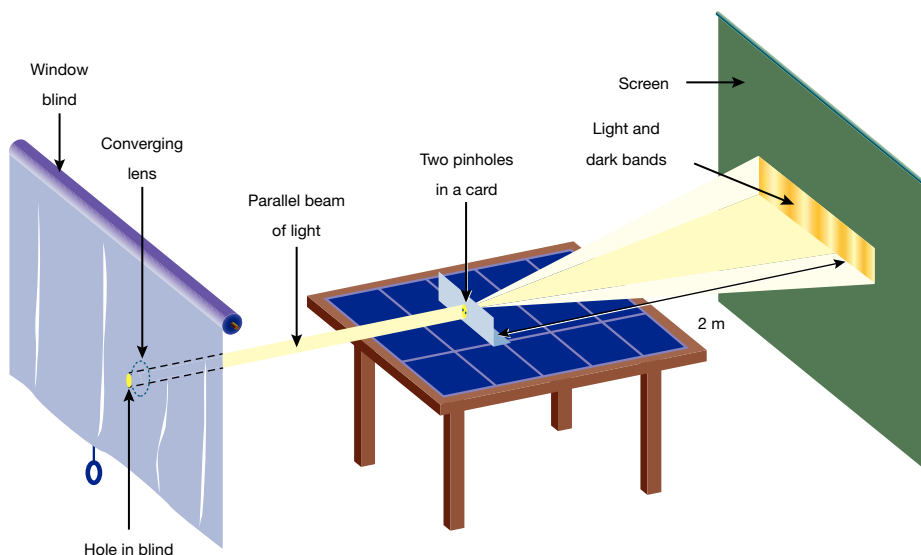
Young had already built a ripple tank to show that the water waves from two point sources with synchronised vibrations show evidence of interference. He was keen to see if he could observe interference with two beams of light. He held a fine hair close to his eye while staring past it at a distant candle. The light from the candle flame passed on both sides of the hair to reach his eyes. He did not notice a scattering of light in all directions as predicted by the particle model. Instead, a beautifully coloured pattern of bands parallel to the hair spread out across his view of the candle. Young's interpretation of what he saw was that light behaved like waves as it spread out from the candle.

It occurred to me that their cause must be sought in the interference of two portions of light, one reflected from the fibre, the other bending round its opposite side, and at last coinciding nearly in the direction of the former portion.

Young described this and other experiments in lectures at the Royal Institution in London in 1801 and 1802. He did not convince his audience! His listeners were reluctant to remove their confidence from the particle model that Newton apparently supported. Young was determined to produce quantitative evidence of the phenomenon that he had observed. He analysed the published results of similar experiments performed by Newton and made further measurements of his own.

In one of his experiments, Young made a small hole in a window blind. He placed a converging lens behind the hole so that the cone of sunlight became a parallel beam of light. He then allowed light from the small hole to pass through two pinholes that he had punctured close together in a card. On a screen about two metres away from the pinholes, he again noticed coloured bands of light where the light from the two pinholes overlapped. Figure 10.44 shows Young's experimental arrangement.

FIGURE 10.44 Young's experiment



Young deliberately had just one source, the hole in the blind, because he wanted the one wavefront to arrive at the two pinholes so that light coming through one pinhole would be synchronised with the light coming through the other pinhole. Today, light coming from the two pinholes would be described as **coherent**. When coherence occurs, constant phase difference is observed and the light has the same frequency. This can also be described as being in phase (as mentioned in topic 9). If Young had used two separate sources of light, one for each pinhole, their light would have been incoherent, with a random relationship between the light coming from the two pinholes and no discernible pattern on the screen. It is important to note that this is often the case with white light, as white light often has a wide range of frequencies, and therefore is often not coherent.

FIGURE 10.45 Light waves in Young's experiment

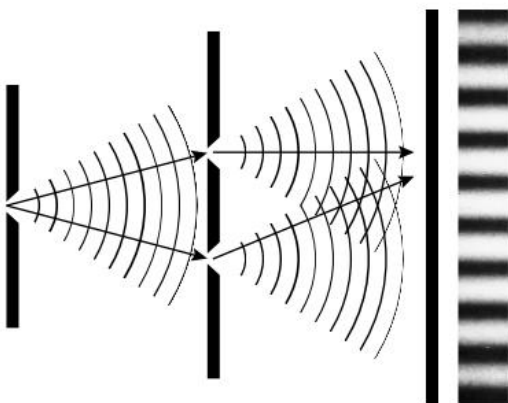


FIGURE 10.46 A light pattern produced by a modern performance of Young's experiment



Resources



Video eLesson Young's experiment (interference effects with white light) (eles-0027)



Interactivity Young's experiment (interference effects with white light) (int-0051)

10.6.2 Interpreting Young's experiment

Young used the wave model for light to analyse his observations. Each hole in the window blind is a source of spherical waves. When these waves pass through the pinholes, each pinhole becomes a source of spherical waves. Waves from the two pinholes overlap on the screen, and their effects add together to produce the pattern (as seen in figure 10.47). In reaching a particular point on the screen, waves have travelled from the source along two alternative routes, through one pinhole or the other. The difference between the lengths of the two paths is called the **path difference**. If the path difference results in the crests of the wave from one pinhole always meeting the troughs of the wave from the other pinhole (that is, exactly out of phase) then destructive interference occurs and that place on the screen is a dark band. This links back to the diffraction patterns discussed in subtopic 10.5. Destructive interference occurs when the path difference is a whole number, minus one half, multiplied by the wavelength of the light: $(n - 0.5)\lambda$ where n is the number of bright bands from the central bright band. A bright band occurs when, in spite of a path difference, the waves are in phase: crests reinforcing crests and troughs meeting troughs.

Constructive interference occurs when the path difference is a whole number multiple of the wavelength of the light, n , again where n is the number of bright bands from the central bright band.

This can be summarised as:

Constructive interference: $n\lambda$

Destructive interference: $(n - \frac{1}{2})\lambda$

where: n is the number of bright brands from the central point

λ is the wavelength of the light source

Think about performing Young's experiment with a light source emitting light of only one wavelength, say 600 nm (6×10^{-7} m) in the richly yellow part of the spectrum. Constructive interference will occur if the path difference between the two routes to the screen is 0, 600 nm, 1200 nm, 1800 nm, and so on ($n \times 600$ nm). However, if the path difference is 300 nm, 900 nm, 1500 nm, and so on ($(n - 0.5) \times 600$ nm), where n is an integer, then there will be destructive interference.

FIGURE 10.47 Maximum intensity occurs for the maximum amplitude light wave, because of constructive interference. At P, $S_2P - S_1P = \lambda$.

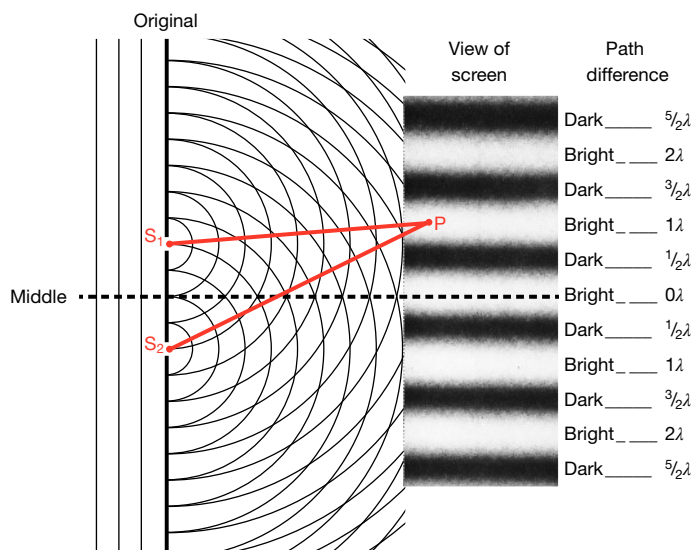
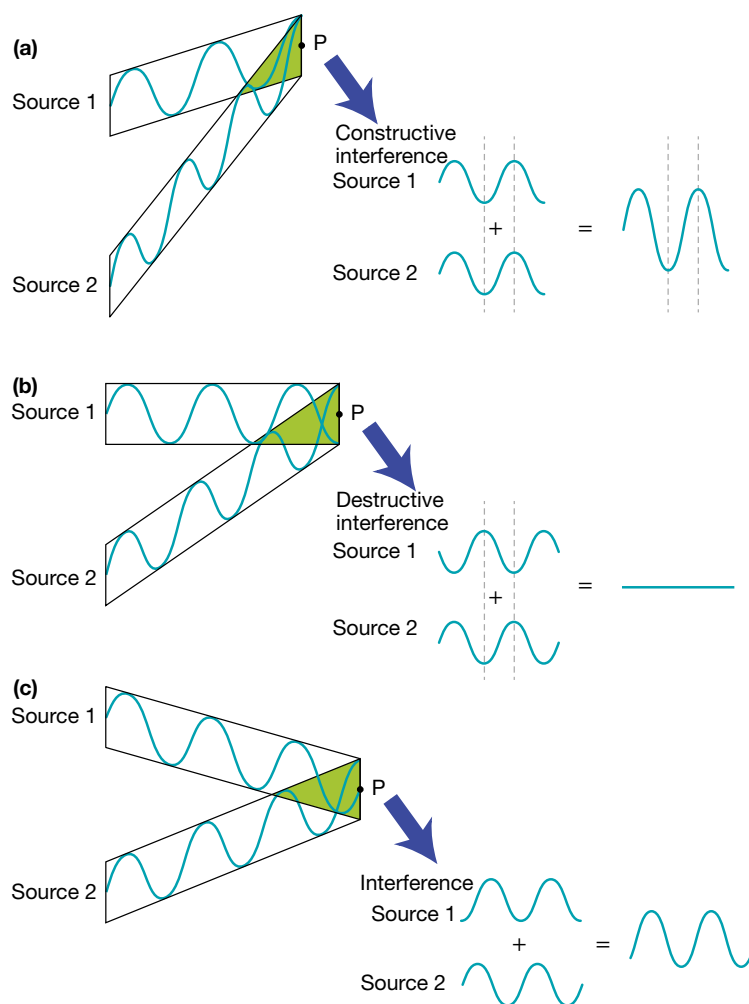


FIGURE 10.48 (a) Constructive interference of waves arriving in phase, (b) destructive interference of waves arriving exactly out of phase, and (c) interference of two waves slightly out of phase



SAMPLE PROBLEM 7

Red light of wavelength 640 nm is passed through a pair of slits, S_1 and S_2 , to produce an interference pattern, like that shown in figure 10.47.

- What is the path difference for the third bright band from the central bright band?
- Consider the second dark band from the central bright band. How much further is S_2 than S_1 from the second dark band?
- Red light is replaced with purple light. What happens to the interference pattern?

THINK

- The third bright band has a path difference of 3λ .
- The second dark band arises because of destructive interference where the path difference is $\frac{3\lambda}{2}$.
- The wavelength for purple light is less than for red light.

WRITE

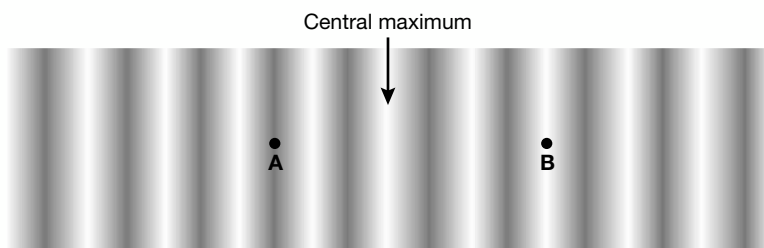
- The path difference is:
 $3 \times 640 = 1920 \text{ nm}.$
- S_2 is further away from this dark band than S_1 by the following distance:

$$\frac{3\lambda}{2} = \frac{3 \times 640}{2}$$

$$= 960 \text{ nm}$$
- The pattern is now more compact or compressed as the distance between the bands is decreased, due to the smaller wavelength of the purple light.

PRACTICE PROBLEM 7

A student creates an interference pattern using green light of wavelength 530 nm. The pattern is shown in the following diagram.



- Calculate the path difference for the points marked A and B.
- The student increases the distance between the two slits. Describe what happens to the pattern.
- She now changes the light source from green to red. Describe what happens to the pattern now.
- Explain why the interference pattern is strong evidence for the wave nature of light.



Resources



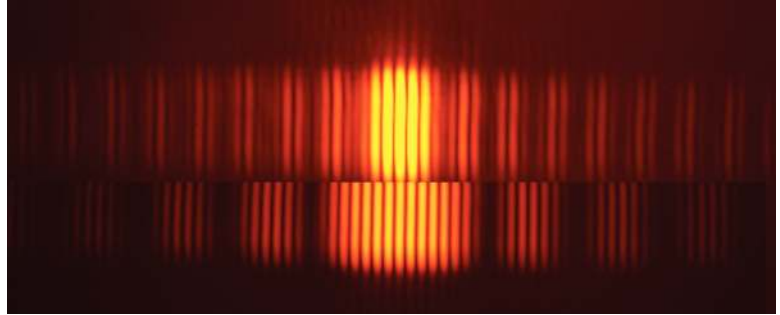
Weblink The atomic lab: wave interference

10.6.3 Linking diffraction and two-slit interference

When light from a point source illuminates a double slit, each slit produces its own diffraction pattern with a wide central maximum and smaller side maxima. If the two slits are close together, these two patterns overlap, and the light coming from each slit interferes with the light coming from the other slit. This causes light and dark bands where the two central maxima overlap and also where the side maxima overlap. Diffraction, which was covered in subtopic 10.5, is vital for interference to occur.

Normally, to emphasise the key features of interference, the pattern is prepared with slits that are so narrow that the central maximum fills the screen and the side maxima are not observed.

FIGURE 10.49 Interference pattern from two slits that are not extremely narrow. The slits in the bottom section of the image are narrower than those for the top section of the image because the central maximum is wider.



10.6.4 Spacing of bands in an interference pattern

The previous section developed expressions relating the path difference to the light and dark bands in an interference pattern. These expressions are important in understanding Young's experiment, but the path difference cannot be measured. What can be measured in this experiment is:

- the separation of the two slits, d
- the wavelength, λ
- the distance of the screen from the two slits, L
- the spacing between alternate bands in the pattern (either the bright or dark bands), x .

A relationship between these four quantities would be useful. It could be used to calculate the wavelength of an unknown light source from a slide with a known slit separation, or to calculate an unknown slit separation with light of a known wavelength.

If the separation of the two slits, d , is very much less than the distance L , then the two lines S_1P and S_2P are effectively parallel, as shown in figure 10.50. Typically, d is about 1 mm and L is about 2 metres.

FIGURE 10.50 Exploring the relationship between d , λ , L and x

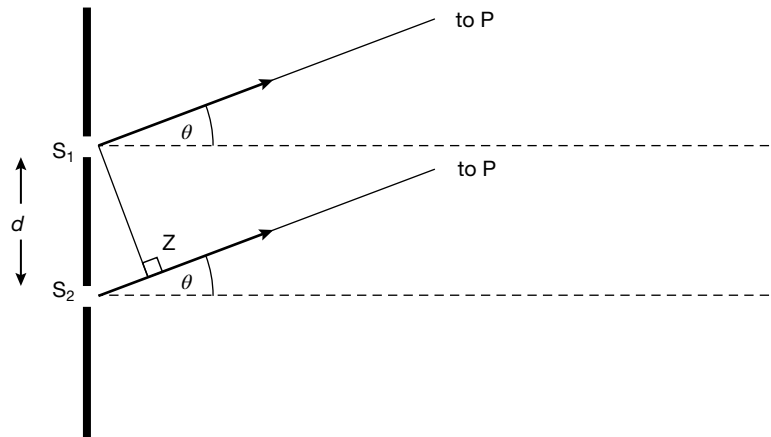
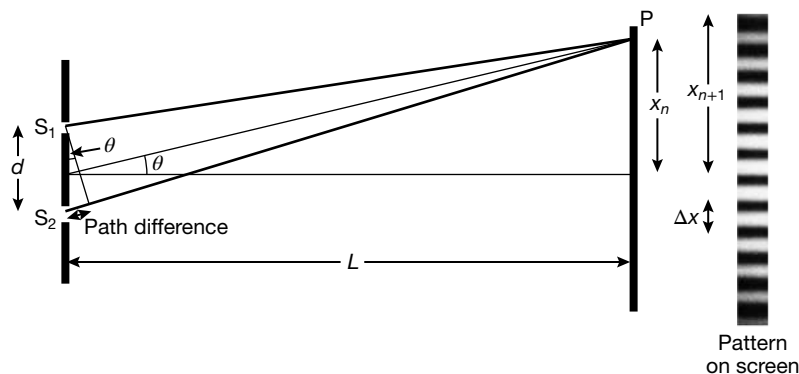


FIGURE 10.50 Exploring the relationship between d , λ , L and x (Continued)



In the first of the two diagrams, S_1Z is a line drawn across the two light paths at right angles. The distances from S_1 to P and from Z to P will be equal to each other. This means the path difference is S_2Z . From the right-angled triangle with corners at S_1 , Z and S_2 , and a right angle at Z , $\sin \theta = \frac{\text{path difference}}{d}$, or path difference $= d \sin \theta$.

For bright lines, $d \sin \theta = n\lambda$, where n is a positive integer.

From the second of the two diagrams in figure 10.50, $\tan \theta = \frac{x_n}{L}$, but for small angles less than 10° , $\tan \theta$ and $\sin \theta$ have similar values to within about 1%.

So, for small angles, $\frac{n\lambda}{d} = \frac{x_n}{L}$, giving $x_n = \frac{n\lambda L}{d}$, and for $n + 1$, $x_{n+1} = \frac{(n + 1)\lambda L}{d}$.

The spacing between adjacent bright lines, $x_{n+1} - x_n = \Delta x$ is given by:

$$\Delta x = \frac{\lambda L}{d}$$

where: Δx is the spacing between bands (either light or dark)

λ is the wavelength of the light waves

L is the distance of the screen from the slits

d is the slit separation

SAMPLE PROBLEM 8

Sodium light of wavelength 589 nm is directed at a slide containing two slits that are 0.500 mm apart. What will be the spacing between the bright bands in the interference pattern on a screen that is 1.50 m away?

Teacher-led video: SP8 (tlvd-0201)

THINK

- List the known information, ensuring that all values are in the same unit.
- Use the relationship $\Delta x = \frac{\lambda L}{d}$ to calculate the spacing between bright bands.

WRITE

$$\begin{aligned} \lambda &= 589 \text{ nm} = 589 \times 10^{-9} \text{ m}; \\ L &= 1.50 \text{ m}; d = 0.500 \times 10^{-3} \text{ m}; \\ \Delta x &= ? \\ \Delta x &= \frac{\lambda L}{d} \\ &= \frac{589 \times 10^{-9} \times 1.50}{0.500 \times 10^{-3}} \\ &= 0.00177 \text{ m} \\ &= 1.77 \text{ mm} \end{aligned}$$

PRACTICE PROBLEM 8

Interference bands are formed on a screen that is 2.00 m from a double slit with separation 1.00 mm. The bands are measured to be 1.30 mm apart.

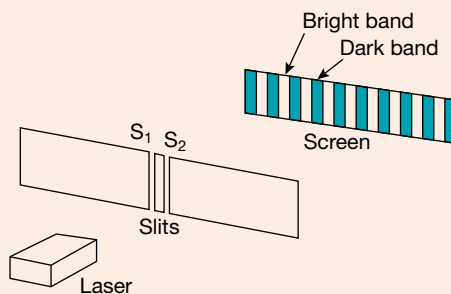
- What is the wavelength of the light?
- What is its colour?
- How would the pattern change if blue light was used?
- How could the experimental design be changed to make it easier to measure the line spacing in the pattern?

10.6 EXERCISE

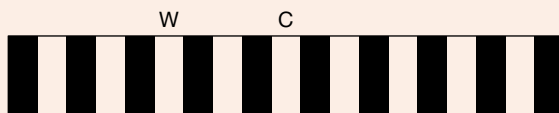
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- Young's double-slit experiment was a significant experiment in the development of understanding about light and matter.
 - What has been learned about the nature of light from Young's experiment?
 - When light is passed through a pair of narrow closely spaced slits, an interference pattern is formed.

What is an interference pattern and how is it formed?
- Jill and William are studying the effect of passing laser light of wavelength 530 nm through a pair of slits and forming a pattern on a screen several metres away. The following diagram shows the experimental arrangement.

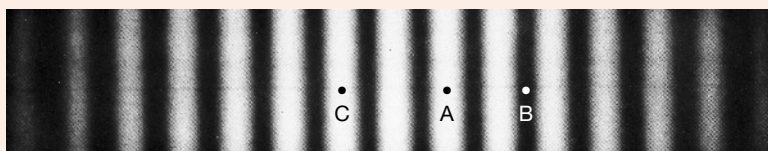


Part of the interference pattern observed by Jill and William is shown in the next diagram. Point C represents the position of the central maximum (bright band), and point W represents the second maximum (bright band) from the centre of the pattern.



- Is the pattern on the screen evidence for the wave nature of light or for the particle nature of light? Explain your choice.
- Is W a point where constructive or destructive interference is occurring?
- What is the path difference $|S_1C - S_2C|$?
- What is the path difference $|S_1W - S_2W|$?
- State the three smallest path differences that would give rise to dark regions on the screen.
- How many dark regions are there in between C, the central maximum, and W, the second maximum from the central maximum?

3. A student shines a helium–neon laser, which produces light with a wavelength of 633 nm, through two slits and produces a regular pattern of light and dark patches on a screen as shown in the following diagram. The centre of the pattern is the band marked A. Using a wave model, light can be described as having *crests* and *troughs*.



- (a) Use these terms to explain:
- the bright band labelled A
 - the dark band labelled B.
- (b) What is the path difference in the distance light has travelled from the two slits to:
- the bright band labelled A
 - the dark band labelled B
 - the bright band labelled C?
- (c) Using the same experimental setup, but replacing the laser with a green argon ion laser emitting 515 nm light, what changes would occur to the interference pattern?
- (d) The helium–neon laser is set up again. The distance between the two slits is now increased. What changes to the interference pattern shown in the diagram would occur?
- (e) The screen on which the interference pattern is projected is moved further away from the slits. What changes to the interference pattern shown in the diagram would occur?
4. Infra-red radiation can be passed through a pair of narrow slits and an interference pattern produced.
- (a) List several different path differences that would produce constructive interference for infra-red radiation with a wavelength of $1.06\ \mu\text{m}$.
- (b) Now list several path differences that would produce destructive interference.
5. Light of wavelength 430 nm falls on a double slit of separation 0.500 mm. What is the distance between the central bright band to the first, second and third bright band respectively in the pattern on a screen placed 1.00 m from the double slit?
6. A group of students is planning to measure the wavelength of light emitted from a laser. They do this by producing an interference pattern cast onto the wall of a classroom. The wall is 3.80 m away from the pair of slits, and they locate the central maximum and measure the distance from it to the first bright fringe immediately opposite the central maximum to be 1.90 cm. Their teacher informs them that the slits are separated by a distance of 0.134 mm.
- (a) Determine the wavelength of the laser light.
- (b) Describe any changes in the pattern if the slits were separated by 0.100 mm.
7. A double slit is illuminated by light of two wavelengths, 600 nm and the other unknown. The two interference patterns overlap with the third dark band of the 600 nm pattern coinciding with the fourth bright band from the central band of the pattern for the light of unknown wavelength. What is the value of the unknown wavelength?

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10.7 Light as a transverse electromagnetic wave

KEY CONCEPTS

- Describe light as an electromagnetic wave, which is produced by the acceleration of charges, which in turn produces changing electric fields and associated changing magnetic fields
- Identify that all electromagnetic waves travel at the same speed, c , in a vacuum
- Compare the wavelength and frequencies of different regions of the electromagnetic spectrum, including radio, microwave, infra-red, visible, ultraviolet, X-ray and gamma, and identify the distinct uses each has in society
- Explain polarisation of visible light and its relation to a transverse wave model.

10.7.1 Electromagnetic waves

Young had shown that the behaviour of light passing through narrow slits could be explained using the ideas of waves. He had even measured the wavelengths of light in the visible spectrum, but he did not know what sort of wave might explain light. James Clerk Maxwell (1831–1879) provided the answer in 1864. He began with the ideas of electric and magnetic interactions where a changing magnetic flux in time gave rise to an induced voltage and associated electric field. From these ideas, he developed a theory predicting that an oscillating electric charge would produce an oscillating electric field, together with a magnetic field oscillating at right angles to the electric field. These inseparable fields would travel together through a vacuum like a wave, and the speed of the wave would be the same, whether the oscillations were rapid (high frequency and a short wavelength) or very slow (low frequency and a long wavelength). Maxwell predicted their speed, using known electric and magnetic properties of a vacuum, to be $3 \times 10^8 \text{ m s}^{-1}$. This is the speed of light! Maxwell had produced a theory that explained how light was produced and travelled through space as electromagnetic waves. This applied not only to visible light, but also to other radiation that people cannot see, such as infra-red and ultraviolet radiation. Furthermore, his electromagnetic model of light indicated that light could be described as a transverse wave.

FIGURE 10.51 An electromagnetic wave. The electric and magnetic fields are uniform in each plane but vary along the direction of the motion of the wave.

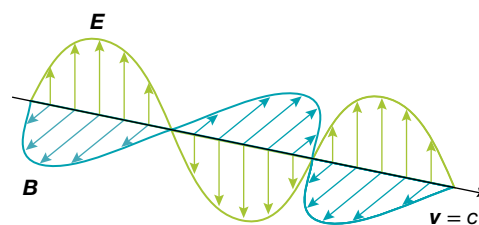


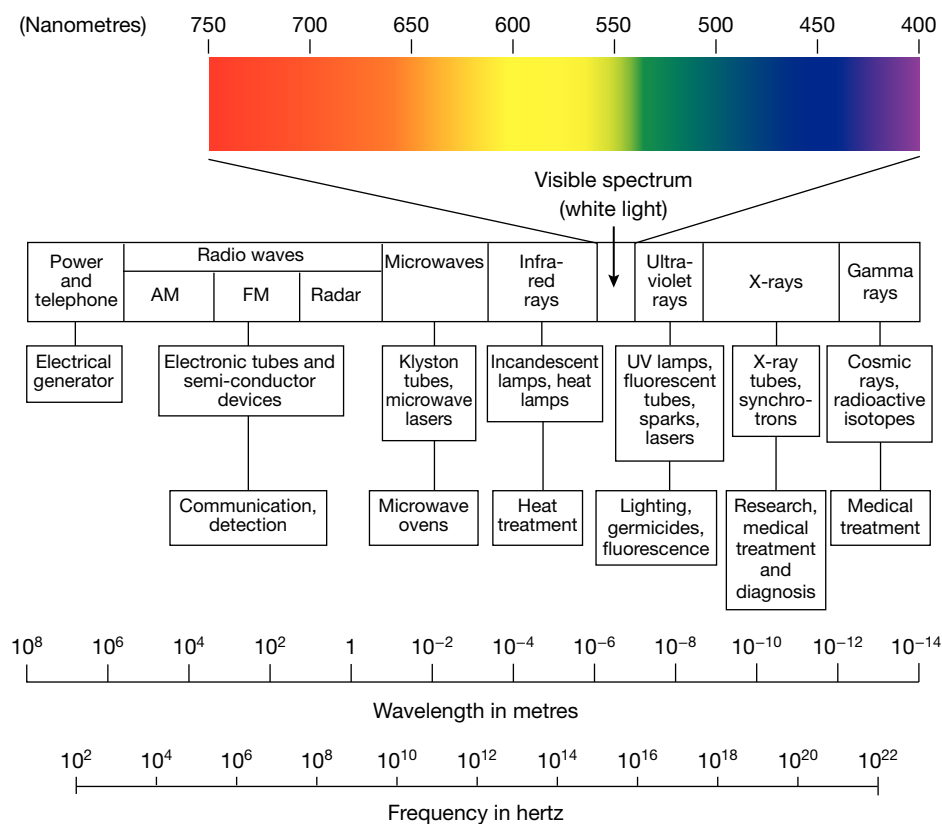
TABLE 10.3 Frequency and wavelength of colours

	Red	Orange	Yellow	Green	Blue	Violet
Frequency ($\times 10^{12}$ hertz)	430	480	520	570	650	730
Wavelength (nanometres)	700	625	580	525	460	410

The frequency of a light ray is determined by the source (that is, the object producing the light). The speed of the light is determined by the material the light is passing through. (The refractive index is a measure of how much the light is slowed down by the material.) This means that, when light passes from air into water, the frequency stays the same, the speed decreases and the wavelength must also decrease.

When you are under water and you look around, the objects you see still have the same colour. This means that your eye is responding to the frequency of the light ray and not to its wavelength. The world would be a strange place if the eye's response was the other way round.

FIGURE 10.52 Forms of radiation and their place in the electromagnetic spectrum. The visible portion of the spectrum is shown enlarged in the upper part of the diagram.



SAMPLE PROBLEM 9

When light with a frequency of 5.6×10^{14} Hz travels through a vacuum, what are the values of the following?

- Its period
- Its wavelength (in nanometres)

The speed of light in a vacuum is 3.0×10^8 m s⁻¹.

THINK

- The period of a wave is the reciprocal of its frequency.

WRITE

$$\text{a. } T = \frac{1}{f}$$

$$= \frac{1}{5.6 \times 10^{14}}$$

$$= 1.8 \times 10^{-15} \text{ s}$$

The period of the light is 1.8×10^{-15} s.

b. 1. Use the relationship $\lambda = \frac{c}{f}$ to determine the wavelength.

2. The wavelength of visible light is usually expressed in nanometres (nm) where $1.0 \text{ nm} = 1.0 \times 10^{-9} \text{ m}$.

$$\begin{aligned} \text{b. } \lambda &= \frac{c}{f} \\ &= \frac{3.0 \times 10^8}{5.6 \times 10^{14}} \\ &= 5.4 \times 10^{-7} \text{ m} \\ \lambda &= \frac{5.4 \times 10^{-7}}{1.0 \times 10^{-9}} \text{ nm} \\ &= 5.4 \times 10^2 \text{ nm} \end{aligned}$$

The wavelength of the light is 540 nanometres.

PRACTICE PROBLEM 9

Find the frequency and period of light with a wavelength of 450 nm.

10.7.2 Polarisation

The transverse wave model of electromagnetic radiation developed by James Maxwell in 1873 proposes that light and other electromagnetic waves travel in many planes. Two hundred years earlier, the wave model of Christiaan Huygens proposed that light travelled as longitudinal waves — like sound.

Figure 10.53 shows what happens when a transverse wave in a vertical plane passes through a vertical slit. A transverse wave in a horizontal plane is unable to pass through a vertical slit. If transverse waves in many planes were to approach the slit, only the waves in the vertical plane would pass through.

This blocking of waves except for those in a single plane is called **polarisation**.

Figure 10.54 shows how a longitudinal wave can pass through both slits. Longitudinal waves cannot be polarised.

Observations of the polarisation of light show that light is a transverse wave rather than a longitudinal wave, as longitudinal waves cannot be polarised. The polarisation of light is observed when it passes through some materials. These materials, which allow light waves in one plane to pass while blocking light in all other planes, are called polarising filters.

FIGURE 10.53 Waves in a vertical plane pass through the slit. The waves in a horizontal plane cannot pass through.

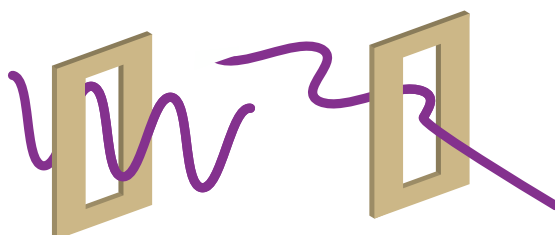


FIGURE 10.54 Longitudinal waves can pass through both vertical and horizontal slits.

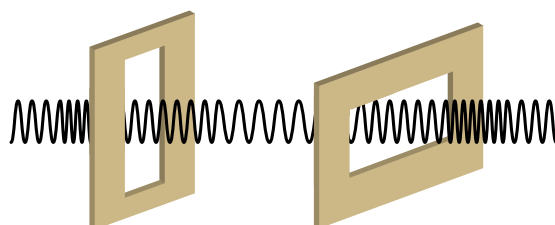


FIGURE 10.55 Light passed through crossed polarisers — polarising filters at right angles to each other

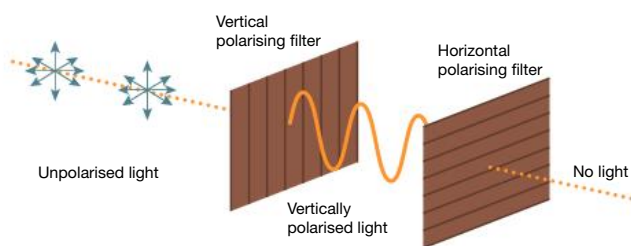
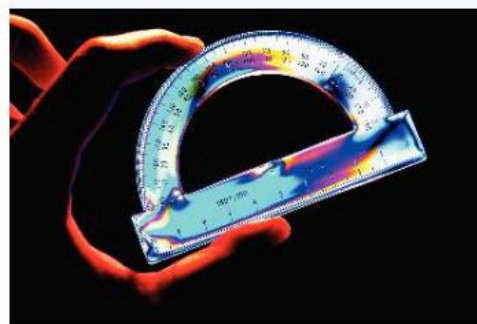


FIGURE 10.56 A protractor seen through crossed polarisers



APPLICATIONS OF POLARISATION

- Sunglasses with polarising lenses cut out the glare from reflective surfaces such as water and roads. Reflected light is polarised in the horizontal direction, so putting the plane of the polarising filter in the vertical direction cuts out glare.
- Bees can see the polarisation pattern of the sky and use it to locate sources of pollen. In fact, many insects, fish, amphibians, arthropods and octopi use the polarisation of light to their benefit.
- Stresses in transparent objects can be detected using polarisation. To do this, the object is placed between crossed polarisers. Light passes through the object towards a camera. Normally, no light would pass through the crossed polarisers. However, regions under stress can rotate the plane of polarisation. This allows some light to get through, creating a photographic image that reveals the stresses.

on Resources

-  **Weblinks** Polarisation
Polarised light applet

10.7 EXERCISE

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For this exercise, take the speed of light in a vacuum as $c = 3.0 \times 10^8 \text{ m s}^{-1}$.

1. Calculate the period of orange light, which has a frequency of $4.8 \times 10^{14} \text{ Hz}$.
2. Microwaves have a frequency ranging from 1.0×10^{10} through to $1.0 \times 10^{12} \text{ Hz}$. Determine the range of wavelengths associated with microwaves.
3. X-rays used by dentists have a wavelength of $2.7 \times 10^{-11} \text{ m}$. What is the frequency and hence the period of the X-rays produced?
4. Place the following types of electromagnetic waves in order of ascending frequency: gamma rays, radio waves, visible light, microwaves and ultraviolet rays.
5. Power lines that carry electrical energy use an AC current. These cables emit electromagnetic radiation with a period of 20 ms.
 - (a) What is the frequency of the radiation emitted by power lines?
 - (b) What is the wavelength of this radiation?
6. Which radio waves, AM or FM, would be more susceptible to the effects of diffraction? Explain your answer.
7. When blue light of frequency $6.5 \times 10^{14} \text{ Hz}$ travelling through the air meets a glass prism, its speed decreases from $3.0 \times 10^8 \text{ m s}^{-1}$ to $2.0 \times 10^8 \text{ m s}^{-1}$. Calculate the following:
 - (a) the wavelength of the blue light in the air
 - (b) the wavelength of the blue light in the glass
 - (c) the frequency of the blue light in the glass
 - (d) the refractive index of the glass used.

8. Explain, with the aid of a diagram, why polarisation would not be possible if light behaved like a longitudinal wave.
9. Glare at the beach is partly caused by polarised light reflected from the sand and the water. The light is polarised in the horizontal plane of the two surfaces. What should be the orientation of polaroid sunglasses to block out the glare?
10. 3D movies are shown at cinemas where patrons use special glasses. Research and give a simple description of how the system works, focusing on the ability of light to be polarised.
11. Describe how a moving charged particle that changes its motion produces an electromagnetic wave. Your answer should relate to both electric and magnetic fields around a moving charged particle.

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10.8 Review

10.8.1 Summary

- Light bends as it travels from one medium to another. A measure of a medium's capacity to bend light is given by its refractive index.
- If light travels into a medium of a higher refractive index, the light is bent towards the normal. If light travels into a medium of a lower refractive index, the light is bent away from the normal. This change in direction is summarised in Snell's Law. Snell's Law can be expressed as $n_1 \sin \theta_1 = n_2 \sin \theta_2$.
- Light consists of a mixture of colours and, when these colours enter a material, they refract at different angles. This means that a material has a different refractive index for each colour. The resulting separation of light into different colours is called dispersion.
- The speed of light in a uniform medium is a constant and is given by the equation $v = \frac{c}{n}$, where c is the speed of light in a vacuum and n is the refractive index of the medium. The greater the refractive index, the lower the speed of light is in that medium.
- When light passes from medium 1 into medium 2, the respective refractive indices and speeds are related by the equation $n_1 v_1 = n_2 v_2$.
- When light travels into a medium of a lower refractive index, there will be an angle of incidence for which the angle of refraction is 90° . This angle of incidence is called the *critical angle*. For angles of incidence greater than the critical angle, all the light is reflected back into the medium. This phenomenon is called *total internal reflection*.
- The amount of diffraction is determined by the ratio $\frac{\lambda}{w}$, where λ is the wavelength and w is the width of a slit or size of an obstacle.
- The amount of diffraction is related to the wavelength of light and the size of an opening or obstacle. The greater the wavelength, the more evident are the diffraction effects. The smaller the size of an opening or obstacle, the more evident are the diffraction effects also.
- Interference patterns resulting from light passing through two narrow slits can be explained using the wave principles of constructive and destructive interference of waves that are in phase and out of phase respectively. This interference results from a path difference to a point from each of the slits.
- In an interference pattern, a region of intense light, or maxima, results from a path difference of $0, \lambda, \pm 2\lambda, \pm 3\lambda, \dots$

- In an interference pattern, a region of no light, or minima, results from a path difference of $\pm\frac{1}{2}\lambda$, $\pm\frac{3}{2}\lambda$, $\pm\frac{5}{2}\lambda$, ...
- The behaviour of light, particularly refraction, diffraction and two-slit interference, is strong evidence for the wavelike properties of light.
- The speed of electromagnetic waves in a vacuum is $c = 3.0 \times 10^8 \text{ m s}^{-1}$. The wave equation is $v = f\lambda$ where f is the frequency and λ is the wavelength.
- Maxwell produced a mathematical model that represents light as a transverse wave consisting of perpendicular in-phase electric and magnetic fields. The wave propagates at a unique speed in uniform media. These waves are called electromagnetic waves. This model explained all the known observations of light up to the late nineteenth century.
- Visible light is a form of electromagnetic radiation that can be modelled as transverse waves with colours differing in frequency.
- Radio waves, microwaves, infra-red rays, ultraviolet rays, X-rays and gamma rays are all examples of electromagnetic radiation, differing only in frequency.
- Transverse waves, including light, can be polarised. Polarisation is the blocking of transverse waves except for those in a single plane.

on Resources



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10.8.2 Key terms

The **absolute refractive index** of a substance is the relative refractive index for light travelling from a vacuum into the substance. It is commonly referred to as the refractive index.

The **angle of incidence** is the angle between an incident ray and the normal.

The **angle of reflection** is the angle between a reflected ray and the normal.

The **angle of refraction** is the angle between a refracted ray and the normal.

Two waves are **coherent** if there is a constant relative phase between them.

The **critical angle** is the angle of incidence for which the angle of refraction is 90° . The critical angle exists only when light passes from one substance into a second substance with a lower refractive index.

Diffuse reflection is reflection from a rough or irregular surface.

Dispersion is the separation of light into different colours as a result of refraction.

Incandescent objects are luminous objects that produce light because they are hot. The higher the temperature, the brighter the light, and the colour also changes.

A **light ray** can be considered as an infinitely narrow beam of light and can be represented as a straight line.

Luminous objects are objects that are seen because they give off their own light.

The **normal** is a line that is perpendicular to a surface or a boundary between two surfaces.

An **optical fibre** is a thin tube of transparent material that allows light to pass through without being refracted into the air or another external medium.

Path difference is the difference between the lengths of the paths from each of two sources of waves to a point.

Polarisation is the blocking of transverse waves except for those travelling in a single plane.

Refraction is the bending of light as it passes from one medium into another.

Regular reflection (also referred to as specular reflection) is reflection from a smooth surface.

Relative refractive index is a measure of how much light bends when it travels from any one substance into any other substance.

Total internal reflection is the total reflection of light from a boundary between two substances. It occurs when the angle of incidence is greater than the critical angle.

10.8.3 Practical work and investigations

Investigation 10.1

Luminous or not?

Aim: To determine, from a list, which items are luminous and which items are non-luminous

Digital document: doc-31612

Investigation 10.2

Luminosity and temperature

Aim: To investigate the change in colour and brightness with temperature

Digital document: doc-31613

Investigation 10.3

Seeing is believing

Aim: To observe the bending of light

Digital document: doc-31614

Investigation 10.4

Snell's Law

Aim: To observe the refraction of light and to use Snell's Law to determine the refractive index of a medium

Digital document: doc-32090

Teacher-led video: tlvd-0251



Investigation 10.5

Separating colours

Aim: To determine which colour is bent the most by a prism

Digital document: doc-31615

Investigation 10.6

Refraction of particles

Aim: To measure the refraction of particles using surfaces at different heights

Digital document: doc-32086

Investigation 10.7

Refraction of waves

Aim: To observe the wavelength and refraction of waves travelling from deep to shallow water

Digital document: doc-31617

Investigation 10.8

Using apparent depth to determine the refractive index

Aim: To determine the refractive index using apparent depth

Digital document: doc-32333

Teacher-led video: tlvd-0849



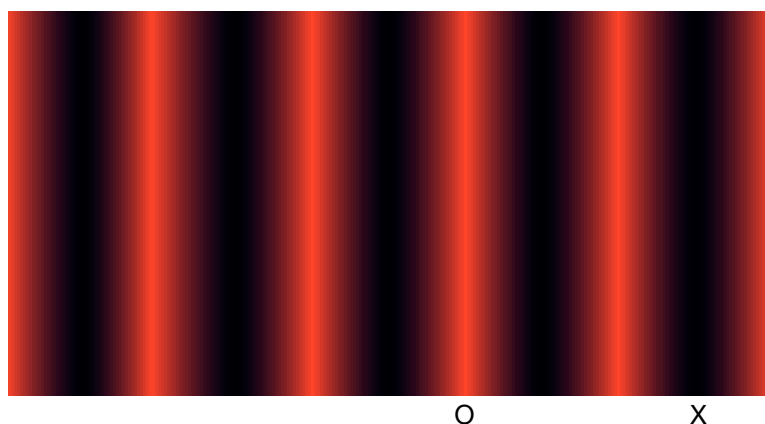
10.8 Exercises

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10.8 Exercise 1: Multiple choice questions

1. A group of students is trying to measure the speed of light on a sports oval. They have placed a mirror 120 m from a laser source and light sensor, both of which are connected to a timer. The timer starts when the laser is switched on and stops when a pulse arrives at the sensor. Light from the laser strikes the mirror and is reflected directly back to the sensor. Which one of the following do the students accurately measure the time to be?
 - A. 4.0×10^{-7} s
 - B. 1.6×10^{-6} s
 - C. 8.0×10^{-6} s
 - D. 8.0×10^{-7} s
2. In a practical session, students use a semicircular prism to investigate the refraction of light. When a narrow beam of light has an angle of incidence of 35.0° , the angle of refraction is 26.0° . Which one of the following is the refractive index of the prism?
 - A. 1.31
 - B. 1.28
 - C. 0.75
 - D. 0.85
3. A ray of light inside a rectangular block of glass ($n_{\text{glass}} = 1.53$) makes an angle of incidence of 47.0° . The rectangular block is immersed in water ($n_{\text{water}} = 1.33$). Calculate the angle of refraction for the ray of light as it exits into the water from the glass block.
 - A. 39.8°
 - B. 57.3°
 - C. 43.6°
 - D. 48.7°
4. Consider two optical fibres each of length 10 m. Optical fibre X has a core refractive index of 1.54 whereas optical fibre Y has a core refractive index of 1.58. Which one of the following statements is correct regarding the propagation of pulses of light sent down both fibres?
 - A. It will take a shorter time for the light pulse to pass down optical fibre Y than optical fibre X.
 - B. It will take the same time as the fibres have the same length, and the speed of light in both fibres is the same for all observers.
 - C. It will take a shorter time for the light pulse to pass down optical fibre X than optical fibre Y.
 - D. It will take a different amount of time but one that is not possible to determine.
5. Students are asked to calculate the critical angle for light propagating inside a transparent crystal. Their teacher tells them that the refractive index for the crystal is 1.387. Which one of the following is the critical angle for this crystal when placed in air?
 - A. 47.3°
 - B. 45.4°
 - C. 48.5°
 - D. 46.1°

6. White light is incident on an air–glass interface. Due to dispersion, the white light separates into colours. Which one of the following statements is correct?
- A. Blue light will have an angle of refraction that is greater than the angle of refraction of red light.
 - B. Red light will have an angle of refraction that is greater than the angle of refraction of green light.
 - C. Green light will have an angle of refraction that is greater than the angle of refraction of yellow light.
 - D. Orange light will have an angle of refraction that is greater than the angle of refraction of red light.
7. A student attempts to illustrate the diffraction of light. She makes a single slit of width 3.0 mm, and no significant diffraction is observed when she uses green light. Which one of the following statements offers the best advice to her so that diffraction can be observed?
- A. Advise the student to use blue light instead of green light.
 - B. Advise the student to make the slit narrower, closer to the wavelength of green light.
 - C. Advise the student to make the slit wider, closer to the wavelength of green light.
 - D. Advise the student to use red light instead of green light.
8. Students passing a laser light of wavelength 650 nm through a closely spaced narrow double slit produce the interference pattern shown below. The bright fringe O is identified as the central maximum.

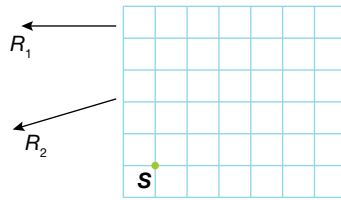


The point X is a region on the screen where there is no light. What is the path difference from each of the slits to the point X?

- A. 975 nm
 - B. 325 nm
 - C. 1300 nm
 - D. 1625 nm
9. Students produce an interference pattern using a green light laser. They cast a pattern onto a screen that is 2.5 m from the slits. The narrow slits are separated by 0.075 mm. A member of the group measures the distance between two adjacent bright fringes to be 1.60 cm. Which one of the following wavelengths of green light is the one used?
- A. 420 nm
 - B. 440 nm
 - C. 460 nm
 - D. 480 nm
10. Which one of the following statements is correct regarding an observation about light and a model for light?
- A. Interference demonstrates that light is a type of transverse wave.
 - B. Polarisation of light demonstrates that light is a type of transverse wave.
 - C. Interference demonstrates that light is a type of longitudinal wave.
 - D. Polarisation of light demonstrates that light is a type of longitudinal wave.

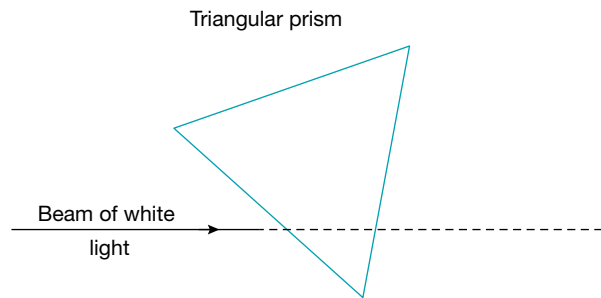
10.8 Exercise 2: Short answer questions

- The following diagram shows a light source S placed in front of a plane mirror that is not shown. Two light rays R_1 and R_2 that are reflected from the mirror are shown.

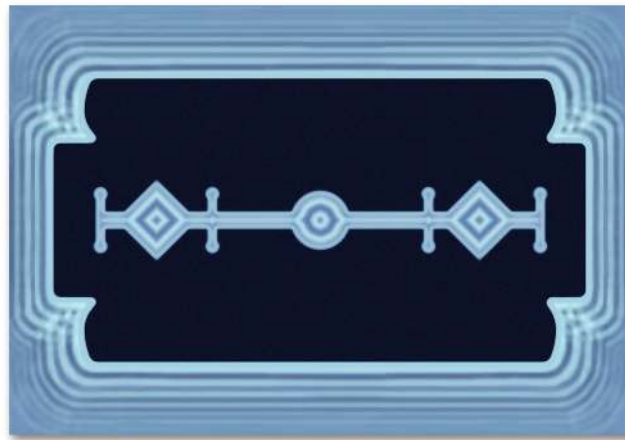


- On a copy of the diagram, locate the position of the image S and mark that point with the letter I .
 - Draw in the location of the plane mirror using a straight line to represent the mirror.
- Blue light has a frequency of 6.5×10^{14} Hz, and yellow light has a frequency of 5.2×10^{14} Hz.
 - Determine the wavelength of both blue and yellow light in air. Take the speed of light in air to be 3.0×10^8 m s⁻¹.
 - Determine the wavelength of both blue and yellow light, this time in glass with a refractive index of 1.50 for both colours.
 - Lasers can be rapidly switched on and off to produce a pulse of light. A particular pulse of blue light (6.5×10^{14} Hz) consists of 1.0×10^6 complete cycles. What is the distance between the start and end of this particular pulse? Hint: how much time would it take to produce this pulse?
 - Consider a ray of light incident on an air–perspex interface such that the angle of refraction is 16° when the angle of incidence is 22° .
 - Calculate the refractive index of the perspex, assuming the refractive index of air is 1.00.
 - If the angle of incidence is increase by 10° , what is the increase in the angle of refraction?
 - Now consider a ray of light propagating from the perspex into the air with an angle of incidence of 22° . Calculate the angle of refraction and comment on your answer.
 - A group of students is investigating the refraction of light as it passes from a transparent block of carbon disulfide ($n = 1.63$) into very salty water ($n = 1.38$).
 - Calculate the speed of light in carbon disulfide.
 Consider a ray of light passing from carbon disulfide into very salty water.
 - Will the light speed up or slow down in the very salty water compared to its speed in carbon disulfide?
 - Will the light bend towards the normal or away from the normal at the interface between carbon disulfide and the very salty water?
 - If the angle of incidence is 45° , calculate the angle of refraction.
 - Consider a ray of white light incident on an air–flint glass interface with an angle of incidence of 25° . The refractive index for red light in flint glass is 1.571 and, for blue light, the refractive index is 1.594. The refracted beam disperses as it passes into the glass.
 - Explain what is meant by the word ‘disperses’ in this context.
 - Determine the angle between the refracted red light and the refracted blue light in the flint glass. The angle of incidence is now increased from 25° to 50° .
 - What is the angle between the red and blue refracted rays now?
 - A beam of white light is fired at a triangular prism as shown in the following diagram. The dotted line gives the direction of the incident beam as a reference line for your drawing.

By drawing onto a copy of the diagram, show how the white light is dispersed as it passes through the prism. Clearly indicate on your diagram both the red and violet end of the spectrum produced by white light passing through the prism.



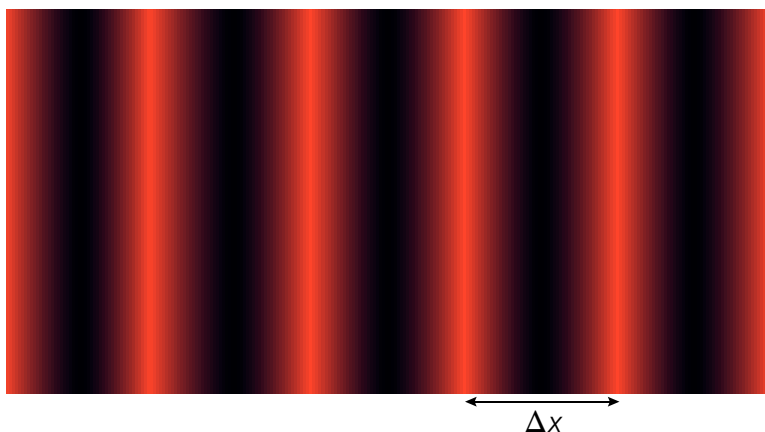
8. Consider three different types of glass X, Y and Z. Their refractive indices are $n_X = 1.53$, $n_Y = 1.55$ and $n_Z = 1.57$ respectively.
 - a. Of the three different types of glass, state the glass with the smallest critical angle.
 - b. Using your choice for part (a), determine the critical angle for light.
 Now, consider glass Z making an optical interface with glass X.
 - c. Determine the critical angle for this arrangement.
9. The following image shows the shadow produced when light has passed the edge of a razor blade. Explain why the shadow is not sharp and why there are regions of bright and dark light. Use the words *diffraction* and *interference* in your answer.



Source: National High Magnetic Field Laboratory

10. When light passes through a narrow slit, a diffraction pattern is produced and can be displayed on a screen. State two ways in which the amount of diffraction can be increased so that the pattern appears to be more spread out.
11. Using your knowledge of interference, explain why a pattern consisting of many bright and dark regions appears on a screen when light from a single source passes through two closely spaced, narrow slits.
12. The path difference to the third dark fringe in a standard two-slit interference pattern is 1250 nm.
 - a. What is the wavelength of the light used to make the interference pattern?
 - b. What is the path difference for the second bright fringe?

13. A two-slit interference pattern is constructed by a group of students, and a clear pattern like the one shown in the following image is cast onto the wall of a classroom. The distance between two adjacent bright fringes is shown as Δx .



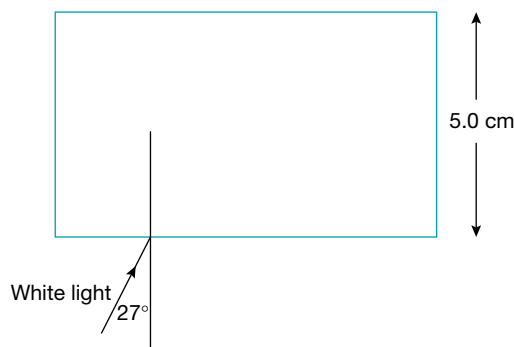
State three different ways in which the spacing Δx could be increased by a factor of 2.

14. A group of students is using a laser that emits light of wavelength 650 nm. They point the beam at a pair of slits that they know has a slit separation of 0.10 mm. They wish to produce a two-slit interference pattern, where the bright fringes are separated by 2.0 cm, as part of a display for an open day at their school. Calculate the distance they must position the screen from the pair of slits to achieve this.
15. Would it be possible to polarise microwaves? Discuss.

10.8 Exercise 3: Exam practice questions

Question 1 (7 marks)

A narrow beam of white light makes an angle of incidence with a rectangular prism having a width of 5.0 cm, as shown in the following diagram. The refractive index for red light in the prism is $n_{\text{red}} = 1.530$, and for blue light, the refractive index is $n_{\text{blue}} = 1.548$.



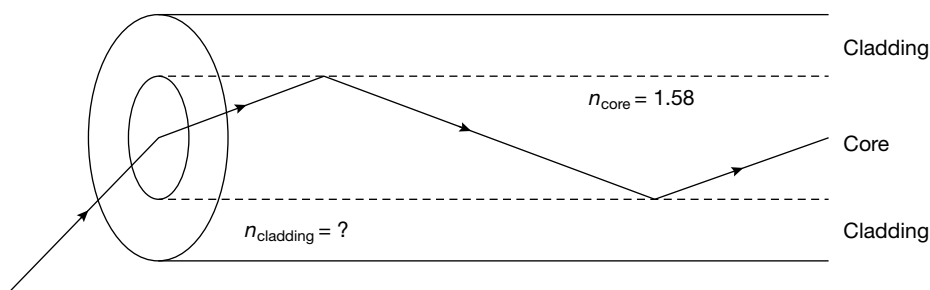
- a. Onto a copy of the diagram, carefully draw rays to indicate the propagation of red and blue light through the block of glass. For each path, indicate two points where refraction occurs and one where a reflection also occurs. **2 marks**

The narrow beam of white light makes an angle of incidence with the air–prism interface of 27° .

- b. Determine the angle of refraction for red light. **2 marks**
- c. Consider the time it takes for red light and blue light to propagate through the prism. Which colour would take the least time? Or does it take the same time? **3 marks**

Question 2 (8 marks)

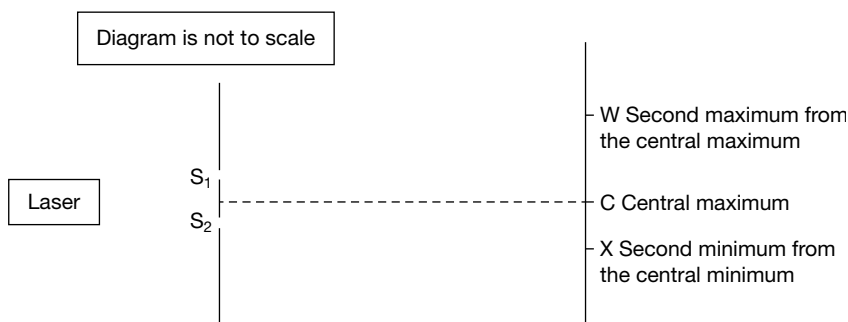
Optical fibres consist of transparent materials having an inner core and an outer cladding with different refractive indices. The following diagram shows a typical optic fibre. The refractive index of the core is 1.58 and the critical angle for light at the core–cladding boundary 84° .



- For the fibre to operate correctly, would the refractive index of the cladding be greater than, the same size as, or smaller than the refractive index of the core? Explain your choice without a calculation. **2 marks**
- Calculate the refractive index of the cladding, n_{cladding} . **2 marks**
- Determine the speed of light in the core of the fibre optic. **1 mark**
- In one instance, light of wavelength 400 nm is shone from air into the optical fibre. Calculate the wavelength of the light in the core of the optical fibre. **3 marks**

Question 3 (10 marks)

William and Jill are studying laser light of wavelength $\lambda = 530$ nm passing through a pair of slits. The light forms a pattern on a screen, several metres away, consisting of bright and dark fringes. The following diagram shows the experimental arrangement.



- Calculate the frequency of the light emitted by the laser. **2 marks**
 - What is the path difference $|S_2X - S_1X|$? Give your answer in metres. **2 marks**
 - What is the path difference $|S_2W - S_1W|$? Give your answer in metres. **2 marks**
 - The slits are moved further apart. Describe what happens to the spread of the light pattern on the screen. **1 mark**
- Julian, a friend of Jill, states, 'I am confused. The pattern on the screen is not what I would expect as there are only two slits and I'd expect there to be only two bright regions on the screen.'
- Is the pattern on the screen evidence for the wave nature of light? Describe what features match the expectations for the wave nature of light. **3 marks**

Question 4 (8 marks)

In the late nineteenth century, light was regarded as an electromagnetic wave because of the theoretical work done by James Maxwell.

- a. Explain what is meant by the phrase ‘electromagnetic wave’. **1 mark**
- b. Explain why electromagnetic waves can be polarised and yet sound waves cannot, though both are a type of wave. **2 marks**

Consider four different types of electromagnetic waves: γ -rays, radio waves, UV light, microwaves.

- c. Match each of the four types of electromagnetic waves with the wavelengths listed in the following table. **4 marks**

	Wavelength (m)	Electromagnetic wave type
i.	1×10^3	
ii.	1×10^{-2}	
iii.	1×10^{-12}	
iv.	1×10^{-8}	

- d. Which one of the four categories of electromagnetic waves would diffract most significantly when propagating past a building? **1 mark**

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UNIT 4 | AREA OF STUDY 1 REVIEW

AREA OF STUDY 1 How can waves explain the behaviour of light?

OUTCOME 1

Apply wave concepts to analyse, interpret and explain the behaviour of light.

PRACTICE EXAMINATION

STRUCTURE OF PRACTICE EXAMINATION		
Section	Number of questions	Number of marks
A	20	20
B	5	20
Total		40

Duration: 50 minutes

Information:

- This practice examination consists of two parts. You must answer all question sections.
- Pens, pencils, highlighters, erasers, rulers and a scientific calculator are permitted.
- You may use the VCAA Physics formula sheet for this task.



Resources

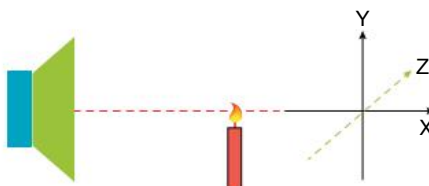


Weblink VCAA Physics formula sheet

SECTION A — Multiple choice questions

All correct answers are worth 1 mark each; an incorrect answer is worth 0.

1. A candle is placed in front of a loudspeaker as shown in the following diagram. Which of the following statements best describes the motion of the flame as the speaker plays a continuous tone?

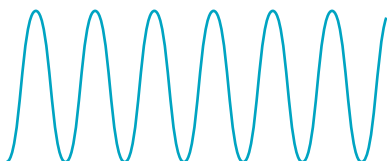


- A. Towards and away from the speaker (X-axis)
- B. Moving up and down (Y-axis)
- C. Moving side to side (Z-axis)
- D. Constantly leaning away from the speaker

2. It has been observed that light can be polarised using natural polarisers such as calcite crystals. This observation suggests that light can be modelled as a:
- Longitudinal wave
 - Transverse wave
 - Mechanical wave
 - Sound wave

3. The following two diagrams depict waves:

(a)



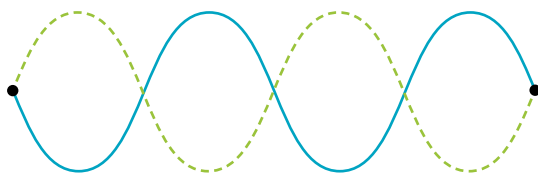
(b)



Diagram (a) represents a bright, green light source. The vertical scale is the amplitude of the waves, whereas the horizontal scale represents time. What is the best description for the waves in diagram (b)? The scale is the same in both diagrams.

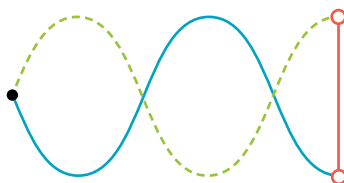
- Brighter, red light
 - Dimmer, red light
 - Brighter, blue light
 - Dimmer, blue light
4. The brightness of a light source depends on:
- The amplitude of the electromagnetic wave
 - The speed of the electromagnetic wave
 - The frequency of the electromagnetic wave
 - The period of the electromagnetic wave
5. Which of the following types of electromagnetic radiation has the shortest wavelength?
- Gamma rays
 - Infra-red radiation
 - Radio waves
 - Ultraviolet light
6. Voice communication between Houston and Apollo 11 used radio frequency 2.28 GHz. What is the wavelength of this communication link?
- | | |
|----------------------------------|----------------------------------|
| A. 1.3×10^2 m | B. 1.3×10^{-1} m |
| C. 1.3×10^{-4} m | D. 1.3×10^{-7} m |
7. Rina attended the Formula One race held in Melbourne recently. At one point in the race, a car approached where she was sitting. Which of the following physical characteristics of the sound waves from the car would be observed to increase as the car approached Rina?
- The period of the sound waves
 - The frequency of the sound waves
 - The speed of the sound waves
 - The wavelength of the sound waves
8. Astronomers use the Doppler effect to determine if a nearby galaxy is approaching the Earth or receding from the Earth. What is the expected observation for a galaxy that is approaching the Earth?
- Blue shift of the light from the galaxy, and the stars in the galaxy appear blue in colour
 - Blue shift of the light from the galaxy, and the stars in the galaxy appear closer to the blue end of the spectrum
 - Red shift of the light from the galaxy, and the stars in the galaxy appear red in colour
 - Red shift of the light from the galaxy, and the stars in the galaxy appear closer to the red end of the spectrum

9. The following diagram depicts a standing wave on a string that is fixed at both ends.



The fundamental frequency of the wave is 220 Hz. What is the frequency shown in the diagram?

- A. 330 Hz
 - B. 440 Hz
 - C. 880 Hz
 - D. 1760 Hz
10. The following diagram depicts a standing wave on a string that is fixed at one end and free at the other.



The fundamental frequency of the wave is 220 Hz. What is the frequency shown in the diagram?

- A. 330 Hz
- B. 660 Hz
- C. 1100 Hz
- D. 1650 Hz

Use the following information to answer questions 11, 12 and 13:

Two loudspeakers, shown in the following diagram, are playing a pure tone frequency. Alexis is walking along a line in front of the speakers from P to Q. She notices that the intensity of the sound from the speakers alternates between loud and soft at intervals that are the same length.

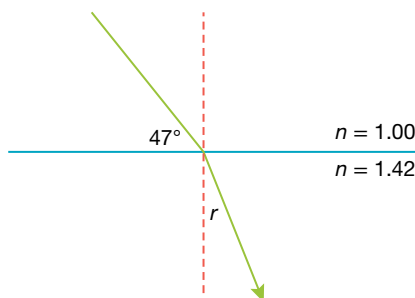


11. The frequency of the pure tone is changed to a higher frequency. What will happen to the length of the intervals between loud and quiet spots?
- A. Increase
 - B. Remain the same
 - C. Decrease
 - D. There is insufficient information, for example, the distance between the two speakers.
12. While the speaker is still playing a pure tone frequency, the two speakers are brought closer together. What will happen to the length of the intervals between loud and quiet spots?
- A. Increase
 - B. Remain the same
 - C. Decrease
 - D. There is insufficient information, for example, the distance to the two speakers.

13. At one of the quiet spots, Alexis measured the distances to both loudspeakers. She found that the distance to speaker 1 is 2.4 m longer than the distance to speaker 2. Taking the speed of sound in air to be 340 m s^{-1} , which of the following frequencies is most likely to be playing at that time?
- A. 142 Hz
B. 213 Hz
C. 283 Hz
D. 425 Hz

Use the following information to answer questions 14 and 15:

A ray of light enters from air ($n = 1.00$) into a block of glass ($n = 1.42$) at an angle of 47° to the surface of the glass as shown in the following diagram:



14. What is the angle of refraction, r , for that ray of light?
 - A. 33°
 - B. 31°
 - C. 29°
 - D. 27°
15. A student wishes to observe total internal reflection of that ray of light. What is the critical angle of the ray from air to glass?
 - A. It is not possible to obtain total internal reflection from air to glass.
 - B. 44°
 - C. 46°
 - D. 48°
16. One of the reasons why cut diamonds sparkle is because entering light rays are totally internally reflected numerous times off the facets, cut into the diamond, before the rays emerge. Given that the refractive index of diamond is 2.42 and that of air is 1.00, what is the critical angle of diamond to air?
 - A. 22°
 - B. 24°
 - C. 66°
 - D. 68°
17. Sound is a longitudinal wave. The following phenomena would be observed for sound waves except for:
 - A. Diffraction
 - B. Polarisation
 - C. Refraction
 - D. Standing waves
18. All of the following electromagnetic radiation has a longer wavelength than yellow light except:
 - A. Green light
 - B. Infra-red
 - C. Orange light
 - D. Microwave
19. When white light is passed through a glass prism, the constituent colours are dispersed across the visible light spectrum. Which one of the following statements does not explain the process of dispersion?
 - A. The different colours in the spectrum are refracted by different amounts.
 - B. The different colours in the spectrum are sped up differently by the glass prism.
 - C. The different wavelengths of light are bent by different amounts.
 - D. The different colours in the spectrum are slowed down differently by the glass prism.

20. Which one of the following statements is not a correct description of sound and light waves?
- A. Sound waves cannot travel through a vacuum but electromagnetic waves can travel through a vacuum.
 - B. Sound waves transfer matter but electromagnetic waves transfer energy.
 - C. Sound is a longitudinal wave and light may be described as a transverse wave.
 - D. Sound is a mechanical wave and light is a non-mechanical wave.

SECTION B — Short answer questions

Question 1 (4 marks)

Students use a 4.5 m slinky to propagate a single pulse from one end to the other. They measure the time it takes to do this. Their average result is 0.65 s.

- a. Determine the speed of the pulse. 1 mark

The students then send a periodic wave from one end to the other, making 5 complete cycles in 1.8 seconds.

- b. What is meant by the frequency of the periodic wave? Calculate the frequency in this scenario. 2 marks
- c. Calculate the wavelength of the periodic wave. 1 mark

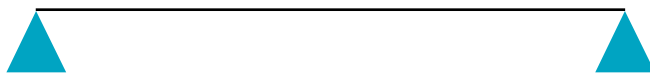
Question 2 (7 marks)

A guitar string of length 0.65 m is fixed at both ends. When it is plucked, a fundamental frequency of 330 Hz is detected.

- a. What is the wavelength of the fundamental frequency? 2 marks
- b. Determine the speed of the transverse waves on the string. 1 mark

The string is now made to vibrate as a standing wave so that there are four antinodes.

- c. On the following diagram, sketch the shape of this standing wave on the guitar string. 2 marks



- d. Calculate the frequency of this standing wave. 2 marks

Question 3 (4 marks)

Coherent light of wavelength 530 nm from a laser passes through a pair of slits, and an interference pattern is formed.

- a. What is the path difference for the third dark band from the central maximum? Give your answer in nm. 2 marks
- b. What is the path difference for the second bright band from the central maximum? Give your answer in nm. 2 marks

Question 4 (3 marks)

The refractive index of flint glass is 1.68, and the refractive index of air is 1.00.

- a. What is the speed of light in flint glass? 1 mark
- b. A beam of light incident on a block of flint glass has an angle of incidence of 25° . Calculate the angle of refraction. 2 marks

Question 5 (2 marks)

An interference pattern is produced using slits separated by 0.15 mm, and a monochromatic light source casting a pattern onto a screen that is 1.65 m from the slits. The distance between two adjacent bright fringes is measured at 5.8 mm.

- Calculate the wavelength of the light source used. 2 marks

ASSESSMENT TASK — A REPORT OF A PHYSICS PHENOMENON

In this task, you will be required to explain a physics phenomenon, exploring the wave phenomenon using a ripple tank.

- This practice SAC requires you to report on the phenomenon of waves using a ripple tank; a structured set of questions is supplied to assist you to write your description.
- You may use the VCAA Physics formula sheet and a scientific calculator for this task.

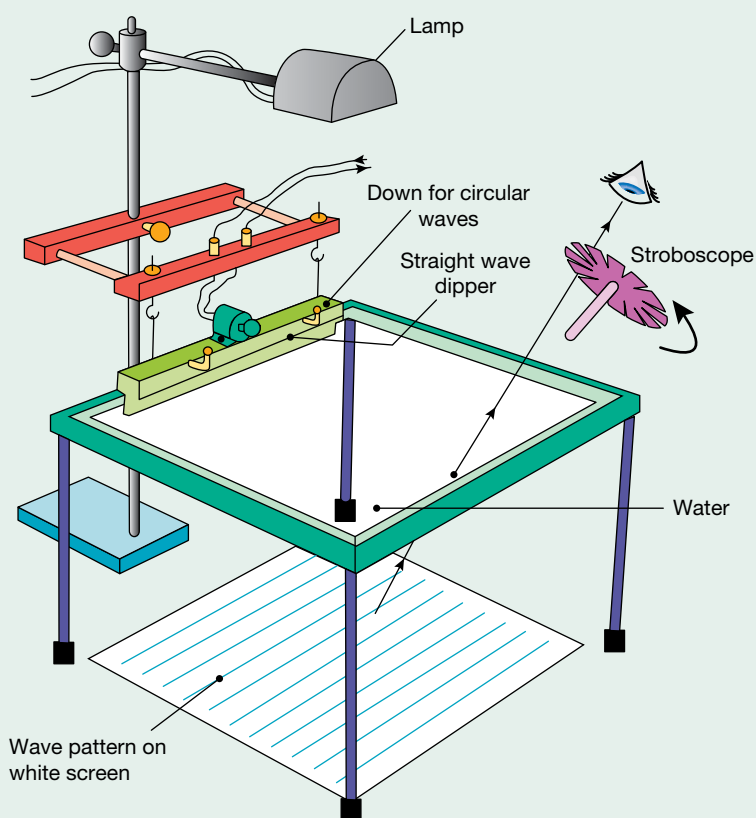
Total time: 55 minutes (5 minutes reading, 50 minutes writing)

Total marks: 50 marks

MAKING WAVES — EXPLORING THE WAVE PHENOMENON USING A RIPPLE TANK

Understanding the properties of waves plays an important role in understanding nature. Waves model the behaviour of sound, light and, surprisingly, the behaviour of matter as well.

A group of students are studying wave phenomena using a ripple tank to make surface waves in water. A typical ripple tank is shown in the following diagram.

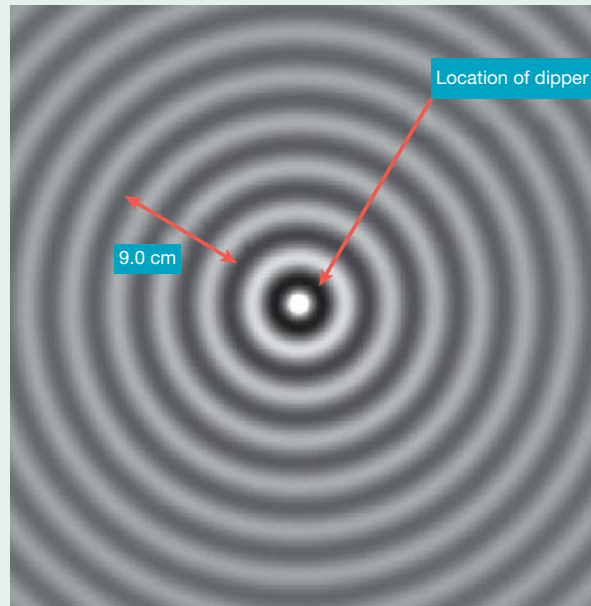


The students plan to photograph patterns made on a screen below the tank and explain what they observe.

When the dipper (refer to diagram) is placed in the water and made to vibrate periodically, surface waves on the water are made and their pattern appears on the screen. Surface waves of this type are known as transverse waves.

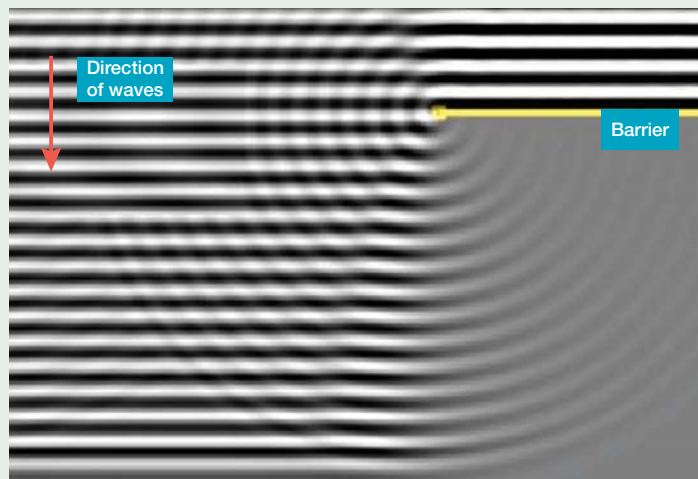
1. Explain why these surface waves are transverse waves and how they differ from longitudinal waves. Waves appear as light or dark patches on the screen, based on the location of the crests and troughs in the waves.
2. Explain why the light source is required to produce the pattern on the white screen below the ripple tank when surface waves are produced in the tank. Ensure you link your response to the crests and troughs in the wave.

In their first experiment, the students decide to use a single spherical dipper (rather than the straight dipper) to produce circular waves. The frequency is set at 8.0 Hz. They take the following photograph and, at that instant, the dipper is making a crest.



3. What do the evenly spaced concentric rings in the photograph tell you about the motion of surface waves moving away from their source?
4. The double-ended arrow on the photograph is 9.0 cm long. How many wavelengths does this correspond to?
5. Determine the speed of the surface waves.
6. The frequency of the dipper is increased. Describe what changes this would make to the speed and wavelength of the surface waves.
7. How could the phenomenon shown in the photograph relate to sound and light? Give an example of where it might be relevant.

In the next experiment, the straight wave dipper is used to generate periodic plane waves. A barrier is put in position and a wave pattern is photographed. This is shown in the following diagram:

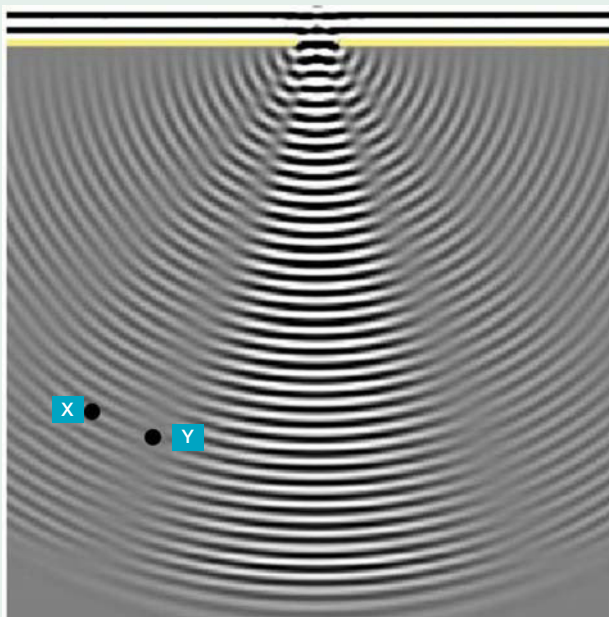


The waves appear to bend around the barrier as they pass the barrier.

8. What name is given to this phenomenon?
9. The frequency of the straight wave dipper is increased. What effect, if any, would this have on the pattern?

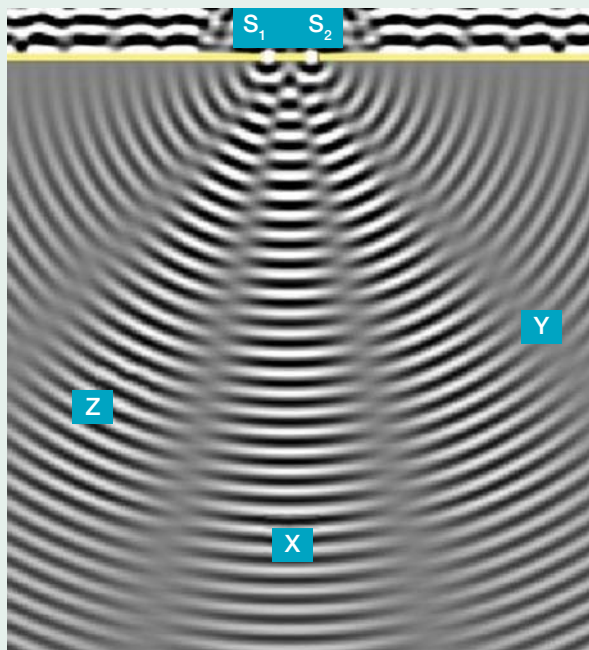
To investigate this phenomenon in more detail, a second barrier is positioned so that the waves now pass through a narrow opening. Following is a photograph of the wave pattern.



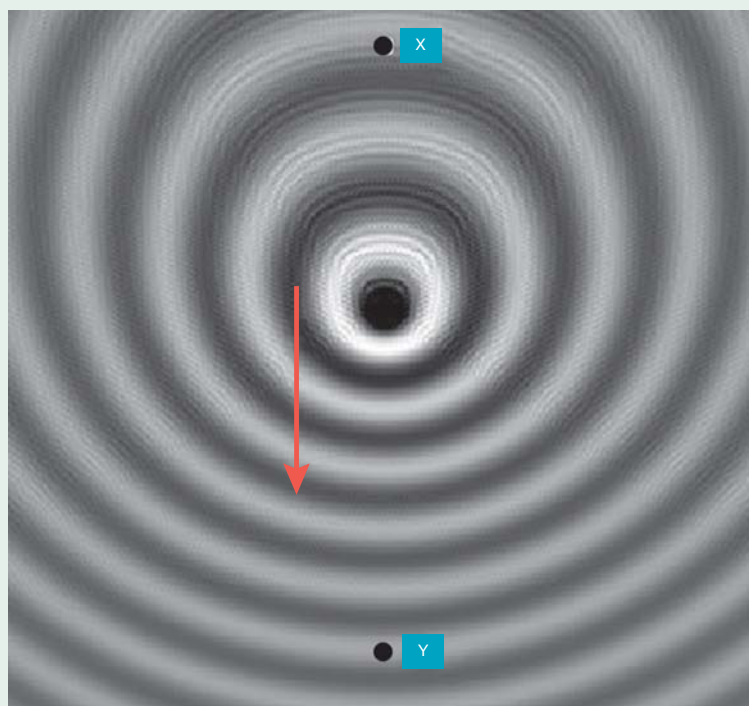


10. Point X corresponds to a region where the waves are relatively large, and point Y corresponds to a region where there is almost no wave action at all, yet both points are the same distance from the opening between the two barriers. Use your knowledge of waves to explain why this is so.
11. The pattern can be made to change in such a way that the waves passing through the narrow opening are more spread out and diverging in all directions with approximately the same amplitude. Suggest two changes to the current arrangement of the barriers and the straight line dipper that would bring about this change.

The students continue to investigate the passage of waves through narrow openings but this time use a specially constructed barrier having two closely spaced openings. When they direct plane waves at the double slit, a new pattern is observed for waves having passed through the double slit. This new pattern is shown in the following diagram. The openings are marked S_1 and S_2 respectively. The pattern consists of regions of large amplitude waves and regions of very little wave action.



12. The regions X and Z have large amplitude waves. Explain why this is the case. Use the concept of path difference in your answer.
13. The region Y has very little wave action. Give a detailed reason why.
14. The students are able to measure the distance S_1Y to be 22.4 cm and the distance S_2Y to be 20.7 cm. Use this information to determine the wavelength of the waves in the pattern.
15. The slits are moved further apart — that is, S_1S_2 increases. What effect will this have on the pattern?
- One of the students makes a suggestion. She wonders what the wave pattern would look like if one of the dippers is moved at a constant speed above the water. After some practice runs, they finally come up with a consistent pattern that they then photograph. This is shown as follows, with the arrow giving the direction of motion of the dipper.



16. What type of wave phenomenon does this photograph show? Do sound and light display this phenomenon?

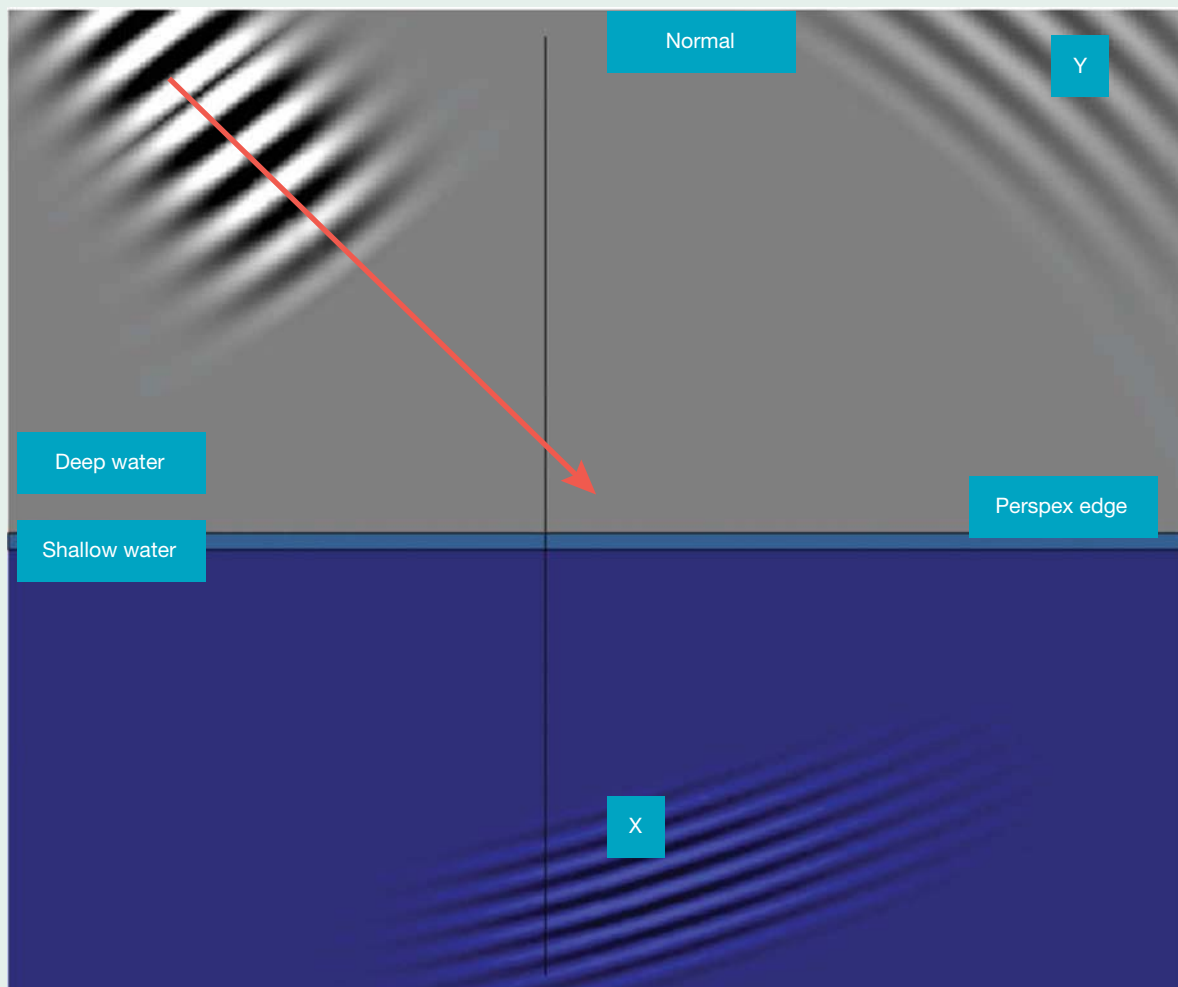
The waves travel through the water at X with a speed, v_x , a wavelength, λ_x and a frequency, f_x . The waves also travel through the water at Y with a speed, v_y , a wavelength, λ_y and a frequency, f_y .

17. How would the speeds v_x and v_y compare? Give an explanation for your answer.
18. Compare the wavelengths of the waves at X and Y. What evidence have you used to make your comparison?
19. Consider the ratio $\frac{f_x}{f_y}$. Is this ratio equal to 1, greater than 1 or less than 1? Explain your choice. Give an example of this phenomenon using sound.

In their final experiment, the students plan to investigate what happens when surface waves pass from deep water into shallower water. They place a rectangular sheet of perspex into the tank to divide the tank into two sections, each with a distinct water depth. They use the straight line dipper to pulse waves towards the perspex edge.

The following photograph shows the pattern at one instant. The red arrow shows the direction in which the waves are pulsed towards the perspex edge.





20. Explain why there are waves in region Y.
21. The process that has produced waves in region X is called refraction. What two properties of the waves are changed by refraction regarding the properties of the transmitted wave?
22. Compared to the speed at which the waves travel towards the perspex edge, what is the speed of the waves in the regions X and Y? Are they the same, less than or greater than? How can you tell?
23. On a copy of the figure shown above, draw, measure and state the angle of incidence and the angle of refraction for the wave pattern.
24. Would total internal reflection of the waves be possible for this particular arrangement? Give a reasoned answer.

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Digital document School-assessed coursework (doc-32302)

11 Behaviour of light as a particle

11.1 Overview

Numerous **videos** and **interactivities** are available just where you need them, at the point of learning, in your digital formats, learnON and eBookPLUS at www.jacplus.com.au.

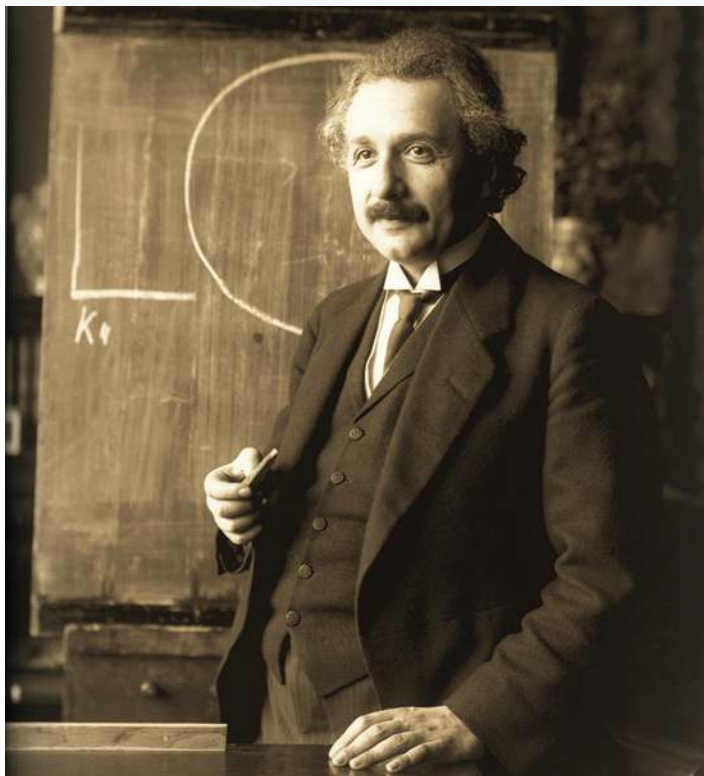
11.1.1 Introduction

How can it be that the wave model of light works extremely well in some circumstances but not in others? This was the problem facing scientists at the start of the twentieth century.

The answer, of course, was to propose a new model to explain the behaviour of light. Albert Einstein challenged everyone's understanding of the nature of light when he presented his quantum theory of light, controversially contradicting Charles Maxwell's well-regarded wave theory by suggesting that light exists as particles. This led to a revolutionary new area of physics named quantum mechanics.

Today it is accepted that neither the wave model nor the particle model adequately describes the properties of light on its own, so scientists delicately juggle the two models. Famous physicist Sir William Bragg describes this wave–particle duality as ‘On Mondays, Wednesdays and Fridays light behaves like waves, on Tuesdays, Thursdays and Saturdays like particles, and like nothing at all on Sundays’.

FIGURE 11.1 The work of Albert Einstein is central to the present-day understanding of the photoelectric effect.



11.1.2 What you will learn

KEY KNOWLEDGE

After completing this topic, you will be able to:

- analyse the photoelectric effect with reference to
 - evidence for the particle-like nature of light
 - experimental data in the form of graphs of photocurrent versus electrode potential, and of kinetic energy of electrons versus frequency
 - kinetic energy of emitted photoelectrons: $E_{k \text{ max}} = hf - \phi$, using energy units of joule and electron volt
 - effects of intensity of incident irradiation on the emission of photoelectrons.
- describe the limitation of the wave model of light in explaining experimental results related to the photoelectric effect.

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PRACTICAL WORK AND INVESTIGATIONS

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

on Resources

 **Digital documents** Key science skills — VCE Units 1–4 (doc-32112)

Key terms glossary (doc-32261)

Practical investigation logbook (doc-32262)

studyon

To access key concept summaries and past VCAA exam questions download and print the **studyON: Revision and past VCAA exam question booklet** (sonr-0060).

11.2 BACKGROUND KNOWLEDGE Physics before the observation of the photoelectric effect

BACKGROUND KNOWLEDGE

- The energy, E , of a quantum of light is calculated using $E = hf = \frac{hc}{\lambda}$
- The momentum contained in an electromagnetic wave is calculated using $p = \frac{E}{c}$
- The kinetic energy of an electron, E_k , is calculated using $E_k = Vq = \frac{1}{2}mv^2$

11.2.1 Planck's equation

By the latter half of the nineteenth century, the ability of Newtonian mechanics to predict and explain much of the material world was unquestioned. At the same time, discoveries in chemistry showed that the world consisted of many elements (each made up of identical atoms), and compounds (each made up of combinations of atoms in fixed proportions). Most scientists believed that all matter was made up of particles and that the universe was governed by deterministic mechanical laws — that is, they thought

the universe was like a big machine. Newtonian mechanics allowed them to explain the workings of the universe in terms of energy transformations, momentum transfer, and the conservation of energy and momentum due to the action of well-understood forces.

The modelling of light was also progressing well, with many experiments indicating light was a wave of some type. James Clerk Maxwell developed a set of equations that were able to explain the observations of light existing at the time, based on the premise that light was an electromagnetic wave, making an assertion as to the nature of light itself. Light came to be modelled as a transverse wave consisting of perpendicular electric and magnetic fields. In an electromagnetic wave (as seen in figure 11.2), the electric and magnetic fields are uniform in each plane, but vary along the direction of the motion of the wave.

Thomas Young had shown that the behaviour of light passing through narrow slits could be explained using the concept of waves. He had even measured the wavelengths of light in the visible spectrum, but he did not know the sort of wave that light might be. James Clerk Maxwell provided the answer in 1864. Maxwell began with the ideas of electric and magnetic interactions that you will have explored in electric power. From these ideas, he developed a theory predicting that an oscillating electric charge would produce an oscillating electric field, together with a magnetic field oscillating at right angles to the electric field. These inseparable fields would travel together through a vacuum. Maxwell predicted their speed, using known electric and magnetic properties of a vacuum, to be $3.0 \times 10^8 \text{ m s}^{-1}$. This is the speed of light! Maxwell had produced a theory that explained how light was produced and travelled through space as electromagnetic waves. This applied not only to visible light but also to other radiation that cannot be seen, such as infra-red and ultraviolet radiation.

Maxwell's theoretical wave model for light was able to show that the energy associated with electromagnetic waves was related to the size or amplitude of the wave. The more intense the wave, the greater the amplitude and hence the energy it contained. He was also able to show that an electromagnetic wave had momentum and was thus capable, in principle, of exerting forces on other objects. According to Maxwell's model, the amount of momentum contained in an electromagnetic wave, p , is related to the energy contained in the wave, E , by the following simple equation:

$$\vec{p} = \frac{E}{c} \text{ or } E = \vec{p} c$$

where: E is the energy of an electromagnetic wave, in J

$\vec{p}$ is the momentum of an electromagnetic wave, in N s (or kg m s^{-1})

$c = 3.0 \times 10^8 \text{ m s}^{-1}$ (the speed of light)

At the same time, Max Planck was trying to understand how hot objects emit electromagnetic waves. That is, he was studying light emitted by incandescent objects such as the Sun, light bulbs or a wood fire. He could make his mathematical models fit the available data only if he conceded that the energy associated with the electromagnetic radiation emitted was directly proportional to the frequency of radiation and, importantly, that the energy came in bundles that he called quanta:

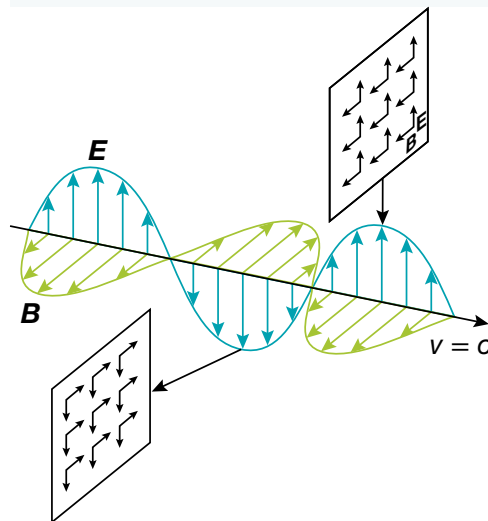
$$E = hf$$

where: E is the energy of a quantum of light, in J

f is the frequency of the electromagnetic radiation, in Hz

$h = 6.63 \times 10^{-34} \text{ J s}$ is a constant known as 'Planck's constant'

FIGURE 11.2 An electromagnetic wave



What all this meant was not clear — Maxwell's wave model for light worked extremely well and yet understanding incandescent objects required a model that concentrated energy into localised packets called quanta that were more like particles.

A pair of problems existed. One question was how matter could convert some of its kinetic and potential energy into light. Max Planck and other scientists were working on this problem as part of their efforts to understand black body radiation (that is, radiation emitted by incandescent objects). The other question was how light could transfer its energy to matter. This process became known as the photoelectric effect.

Planck's conclusion about a particle nature for light did not fit comfortably with the successful wave model of light proposed by Maxwell. It would remain for Albert Einstein over a decade later to interpret this apparent quandary with other experimental data. In reward for his success, he won the Nobel Prize in Physics in 1921. Einstein's interpretation asserted that light is best thought of as a stream of particles, now called photons, with each photon carrying energy $E_{\text{photon}} = hf$ and capable of transferring this energy to other particles such as electrons.

SAMPLE PROBLEM 1

- a. Blue light has a frequency of 6.7×10^{14} Hz.**
- Calculate the energy associated with a bundle of blue light.
 - Find the momentum associated with a quantum of blue light.
- b. Find the momentum of a quantum of red light of wavelength 650 nm.**

THINK

a. i. The energy of the blue light E is given by $E = hf$.

ii. The momentum p is given by $p = \frac{E}{c}$.

b. 1. From the wavelength, find the frequency.
From the frequency, find the energy.

2. From the energy, find the momentum.

3. Substitute the values for h and λ and solve for p , ensuring that the wavelength has been converted to metres ($650 \text{ nm} = 6.5 \times 10^{-7} \text{ m}$).

WRITE

$$\begin{aligned} \text{a. i. } E &= hf \\ &= 6.63 \times 10^{-34} \times 6.7 \times 10^{14} \\ &= 4.4 \times 10^{-19} \text{ J} \end{aligned}$$

$$\begin{aligned} \text{ii. } p &= \frac{E}{c} \\ &= \frac{4.4 \times 10^{-19}}{3.0 \times 10^8} \\ &= 1.5 \times 10^{-27} \text{ N s} \end{aligned}$$

$$\text{b. } f = \frac{c}{\lambda} \text{ and } E = hf \Rightarrow E = \frac{hc}{\lambda}$$

$$p = \frac{E}{c} \Rightarrow p = \frac{hc}{\lambda c} \Rightarrow p = \frac{h}{\lambda}$$

$$\begin{aligned} p &= \frac{h}{\lambda} \\ &= \frac{6.63 \times 10^{-34}}{6.50 \times 10^{-7}} \\ &= 1.02 \times 10^{-27} \text{ N s} \end{aligned}$$

PRACTICE PROBLEM 1

A quantum of light has a momentum of $9.8 \times 10^{-28} \text{ N s}$. Calculate the frequency of the light.

SAMPLE PROBLEM 2

- What is the energy of each photon emitted by a source of green light having a wavelength of 515 nm?
- How many photons per second are emitted by a light source emitting a power of 0.3 W as 515 nm light?

THINK

- The photon energy can be calculated

$$\text{using } E_{\text{photon}} = \frac{hc}{\lambda}$$

Where: $h = 6.63 \times 10^{-34} \text{ J s}$,

$c = 3.0 \times 10^8 \text{ m s}^{-1}$ and

$\lambda = 515 \text{ nm} = 515 \times 10^{-9} \text{ m}$

1. Determine an expression for the power emitted by the globe.

2. Rearrange the power equation to make N the subject.

3. Calculate the number of photons emitted per second by substituting

$\Delta t = 1 \text{ s}$, power = 0.3 W, and

$E_{\text{photon}} = 3.86 \times 10^{-19} \text{ J}$

WRITE

$$\begin{aligned} \text{a. } E_{\text{photon}} &= \frac{hc}{\lambda} \\ &= \frac{6.63 \times 10^{-34} \times 3.0 \times 10^8}{515 \times 10^{-9}} \\ &= 3.86 \times 10^{-19} \text{ J} \end{aligned}$$

$$\begin{aligned} \text{b. power} &= \frac{\text{energy emitted}}{\text{time interval}} \\ &= \frac{E}{\Delta t} \\ &= \frac{N E_{\text{photon}}}{\Delta t} \end{aligned}$$

where: N is the number of photons emitted in the time interval Δt .

$$N = \frac{\text{power} \times \Delta t}{E_{\text{photon}}}$$

$$N = \frac{0.3 \times 1}{3.86 \times 10^{-19}}$$

$$= 8 \times 10^{17} \text{ photons s}^{-1}$$

Since each photon carries a tiny amount of energy, huge numbers of photons are emitted from quite ordinary light sources in each second.

PRACTICE PROBLEM 2

A radio station has a 1000 W transmitter and transmits electromagnetic radiation with a frequency 104.6 MHz. Calculate the number of photons emitted per second by the transmitter.

11.2.2 Measuring the energy of light, electrons and photoelectrons

In order to appreciate the results of the photoelectric effect, it is necessary to be able to calculate both the energy associated with light and the energy associated with a moving particle such as an electron.

Measuring the energy of light

The energy associated with light, E , provided it is treated as a localised object as necessitated by Planck, can be equated to the product of the frequency and Planck's constant: $E = hf$. The speed of light is related to the frequency and wavelength: $c = f\lambda$, in accordance with a wave model for light. For completeness, since $E = pc$, the momentum associated with light, p , can be related to the wavelength λ by the equation

$p = \frac{h}{\lambda}$. It needs to be mentioned at this stage that both a wave model for light and a particle model for light have been used simultaneously. This usage of two models simultaneously came to be known as the wave–particle duality, and for many years it remained an unresolved component in physics. With the development of quantum mechanics in the 1920s, a consistent mathematical model incorporating both aspects emerged.

Measuring the energy of electrons

Potential differences can be used to accelerate and decelerate charged particles. You will now review how the kinetic energy of a charged particle can be related to the electrical potential difference through which it can be made to move. Understanding this relationship will make understanding the photoelectric effect easier. It will also be useful to know how the kinetic energy of matter is related to its momentum, just as in the case for light.

The simplest way to accelerate electrons is with two parallel metal plates in an evacuated chamber (see figure 11.3). The two plates are connected to a DC power supply (similar to a capacitor connected to a battery). An electron will experience an electric force anywhere in the region between the plates: it will be attracted by the positively charged plate and repelled by the negatively charged plate.

FIGURE 11.3 An electric field set up between two parallel plates connected to a battery



The size of this force will be the same throughout this region, as the electric field is uniform. This constant electric force on a charge placed between the plates can be compared to the constant gravitational force on a mass located above the ground. In gravitation, where the force acts on the mass of an object:

$$\text{gravitational force} = \text{gravitational field strength} \times \text{mass}$$

$$F_g = mg$$

With an electric force, the force acts on the electric charge of an object:

$$\text{electric force} = \text{electric field strength} \times \text{electric charge}$$

$$F = Eq$$

The electric field, E , can be expressed as electric force, F , divided by electric charge, q :

$$E = \frac{F}{q}$$

This equation is also applied to the magnitude of the electric field — that is, $E = \frac{F}{q}$. The unit of electric field is newtons per coulomb (N C^{-1}), in the same way that the gravitational field can be measured in newtons per kilogram (N kg^{-1}). However, the magnitude of the electric field can also be shown as follows:

$$\text{electric field} = \frac{\text{voltage across the plates}}{\text{plate separation}}$$

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

These two relationships for the electric field $\left(E = \frac{F}{q} \text{ and } E = \frac{V}{d}\right)$ give it two equivalent units: newtons per coulomb (N C^{-1}) and volts per metre (V m^{-1}).

These two relationships can also be linked by considering energy. The gain in energy of the electron can be obtained by calculating the work done on the charge to move it from one plate to the other. It can also be obtained by recalling that the voltage across a battery equals the energy gained by one coulomb of charge. So:

$$\begin{aligned} \text{work done by the potential difference, } V &= \text{force} \times \text{distance} = \text{voltage} \times \text{electric charge} \\ &= F \times d = V \times q \end{aligned}$$

The work done by the potential difference, V , on a free electron is equal to the change in the kinetic energy of the electron, ΔE_k . Since kinetic energy is given by the expression $\frac{1}{2}mv^2$, and by further making the assumption that the initial kinetic energy of an electron emitted by a filament is zero, a useful non-relativistic equation is obtained:

$$E_k = Vq = \frac{1}{2}m\vec{v}^2$$

where: E_k is the energy of an electron, in J

V is the voltage acting on the electron, in V

$q = 1.6 \times 10^{-19} \text{ C}$ is the charge on one electron

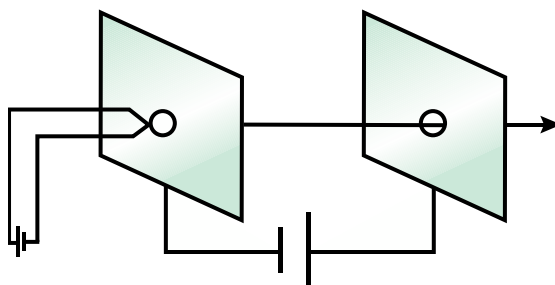
$m = 9.1 \times 10^{-31} \text{ kg}$ is the mass of an electron

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

This equation is interpreted in the following way. For a given voltage, V , acting on an electron, both the speed of the electron and hence its momentum ($p = mv$), as well as its energy, E_k , can be calculated.

Thus, an arrangement of negative and positive charged plates can be used to accelerate a charged particle in a straight line. This arrangement came to be known as an **electron gun**. By reversing the polarity of the charge on the plates, electrons with kinetic energy can be decelerated. The voltage required to achieve this stopping of electrons with energy is known as a stopping voltage and plays a central role in understanding the photoelectric effect.

FIGURE 11.4 The electrons are attracted across to the positive plate and pass through the hole that is in line with the beam.



Measuring the energy of photoelectrons

In the photoelectric effect, energy is transferred from light to electrons. Philipp Lenard, a German physicist, was able to measure the maximum kinetic energy of these electrons by applying a stopping voltage to stop them. Recall that the work done on a charge, q , passing through a potential difference, V , is equal to qV . That is, an electron passing through a potential difference of 3.0 V would have $1.6 \times 10^{-19} \text{ C} \times 3.0 \text{ J C}^{-1} = 4.8 \times 10^{-19} \text{ J}$ or 3.0 eV of work done on it. If the voltage is arranged so that the emitted electrons leave the positive terminal and are collected at a negative terminal, then electrons lose $4.8 \times 10^{-19} \text{ J}$ of energy.

A JOULE AND AN ELECTRON VOLT

Remember that a joule is the electric potential energy change that occurs when one coulomb of charge moves through a potential difference of one volt.

$$1 \text{ V} = \frac{1 \text{ J}}{1 \text{ C}}$$

$$\Rightarrow 1 \text{ J} = 1 \text{ C} \times 1 \text{ V}$$

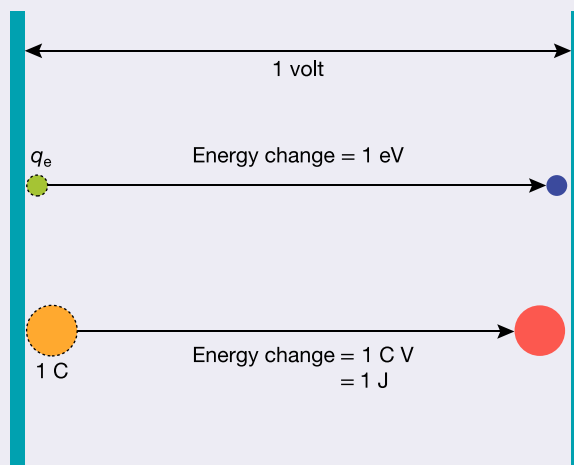
An **electron volt** is defined as the electric potential energy change that occurs when one electronic charge, $q_e = 1.6021 \times 10^{-19} \text{ C}$, moves through one volt.

$$1 \text{ eV} = 1q_e \times 1 \text{ V}$$

Where q_e is the magnitude of charge of an electron:

$$\Rightarrow 1 \text{ eV} = 1.6021 \times 10^{-19} \text{ C} \times 1 \text{ V}$$

$$\Rightarrow 1 \text{ eV} = 1.6021 \times 10^{-19} \text{ J}$$



The electron volt is a very useful unit for calculations involving small amounts of energy. However, to use it in equations such as $E = hf$, which involve Planck's constant, h , you must be very careful. Planck's constant is $6.63 \times 10^{-34} \text{ J s}$, which needs to be converted into electron volts to be used with other variables in electron volts.

$$h = 6.63 \times 10^{-34} \text{ J s}$$

$$= \frac{6.63 \times 10^{-34}}{1.6 \times 10^{-19}} \text{ eV s}$$

$$= 4.14 \times 10^{-15} \text{ eV s}$$

SAMPLE PROBLEM 3

An electron gun uses a 500 V potential difference to accelerate electrons evaporated from a tungsten filament. Model the evaporated electrons as having zero kinetic energy.

- How much work is done on an electron moved across a potential difference of 500 V?
- What type of energy is this work transformed into?
- Calculate the kinetic energy of the electrons in electron volts and joules.

- d. Using the equation for the kinetic energy, E_k , of a particle with mass m , determine the speed, v , of these electrons.
- e. Calculate the momentum of these electrons.

 **Teacher-led video:** SP3 (tlvd-0205)

THINK

- a. Use $W = Vq$ to calculate the work done.
- b. Potential energy available is transformed into the kinetic energy of the electron: $W = Vq = \Delta E_k$.
- c. Assuming the initial kinetic energy of the electrons evaporated from a tungsten filament is 0, the kinetic energy of the electrons is equal to the work done: $E_k = W$.
- d. 1. $E_k = \frac{1}{2}mv^2$, provided the electron speed is sufficiently small to ignore relativistic effects.
2. Take the mass of an electron to be $m = 9.1 \times 10^{-31}$ kg and solve equation for v .

- e. Calculate the momentum using $p = mv$.

WRITE

- a. $W = Vq$
 $= 500 \times 1.6 \times 10^{-19}$
 $= 8.0 \times 10^{-17}$ J
 (or 500 eV)
- b. kinetic energy
- c. $E_k = W$
 $= 8.0 \times 10^{-17}$ J
 (or 500 eV)
- d. $E_k = \frac{1}{2}mv^2 = 8.0 \times 10^{-17}$ J

$$v = \sqrt{\frac{2E_k}{m}}$$

$$= \sqrt{\frac{2 \times 8.0 \times 10^{-17}}{9.1 \times 10^{-31}}}$$

$$= 1.33 \times 10^7 \text{ m s}^{-1}$$

This is substantially slower than the speed of light; therefore, relativistic effects may be ignored.

- e. $p = mv$
 $= 9.1 \times 10^{-31} \times 1.33 \times 10^7$
 $= 1.2 \times 10^{-23}$ N s

PRACTICE PROBLEM 3

An electron in a beam of electrons generated by an electron gun has energy 1.26×10^{-17} J.

- a. Calculate the energy of this electron in electron volts.
- b. State the potential difference required to stop electrons with this energy, that is, to remove their kinetic energy and bring them to rest.
- c. Determine the speed of the electron, assuming that its kinetic energy is given by the equation $E_k = \frac{1}{2}mv^2$.
- d. Use your answer to (c) to calculate the momentum of this electron.

SAMPLE PROBLEM 4

- a. Electrons are emitted from a surface with a kinetic energy of 2.6×10^{-19} J after being struck by light. What is the size of the stopping voltage that will remove all this kinetic energy from the electrons?
- b. What kinetic energy electrons will a 4.2 V stopping voltage stop?

 **Teacher-led video:** SP4 (tlvd-0206)

THINK

- a. 1. Use $E_k = qV_0$ to calculate the stopping voltage.

The kinetic energy of each electron is 2.6×10^{-19} J. The charge on an electron is 1.6×10^{-19} C.

2. Answer the question.

- b. 1. Use $E_k = qV_0$ to calculate the kinetic energy.

The stopping voltage is 4.2 V. The charge of an electron is 1.6×10^{-19} C.

2. Answer the question.

WRITE

- a. $E_k = qV_0$

$$2.6 \times 10^{-19} \text{ J} = 1.6 \times 10^{-19} \text{ C} \times V_0$$

$$V_0 = \frac{2.6 \times 10^{-19} \text{ J}}{1.6 \times 10^{-19} \text{ C}}$$

$$= 1.6 \text{ V (accurate to 2 significant figures)}$$

A stopping voltage of 1.6 V will stop the electrons emitted from the surface.

- b. $E_k = qV_0$

$$= 1.6 \times 10^{-19} \text{ C} \times 4.2 \text{ V}$$

$$= 6.72 \times 10^{-19} \text{ J}$$

$$= 6.7 \times 10^{-19} \text{ J (accurate to 2 significant figures)}$$

A stopping voltage of 4.2 V will stop electrons with energy 6.7×10^{-19} J.

PRACTICE PROBLEM 4

Electrons are emitted from the surface of a photocell with 4.8×10^{-19} J of kinetic energy after being struck by light. What is the size of the stopping voltage that will remove all this kinetic energy from the electrons?

You now have some calculating tools for working with light, although it is modelled at this stage rather ambiguously as something like a particle, a localised packet with energy $E = hf$ and momentum $p = \frac{E}{c}$,

but propagating like a wave with speed $c = f\lambda$, which further implies a momentum $p = \frac{h}{\lambda}$ for a localised packet. This localised packet, as you will see, is now known as a **photon** — a particle of light.

There are also some calculating tools for working with electrons, modelling them as particles. These particles have kinetic energy $E_k = \frac{1}{2}mv^2$ and momentum $p = mv$. The kinetic energy can also be written in terms of the momentum:

$$E_k = \frac{p^2}{2m}$$

This equation, in particular, will prove to be useful later. With the correct experimental apparatus, you can either give or take energy from charged particles by allowing a potential difference V to do work W on a charge q according to the equation $W = Vq$. Electrons can thus be accelerated or decelerated by a potential difference depending solely on the polarity of the potential difference attached to the equipment. This equipment is generically referred to as an electron gun. You are now ready to learn about the photoelectric effect and to interpret data arising from experiments.

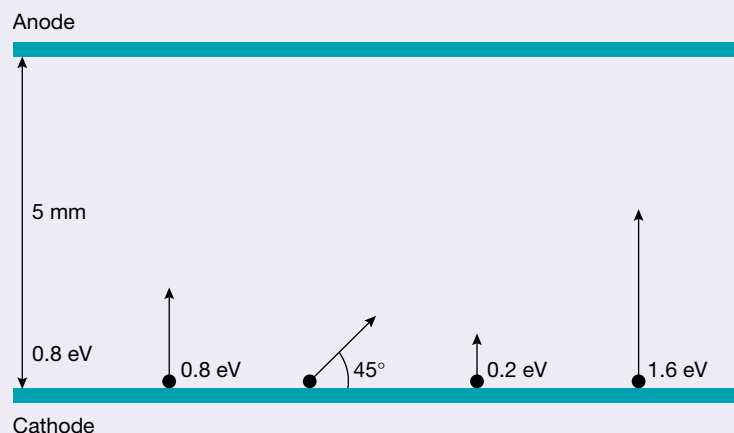
11.2 EXERCISE

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

- The light from a red light-emitting diode (LED) has a frequency of 4.59×10^{14} Hz.
 - What is the wavelength of this light?
 - What is the period of this light?
- You can detect light when your eye receives as little as 2.0×10^{-17} J. How many photons of green light is this?
- Fill in the gaps in the table shown with the missing wavelength, frequency, photon energy and photon momentum values for the five different sources of electromagnetic radiation.

	Source	Wavelength	Frequency	Energy	Momentum
a.	Infra-red from CO ₂ laser	10.6 μm			
b.	Red helium–neon laser			3.14×10^{-19} J	
c.	Yellow sodium lamp				1.125×10^{-27} kg m s ⁻¹
d.	UV from excimer laser		1.55×10^{15} Hz		
e.	X-rays from aluminium			2.01×10^{-16} J	

- A beam of electrons, each electron having a kinetic energy 3.2×10^{-18} J, is to be stopped by a potential difference. Calculate the stopping voltage (potential difference) required to bring these electrons to rest.
- The following diagram shows an anode, a cathode and several electrons that have been ejected from the cathode by light. The electrons leaving the cathode surface have been labelled with their kinetic energy and their initial velocity vector. The anode is 5 mm from the cathode.



- Calculate the speed of the electrons that have a kinetic energy of 0.80 eV or alternatively 1.28×10^{-19} J.
- For each of the following, copy the diagram and sketch the path you would expect each electron to take for each of the potential differences, V . [Hint: think of each electron as a projectile in a uniform electric field, exactly like a ball thrown into the air.]
 - $V = 1.8$ V, with the anode positive relative to the cathode
 - $V = 1.8$ V, with the anode negative relative to the cathode
 - $V = 0.8$ V, with the anode negative relative to the cathode.

Fully worked solutions and sample responses are available in your digital formats.

11.3 The photoelectric effect

KEY CONCEPTS

- Analyse the photoelectric effect with reference to:
 - evidence for the particle-like nature of light
 - experimental data in the form of graphs of photocurrent versus electrode potential, and of kinetic energy of electrons versus frequency
 - kinetic energy of emitted photoelectrons: $E_{k \text{ max}} = hf - \phi$, using energy units of joule and electron volt
 - effects of intensity of incident irradiation on the emission of photoelectrons.

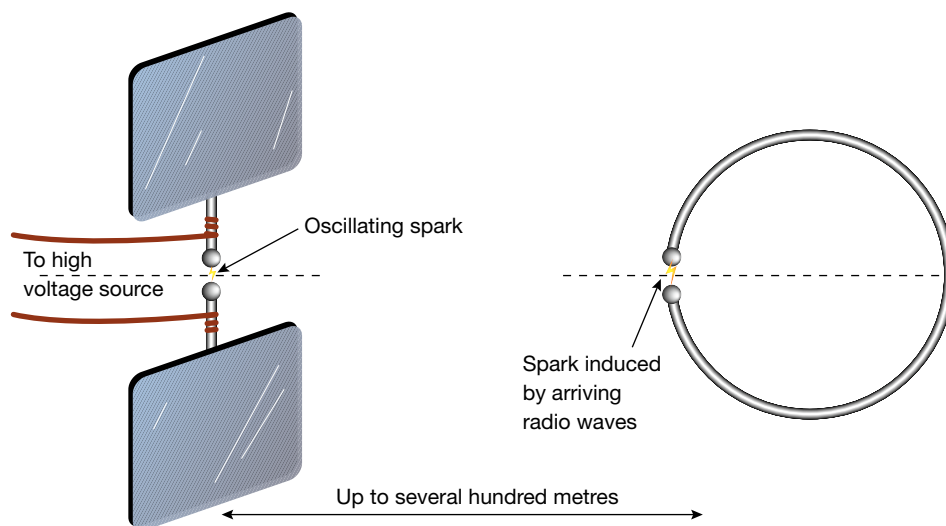
The nineteenth-century view of light was developed as a result of the success of the wave model in explaining refraction, diffraction and interference. The wave model did a great job!

In 1887, the first signs of behaviour that could not be explained using the wave model almost went unnoticed. Heinrich Hertz was in the middle of the experimental work that would show radio waves and light were really the same thing — electromagnetic waves. He produced radio waves with a frequency of about 5×10^8 hertz (yes, the unit for frequency was named after him) by creating a spark across the approximately one-centimetre gap between two small metal spheres. The radio waves were detected up to several hundred metres away, by the spark they excited across another air gap, which was between the pointed ends of a circular piece of wire (as seen in figure 11.5). Hertz was able to show that the radio waves travelled at the speed of light. Although Hertz was not aware of it, this was the beginning of radio communication.

During his experiments, Hertz noticed that the spark showing the arrival of the radio waves at the receiver became brighter whenever the gap was simultaneously exposed to ultraviolet radiation. He was puzzled, and made note of it, but did not follow it up. Now it is known that the reason for the brighter spark was that the ultraviolet radiation ejected electrons from the metal points of the detector. The presence of these electrons reduced the electrical resistance of the air gap, so a spark flashed brighter than usual whenever the radio waves were being detected.

This ejection of electrons by light is called the **photoelectric effect**. Following up Hertz's observations of this effect led to a breakthrough in the way the behaviour of light is viewed.

FIGURE 11.5 Hertz detected radio waves using the spark between two electrodes.



11.3.1 The experiment

Fifteen years passed before Philipp Lenard performed careful experiments to investigate the effect. Lenard replaced Hertz's spark gap with two metal electrodes on opposite sides of an evacuated chamber. He investigated the energies of electrons ejected from one of these electrodes when light shone on it. The experimental arrangement used in 1902 by Lenard is shown in figure 11.6. Lenard designed his experiment so that he could vary several features of this arrangement.

- *The frequency and intensity of the light* could be varied. Light from an electric discharge arcing between two electrodes was introduced into the chamber through a window. The arc produced a spectrum of several different frequencies characteristic of the electrode material. Filters in front of the window were used as frequency selectors to ensure that light of a single chosen frequency reached electrode X. Light sources that emit light of only one frequency are called **monochromatic** light sources. Lenard varied the light intensity either by changing the arc current, or by moving the light source to a different distance from the window.
- *The potential difference between the electrodes in the chamber* could be varied by changing the position of the slide contact on the coiled resistor. By varying the contact position to both right and left of Z, the potential difference could be made either accelerating or retarding for electrons.
- Lenard could vary *the distance between the electrode receiving light, X, and the second electrode, Y.*

First, Lenard used a fixed intensity light source and a fixed accelerating voltage while he varied the distance between the electrodes. He found that the current of photoelectrons, called the photocurrent, increased to a maximum when the electrodes were about 5 mm apart. He reasoned that, after being ejected by light, the electrons flew out in different directions and that at this short distance the second electrode was collecting all the electrons. This separation was used for all later experiments.

Now he was ready to explore the effects of the light on this photoelectric effect. The results of Lenard's further experiments are summarised in the graphs of photocurrent as a function of the potential difference between the electrodes for several light intensities, shown in figure 11.7.

FIGURE 11.6 Philipp Lenard's experiment. Note that the point G is earthed, and this earths the electrode Y. Electrode X could be made either positive or negative relative to electrode Y.

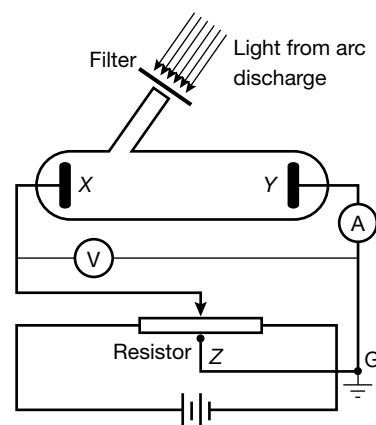
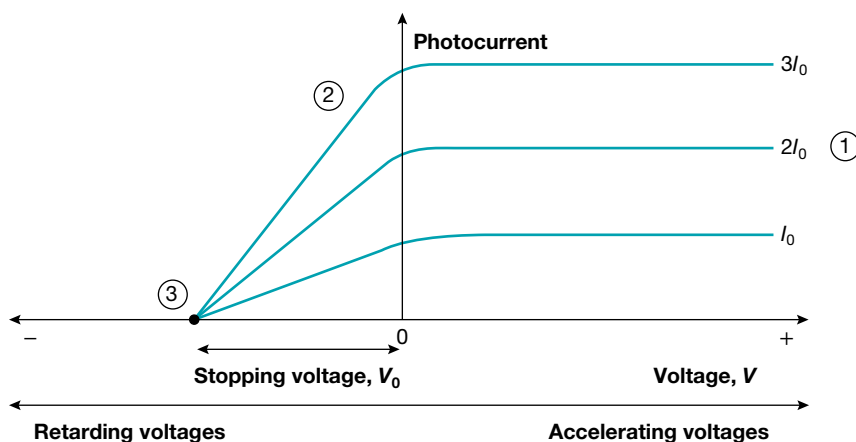


FIGURE 11.7 The effect of changing light intensity from I_0 without changing its frequency



The graphs in figure 11.7 illustrate several important parts of Lenard's investigations. The numbers on the diagrams refer to the following numbered points.

1. Keeping the light frequency constant, Lenard investigated how the maximum photocurrent depended on light intensity. Higher intensity light produced greater values of the maximum. In fact, Lenard's results showed that the maximum photocurrent was directly proportional to the light intensity. To his surprise, this proportionality held true over a wide intensity range, right down to light of a tiny 3×10^{-7} of the highest intensity light he could produce.

2. When Lenard applied a retarding voltage between the electrodes, the current decreased as the magnitude of the voltage increased.

This was not surprising. It was expected that, when the electric field between the plates exerted a force opposing the motion of the electrons, they would slow down and probably reverse direction before reaching the opposite electrode. This is shown in figure 11.8, in which this movement

of the electron is shown to be similar to the movement of a ball thrown into the air. The kinetic energy of the electrons would be converted into electric potential energy. Only the very slow electrons would reverse direction before being collected at the electrode Y when the voltage between the plates was low. So, only a few electrons would then be removed from the stream contributing to the photocurrent. As the magnitude of the voltage was increased, more and more electrons would turn around before reaching the electrode until, at a particular voltage, no electrons completed the crossing and the current dropped to zero. This minimum voltage causing all electrons to turn back is called the stopping voltage.

3. Lenard found that the stopping voltage did not depend on the intensity of incident irradiation being used. Brighter light *did not* increase the kinetic energy of the electrons emitted from the cathode. The same potential difference was required to convert all the kinetic energy of the electrons into electric potential energy, no matter how bright the light.

FIGURE 11.8 (a) An electron in an electric field opposing its motion, and (b) a ball thrown into the air

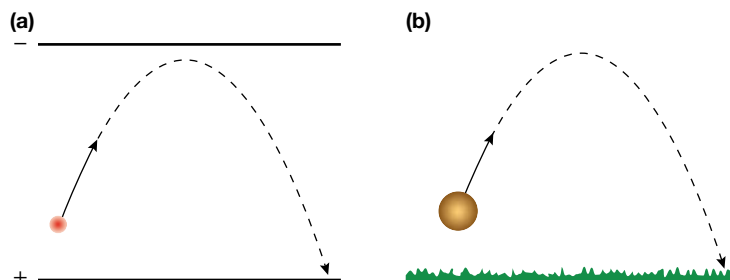
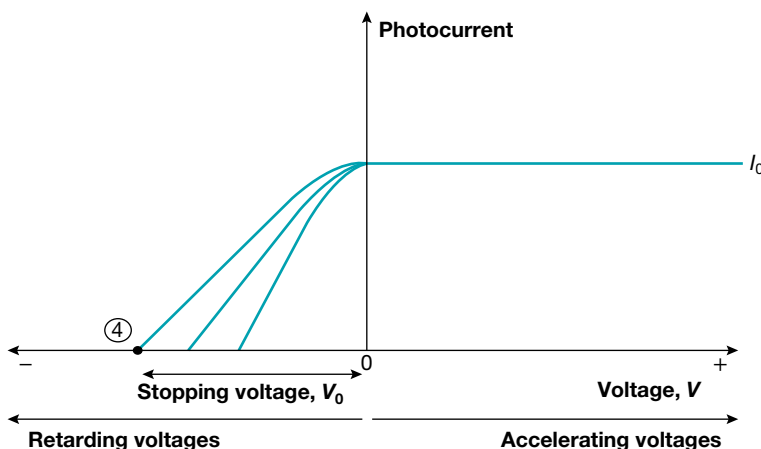


FIGURE 11.9 The effect of changing light frequency, without changing its intensity, on the photocurrent of one material



4. The stopping voltage, however, depended on both the frequency of the light (see figure 11.9) and on the material of the electrode. In fact, for each material a minimum frequency was required for electrons to be ejected. Below this cut-off frequency, no electrons were ever ejected, no matter how intense the light or how long the electrode was exposed to the light. Above this frequency, a photocurrent could

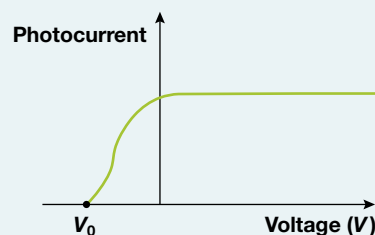
always be detected. The photocurrent could be detected as quickly as 10^{-9} s after turning on the light source. This time interval was independent of the brightness of the light source.

These experiments provided evidence that the energy of light is bundled into packets whose energy depends on the light frequency. In explaining these experiments, the behaviour of light is best described as a stream of particles — very reminiscent of Newton's view! Albert Einstein, in 1905, first proposed the model to explain the photoelectric effect. He won the Nobel Prize in Physics in 1921 for this work, even though he is now better known for his theories of relativity, explaining the behaviour of objects travelling at speeds close to the speed of light. Lenard had already won the Nobel Prize in Physics in 1905 for his experimental investigations.

SAMPLE PROBLEM 5

The diagram shows the current-versus-stopping voltage curve for a typical photoelectric cell using green light.

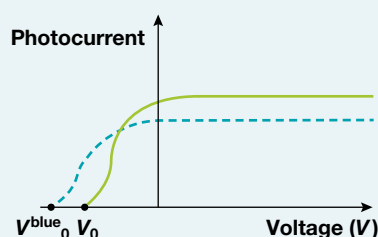
The colour is changed to blue, but with a lower intensity. Sketch the curve that would result from these changes.



THINK

Because blue light has a higher frequency than green light, the stopping voltage would be greater. The lower intensity would make the photocurrent smaller.

WRITE



PRACTICE PROBLEM 5

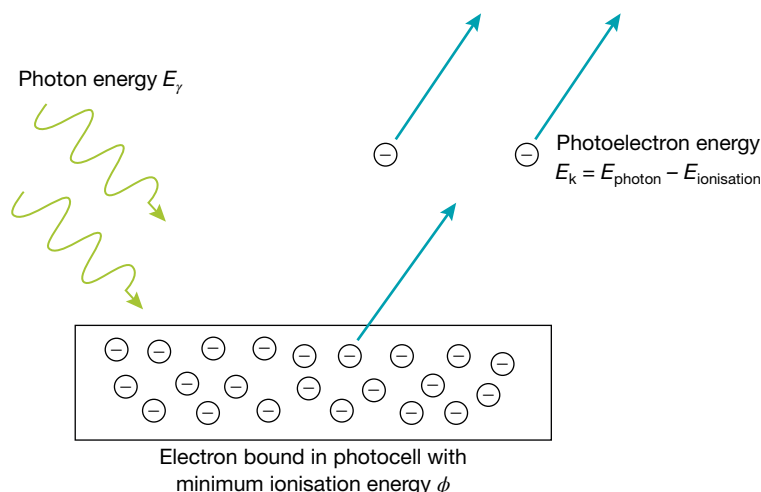
Consider the same arrangement as in sample problem 5 except that, this time, yellow light is used but it is sufficient to cause the photoelectric effect to occur. The intensity of the light is greater than with the green light. Sketch the curve that would result from this change.

11.3.2 The particle model and the photoelectric effect

Now that you have an idea of the wave and particle model descriptions of intensity, let's consider how each of the observations of the photoelectric effect experiment could be explained using a particle model, and why a wave model is not as successful in this situation. Remember, a close inspection of the evidence should allow you to decide whether electrons are being hit by particles or waves.

In the particle model description, the entire energy of a *single* photon is transferred to a *single* electron; the photon is gone. Some of the photon energy is required to enable the electron to escape from the electrode. This transferred energy, which enables an electron to escape the attraction of a material, is called its **ionisation energy**. Electrons in the metal have a range of energy levels, so they also have a range of ionisation energies. The minimum ionisation energy is called the **work function**, ϕ , of the material. The photon energy which is 'left over' becomes the kinetic energy of the electron. Naturally, the electrons requiring the least energy to enable them to escape will leave with the greatest kinetic energy.

FIGURE 11.10 A representation of how photon energy is transferred to electrons



The kinetic energy of each photoelectron is given by the following:

$$\begin{aligned} E_k &= E_{\text{photon}} - E_{\text{ionisation}} \\ &= hf - E_{\text{ionisation}} \end{aligned}$$

The maximum kinetic energy of photoelectrons, $E_{k \text{ max}}$, is given by:

$$\begin{aligned} E_{k \text{ max}} &= E_{\text{photon}} - \phi \\ &= hf - \phi \end{aligned}$$

where: ϕ is the work function of the metal, in J or eV
 h is Planck's constant (6.63×10^{-34} J s)
 f is the frequency of the incident photon, in Hz

Here is how the particle model explains Lenard's experimental observations. The numbering here matches the number of these observations earlier in the topic. (See figures 11.7 and 11.9.)

1. *Maximum photocurrent is proportional to incident irradiation (intensity).*
Doubling the intensity without changing frequency doubles the number of photons reaching the electrode each second, but not their energy. This doubles the rate of electron emission without changing the energy transferred to each electron, and therefore doubles the maximum photocurrent.
2. *Retarding voltage reduces photocurrent. A stopping voltage exists above which no electrons reach the second electrode.*
Ejected electrons have a variety of energies, depending on the photon energy and their ionisation energy. A low retarding voltage turns back only the electrons having low kinetic energies. Increasing the retarding voltage will turn back electrons with higher kinetic energies, until at the stopping voltage none can reach the second electrode.
3. *Stopping voltage is independent of light intensity.*
Changing the light intensity only does not change its frequency, so the photon energy is not changed. Photoelectrons will have the same range of energies, and so the same retarding voltage is needed to reduce the photocurrent to zero.

4. Stopping voltage depends on light frequency and material: a cut-off frequency exists.

Since the stopping voltage reverses the direction of *all* electrons, it is the voltage required to entirely transform the kinetic energy of the fastest electrons into electric potential energy:

$$\begin{aligned} E_{k \text{ max}} &= \text{magnitude of change in electron's electrical potential energy} \\ &= q_e V_0 \end{aligned}$$

where q_e here is the *magnitude* of the electronic charge.

The photon model states the following:

$$\begin{aligned} E_{k \text{ max}} &= E_{\text{photon}} - \phi \\ &= hf - \phi \end{aligned}$$

So,

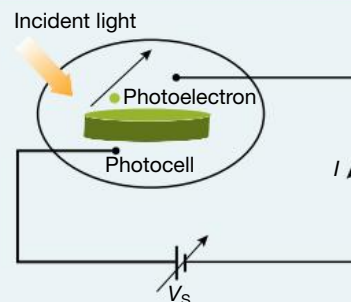
$$q_e V_0 = hf - \phi$$

Clearly V_0 depends on the light frequency, f , and also on the electrode material through its work function, ϕ . A photon whose energy, hf , is less than the work function, ϕ , cannot supply enough energy for an electron to escape. The electron remains trapped by the electrode.

SAMPLE PROBLEM 6

Light with a wavelength of 425 nm strikes a clean metallic surface and photoelectrons are emitted. A voltage of 1.25 V is required to stop the most energetic electrons emitted from the photocell.

- Calculate the frequency of a photon of light whose wavelength is 425 nm.
- Calculate the energy in joules and also in electron volts of a photon of light whose wavelength is 425 nm.
- State the energy of the emitted electron in both electron volts and joules.
- Calculate the work function ϕ of the metal in eV and J.
- Determine threshold frequency, f_0 , and consequently the maximum wavelength of a photon that will just free a surface electron from the metal.
- Light of a wavelength 390 nm strikes the same metal surface. Calculate the stopping voltage.



Teacher-led video: SP6 (tlvd-0208)

THINK

- a. Use $f = \frac{c}{\lambda}$ to calculate the frequency.

- b. 1. Use $E = hf$ to calculate the energy.
Remember to use your non-rounded figure in your calculations

WRITE

$$\begin{aligned} \text{a. } f &= \frac{c}{\lambda} \\ &= \frac{3.0 \times 10^8}{4.25 \times 10^{-7}} \\ &= 7.1 \times 10^{14} \text{ Hz} \end{aligned}$$

$$\begin{aligned} \text{b. } E &= hf \\ &= 6.63 \times 10^{-34} \times 7.1 \times 10^{14} \\ &= 4.7 \times 10^{-19} \text{ J} \end{aligned}$$

2. To convert energy in joules into energy in electron volts, divide by $1.6 \times 10^{-19} \text{ J eV}^{-1}$.

$$E = \frac{4.7 \times 10^{-19}}{1.6 \times 10^{-19}} \\ = 2.9 \text{ eV}$$

- c. Since the stopping voltage is 1.25 V, the energy of the emitted electron is 1.25 eV. The energy in joules can be found by multiplying by 1.6×10^{-19} .

c. $1.25 \times 1.6 \times 10^{-19} = 2.0 \times 10^{-19} \text{ J}$

- d. Using the equation $E_{k \text{ max}} = hf - \phi$, the work function can be found. When the photon energy hf equals 2.92 eV, the electrons have an energy of $1.25 = 2.92 - \phi$.

d. $\phi = 2.9 - 1.25 \\ = 1.7 \text{ eV} \\ = 2.7 \times 10^{-19} \text{ J}$

- e. 1. Again use the equation $E_{k \text{ max}} = hf - \phi$. The threshold frequency, f_0 , is the frequency below which the photoelectric effect does not occur. At this frequency, electrons are just not able to leave the surface. This model implies $0 = hf_0 - \phi$. Rearrange this equation to give the useful result.

e. $f_0 = \frac{\phi}{h} \\ = \frac{2.7 \times 10^{-19}}{6.63 \times 10^{-34}} \\ = 4.0 \times 10^{14} \text{ Hz}$

2. The maximum wavelength can be calculated using $\lambda = \frac{c}{f_0}$.

$$\lambda = \frac{c}{f_0} \\ = \frac{3.0 \times 10^8}{4.0 \times 10^{14}} \\ = 7.4 \times 10^{-7} \text{ m or } 740 \text{ nm}$$

- f. 1. Use the equation $E_{k \text{ max}} = h\frac{c}{\lambda} - \phi$ to find the energy of the emitted electrons.

f. $E_{k \text{ max}} = \frac{6.63 \times 10^{-34} \times 3.0 \times 10^8}{3.90 \times 10^{-7}} \text{ J} - 1.7 \text{ eV} \\ = 5.1 \times 10^{-19} \text{ J} - 1.7 \text{ eV} \\ = \frac{5.1 \times 10^{-19}}{1.6 \times 10^{-19}} - 1.7 \text{ eV} \\ = 3.19 - 1.7 \text{ eV} \\ = 1.5 \text{ eV}$

It is convenient to use eV here.

2. Determine the stopping voltage.

A stopping voltage of 1.5 V is required to stop the emitted electrons.

PRACTICE PROBLEM 6

A new photocell with a different metallic surface is used. Again, light of wavelength 425 nm strikes a clean metallic surface and photoelectrons are emitted. This time, a stopping voltage of 0.87 V is required to stop the most energetic electrons emitted from the photocell.

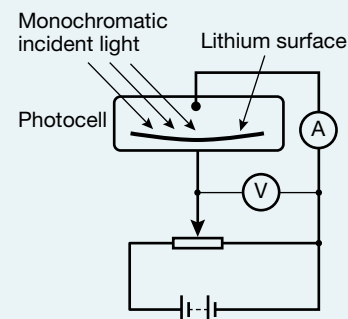
- State the highest energy of the emitted electrons in both electron volts and joules.
- Calculate the work function ϕ of the metal.

- c. Determine threshold frequency, f_0 , and, consequently, the maximum wavelength of a photon that will just free a surface electron from the metal.
- d. Light of wavelength 650 nm strikes the same metal surface. Explain what happens.

SAMPLE PROBLEM 7

The following table gives some data collected by students investigating the photoelectric effect using a photocell with a lithium cathode. This cell is illustrated in the accompanying schematic diagram.

Wavelength of light used (nm)	Frequency of light used ($\times 10^{14}$ Hz)	Photon energy of light used (eV)	Stopping voltage readings (V)	Maximum photo-electron energy (J)
663			0.450	
	6.14			1.84×10^{-19}



- a. Complete the table by filling in the missing values.
- b. Using only the two data points supplied in the table, plot a graph of maximum photoelectron energy in electron volts versus photon frequency in hertz for the lithium photocell.
- c. Using only your graph, state your values for the following quantities. In each case, state what aspect of the graph you have used.
 - i. Planck's constant, h , in the units J s and eV s as determined from the graph
 - ii. The threshold frequency, f_0 , for the metal surface in Hz as determined from the graph
 - iii. The work function, ϕ , for the metal surface as determined from the graph, in the units J and eV.
- d. On the same axes, draw and label the graph you would expect to get when using a different photocell, given that it has a work function slightly larger than the one used to collect the data in the table.

A new photocell is now investigated. When light of frequency 9.12×10^{14} Hz is used, a stopping voltage of 1.70 V is required to stop the most energetic electrons.

- e. Calculate the work function of the new photocell, giving your answer in both joules and electron volts.
- f. When the battery voltage of the new photocell is set to 0 V, the photocurrent is measured to be 48 μ A. The intensity of the light is now doubled. Describe what happens in the electric circuit with the power supply voltage set to 0 V when the light intensity is doubled.
- g. With the intensity still doubled, the voltage is now slowly increased from 0 and the photocurrent slowly reduces to 0 A. State the stopping voltage when the current first equals 0 A with the light intensity still doubled.



THINK

- a. Use $c = f\lambda$ to complete columns 1 and 2. Use $E = hf$ to complete column 3, and use the conversion factor for joules to eV to complete columns 4 and 5.

- b. The graph will contain two points representing the fact that light of frequency 4.52×10^{14} Hz will produce electrons of energy 0.45 eV and light of frequency 6.14×10^{14} Hz will produce electrons of energy 1.15 eV. A line drawn containing these two data points will give a work function of 1.5 eV and a threshold frequency of 3.5×10^{14} Hz.

- c. i. Planck's constant = gradient of graph

- ii. From the line of best fit in graph (b), the threshold frequency = x-axis intercept.

- iii. From the line of best fit in the graph (b), the work function = y-axis intercept.

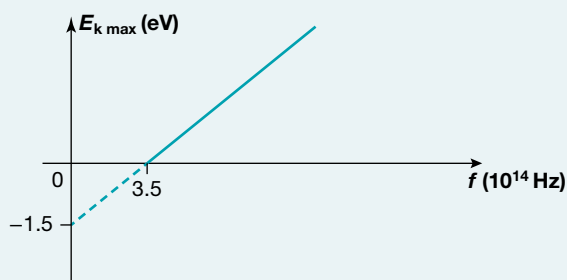
- d. The graph for a photocell with a larger work function will have the same gradient but a lower y-intercept.

WRITE

a.

Wavelength of light used (nm)	Frequency of light used ($\times 10^{14}$ Hz)	Photon energy of light used (eV)	Stopping voltage readings (V)	Maximum photo-electron energy (J)
663	4.52	1.88	0.450	7.20×10^{-20}
489	6.14	2.54	1.15	1.84×10^{-19}

b.

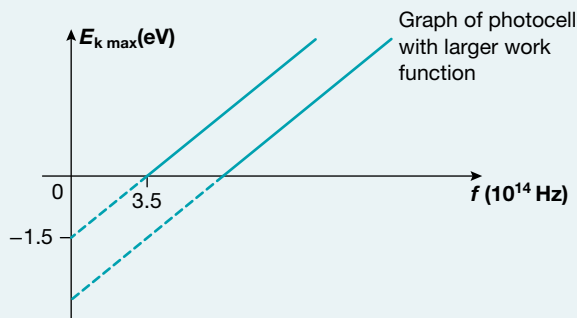


- c. i. gradient = $\frac{1.84 \times 10^{-19} - 7.20 \times 10^{-20}}{(6.14 - 4.52) \times 10^{14}} = 6.9 \times 10^{-34} \text{ J s}$
which is close to the accepted value. It also has the value $4.3 \times 10^{-15} \text{ eV s}$.

- ii. threshold frequency = $3.5 \times 10^{14} \text{ Hz}$.

- iii. work function = $2.4 \times 10^{-19} \text{ J} = 1.5 \text{ eV}$.

d.



- e. Use $E_{k \max} = hf - \phi$ to calculate the work function, ϕ .
- $$\begin{aligned} e. \quad 1.7 \times 1.6 \times 10^{-19} &= 6.63 \times 10^{-34} \times 9.12 \times 10^{14} - \phi \\ \phi &= 6.05 \times 10^{-19} - 2.72 \times 10^{-19} \\ &= 3.33 \times 10^{-19} \text{ J} \\ &= 2.07 \text{ eV} \end{aligned}$$
- f. With the light intensity doubled, the photocurrent would also double.
- f. The photocurrent would double.
- g. The stopping voltage would remain the same, 1.70 V, as the colour and hence the frequency of the light source is unchanged.
- g. Stopping voltage = 1.70 V.

PRACTICE PROBLEM 7

The following table gives some data collected by students investigating the photoelectric effect using a photocell with a clean metallic cathode.

Wavelength of light used (nm)	Frequency of light used $\times 10^{14}$ (Hz)	Photon energy of light used (eV)	Stopping voltage reading (V)	Maximum photoelectron energy (J)
		3.19		3.78×10^{-19}
524			1.54	

- Complete the table by filling in the missing values.
- Using only the two data points supplied in the table, plot a graph of maximum photoelectron energy in electron volts versus photon frequency in hertz for the photocell.
- Using only your graph, state your values for the following quantities. In each case, state what aspect of the graph you have used.
 - Planck's constant, h , in the units J s and eV s as determined from the graph
 - The threshold frequency, f_0 , for the metal surface in Hz as determined from the graph
 - The work function, ϕ , for the metal surface as determined from the graph, in the units J and eV.
- On the same axes, draw and label the graph you would expect to get when using a different photocell, given that it has a work function slightly larger than the one used to collect the data in the table.

A new photocell is now investigated. When light of frequency 8.25×10^{14} Hz is used, a stopping voltage of 1.59 V is required to stop the most energetic electrons. In addition, when the battery voltage is set to 0 V, the photocurrent is measured to be 38 μ A.

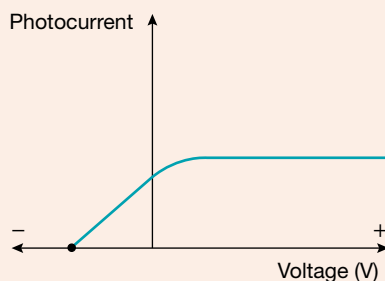
- Calculate the work function of the new photocell.
- Describe what happens in the electric circuit with the power supply voltage set to 0 V when the light intensity is halved.
- With the intensity still halved, the stopping voltage is now slowly increased from 0 V and the photocurrent slowly reduces to 0 A. State the stopping voltage when the current first equals 0 A with the light intensity still halved.

-  **Digital document** Investigation 11.1 Producing and transmitting radio waves (doc-32617)
-  **Interactivity** Using the photoelectric effect (int-0121)
-  **Weblink** The photoelectric effect

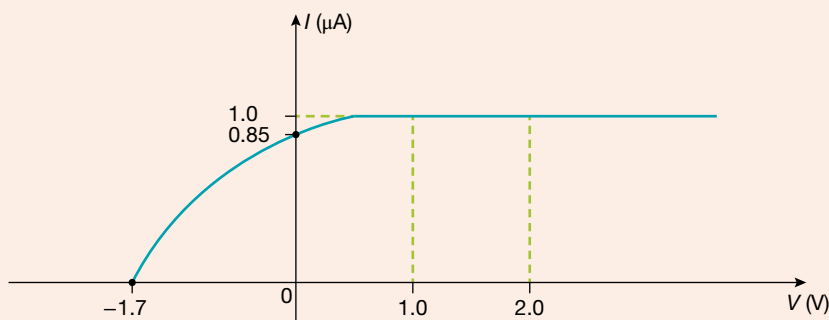
11.3 EXERCISE

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- What is the stopping voltage when UV radiation having a wavelength of 200 nm is shone onto a clean gold surface? The work function of gold is 5.10 eV.
- In the diagram shown at the right, the curve shows how the current measured in an experiment involving the photoelectric effect depends on the potential difference between the anode and cathode.



- Explain the curve. Why does it reach a constant maximum value at a certain positive voltage, and why does it drop to zero at a certain negative voltage?
 - If the intensity of the light was increased without changing its frequency, sketch the curve that would be obtained. Explain your reasoning.
 - If the frequency of the light was increased without changing its intensity, sketch the curve that would be obtained. Explain your reasoning.
 - If the material of the cathode was changed, but the light was not changed in any way, sketch the curve that would be obtained. Explain your reasoning.
- The following curve shows the current in a photoelectric cell versus the potential difference between the anode and the cathode when blue light is shone onto the anode.



- State the current when the voltage is 0 V.
- State the current when the voltage is +1.0 V.
- State the current when the voltage is increased to +2.0 V.
- Why does increasing the voltage have no effect on the current in the circuit?
- The polarity is now reversed and the voltage increased until the current drops to 0 A. State the stopping voltage and hence the maximum energy of electrons emitted from the anode.
- The light source is now made brighter without changing the frequency. Copy the figure and sketch a second curve that illustrates the effect of increasing the intensity of the blue light.

- (g) The light source is now returned to its original brightness and green light is used. A current is still detected. Sketch a third curve to illustrate the effect of using light of a lower frequency.
- (h) The apparatus is altered so that the anode consists of a metal with a smaller work function. Again blue light is used. Sketch a fourth curve to illustrate the effect of changing the anode without changing either the brightness or colour of the light.
4. The work function for a particular metal is 3.80 eV. When monochromatic light is shone onto the photocell, electrons with energy 0.670 eV are emitted.
- What is the stopping voltage required to stop these electrons?
 - What is the frequency of the monochromatic light used?
 - What is the threshold frequency of the metallic surface?
5. In a photoelectric effect experiment, the threshold frequency is measured to be 6.2×10^{14} Hz.
- Calculate the work function of the metal surface used.
 - If electrons of maximum kinetic energy 3.4×10^{-19} J are detected when light of a particular frequency is shone onto the apparatus, what is the stopping voltage?
 - With the same source of light, what is the wavelength and hence the momentum of the photons?
6. One electron ejected from a clean zinc plate by ultraviolet light has a kinetic energy of 4.0×10^{-19} J.
- What would be the kinetic energy of this electron when it reached the anode, if a retarding voltage of 1.0 V was applied between the anode and cathode?
 - What is the minimum retarding voltage that would prevent this electron reaching the anode?
 - All electrons ejected from the zinc plate are prevented from reaching the anode by a retarding voltage of 4.3 V. What is the maximum kinetic energy of electrons ejected from the zinc?
 - Sketch a graph of photocurrent versus voltage for this metal surface. Use an arbitrary photocurrent scale.
7. Robert Millikan performed his photoelectric experiment using a clean potassium surface, with a work function of 2.30 eV. He used a mercury discharge lamp. One wavelength of radiation emitted by the lamp was 254 nm, in the ultraviolet.
- What is the maximum kinetic energy of electrons ejected from the potassium surface by this UV radiation?
 - What voltage would be required to reduce the photocurrent in the cell to zero?
 - Sketch a graph of maximum electron kinetic energy versus frequency for potassium. Show the point on the graph obtained from the 254 nm UV radiation.
 - Repeat this sketch for sodium, which has a work function of 2.75 eV.
8. When the surface of a material in a photoelectric effect experiment is illuminated with light from a mercury discharge lamp, the stopping voltages given in the table are measured.
- Plot the stopping voltage versus the frequency of the light and use the graph to determine the following:
- the threshold frequency
 - the threshold wavelength
 - the work function of the material, in eV
 - the value of Planck's constant.

Wavelength (nm)	Stopping voltage (V)
366	1.48
405	1.15
436	0.93
492	0.62
546	0.36
579	0.24

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11.4 Limitations of the wave model

KEY CONCEPTS

- Describe the limitation of the wave model of light in explaining experimental results related to the photoelectric effect.

In the wave model picture of the photoelectric effect, the energy of light is shared between electrons and accumulated little by little with the arrival of each wavefront. If this were true, the photoelectric effect experiment results would be significantly different.

Higher intensity light, delivering energy at a greater rate, would produce electrons with higher kinetic energies, so the stopping voltage would increase with increasing intensity.

For example, the effect of waves on a beach is cumulative. As each wave breaks along the length of the beach, it adds to the effect of the previous waves until signs of erosion appear.

A time delay would occur while enough shared energy accumulated for electrons to escape, and this delay would be shorter for higher intensity light.

There would be no lower limit on the frequency of light that could eject electrons. The waiting time for electrons to emerge would be longer using lower frequency light, since its wavefronts arrive less frequently; however, eventually a current would be detected.

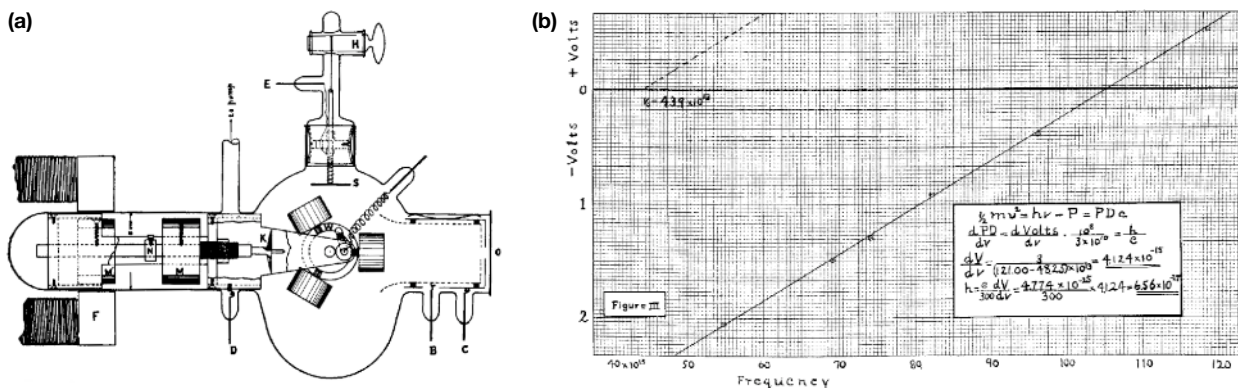
11.4.1 Great photoelectric effect results

Einstein's insights into using a particle model to explain the photoelectric effect led to his 1905 prediction. He predicted that a graph of stopping voltage versus frequency would be a straight line whose gradient was independent of the material emitting electrons:

$$V_0 = \frac{1}{q_e}(hf - \phi)$$

A 'machine shop in a glass tube' was needed to show that this prediction was correct. Robert Millikan, the same Millikan who had earlier measured the minimum value of electric charge, was the engineer of this machine shop, which is shown in figure 11.11a. Strong monochromatic UV sources did not exist, so Millikan used the visible and near-UV lines of a mercury arc lamp. Since the visible and near-UV photons of the lamp have lower energy than UV photons, his studies were limited to materials with low work functions. He used the alkali metals lithium, sodium and potassium.

FIGURE 11.11 (a) Millikan's 'machine shop in a glass tube', and (b) his first published results



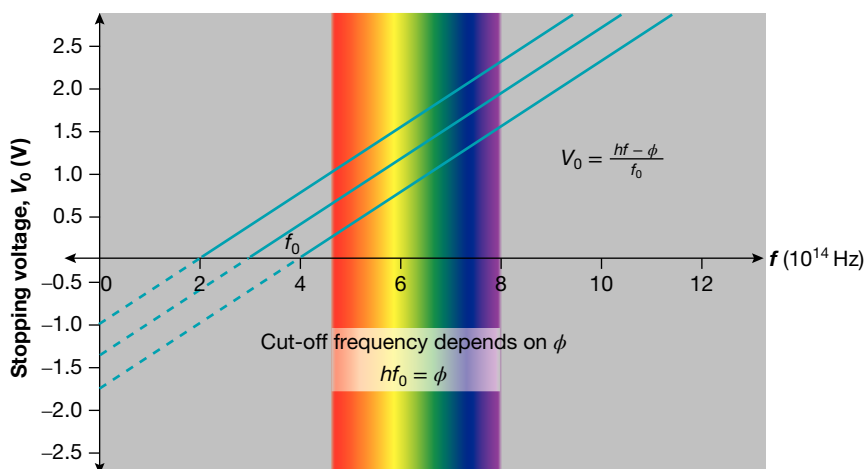
Unfortunately, while a low work function makes their electrons accessible to visible light, it also made these materials vulnerable to reaction with the oxygen in air. The metals quickly become coated with a

thin insulating layer of metal oxide. To overcome this problem, Millikan conducted his experiments in an evacuated glass container. Inside the container, he placed an ingenious mechanism for rotating his electrodes past a sharp knife that scraped a clean metal surface for each experiment.

Figure 11.11a shows his experimental arrangement and figure 11.11b shows his first published results. The gradient of the straight line is $\frac{h}{q_e}$, where h is Planck's constant and q_e is the magnitude of the electronic charge. Millikan determined $\frac{h}{q_e}$ to be $4.1 \times 10^{-15} \text{ J s C}^{-1}$.

The graphs for different materials all have the same slope, $\frac{h}{q_e}$, but are displaced to the right or left, depending on the work function. The cut-off frequency, f_0 , is where the line meets the frequency axis. Its value is equal to $\frac{\phi}{h}$.

FIGURE 11.12 V_0 versus f for three different metals



Einstein said:

It seems to me that the observations associated with . . . the photoelectric effect, and other related phenomena . . . are more readily understood if one assumes that the energy of light is discontinuously distributed through space . . . the energy of a light ray spreading out from a point is not continuously spread out over an increasing space, but consists of a finite number of energy quanta which are localised at points in space, which move without dividing, and which can only be produced and absorbed as complete units.

The word *quanta* is plural for **quantum**, a word meaning a small quantity of a fixed amount. These energy quanta of light are what are now called photons.

This need for a photon model to explain the workings of the photoelectric effect fitted very neatly with Planck's black body radiation model, in which a particle model for light was required to make the theory fit with the experimental evidence of light radiated from hot objects. However, both these phenomena contradicted the enormously successful wave model for light summarised by Maxwell's four equations for electromagnetic phenomena. The wave model for light in terms of perpendicular electric and magnetic fields is consistent with observed interference patterns and diffraction patterns, and with the propagation of light at a single, universal speed, c . A wave model for light is also consistent with a large range of electrical and magnetic phenomena, for example electromagnetic induction.

Another chapter in physics was about to begin. The development of quantum mechanics would completely change the way in which scientists viewed the universe. The Newtonian mechanistic world was about to be overthrown. Confusion between particle and wave models for both light and matter would be resolved, but this would take another thirty years to achieve.

11.4.2 Photons explain phenomena better than waves

Almost thirty years after the first observation of the photoelectric effect, experimental measurements confirmed the need for a photon model for light. The wave model for light was incapable of explaining the observations of the photoelectric effect.

TABLE 11.1 Timeline of key discoveries about the photoelectric effect

Date	Event
1887	It all started with Hertz carefully noting the unusual behaviour of sparks across the gaps in his radio wave detector circuit. This was the first observation of the photoelectric effect.
1901	Max Planck solves the black body radiation problem theoretically, paving the way for light to be modelled not only as a wave but also as a localised particle with energy proportional to the frequency of the light, f .
1902	Philipp Lenard carried out experiments to accumulate knowledge about the behaviour of electrons emitted by light. His results revealed several puzzling aspects: electron energies did not depend on the light intensity, and a unique cut-off frequency was found to exist for each material.
1905	The flash of insight was Albert Einstein's, when he realised that all of Lenard's observations could be explained if he changed the way he thought about light — if light energy travelled as particles not waves. He used the particle model to predict that the graph of stopping voltage versus frequency would be straight, with a slope that was the same for all electron emitters.
1915	Robert Millikan sealed the success of Einstein's theory with plots of V_0 versus f for the alkali metals that were straight and parallel to one another. He used the plots to measure Planck's constant. The photon energy was hf .

TABLE 11.2 Observations made from the photoelectric effect and model predictions

Observation	Wave model prediction	Photon model prediction
For a given frequency of light, the photocurrent is dependent in a linear fashion on the brightness or intensity of light.	✗ The wave model makes no significant prediction other than that brighter light should produce electrons with greater energy, which is not the case.	✓ Intensity of light relates to the number of photons per second striking the photocell. The photocurrent is expected to be dependent on the intensity of light.
The energy of photoelectrons is independent of intensity of light and only linearly dependent on frequency.	✗ The energy of electrons is dependent on the intensity of light: the larger the amplitude of the wave, the larger the energy transferred to electrons.	✓ The energy of photoelectrons is linearly dependent on the frequency of light, provided that the energy of a single photon of light is interpreted as equal to hf .
There is no significant time delay between incident light striking a photocell and subsequent emission of electrons, and this observation is independent of the intensity of incident irradiation.	✗ Time delay is shorter with increasing intensity.	✓ No time delay is expected as individual photons of light strike the photocell and transfer energy to individual electrons.
A threshold frequency exists below which the photoelectric effect does not occur, and this threshold is independent of intensity.	✗ No threshold effect should exist, as energy transfer to electrons from a light source is cumulative and eventually emission will occur.	✓ A threshold frequency is predicted, as photons with energy less than the work function are incapable of freeing electrons from the photocell.

11.4 EXERCISE

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1. If light behaved like a wave when it transferred energy to electrons, as in the photoelectric effect, what would you expect to happen to the stopping voltage if the intensity of the light were increased?
2. Give two observations that support the particle model for light in the photoelectric effect.
3. Explain why, when treating light as a wave, there would be no threshold frequency but, when treating light as a particle, the observation of a threshold frequency is naturally explained.
4. Calculating the energy of a 'particle' of light — a photon — by using the frequency associated with an electromagnetic 'wave' of light seems contradictory. Discuss.

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11.5 Review

11.5.1 Summary

- The equation $c = f\lambda$ describes the speed of a wave in terms of its frequency, f , and wavelength, λ .
- The photoelectric effect is the emission of electrons from materials, usually metals, by the action of light.
- The photoelectric effect is best explained by considering light as consisting of a stream of particles called photons. Each photon has an energy, E , that is dependent on only the frequency of the light, f , according to the equation $E = hf$. This is the Einstein interpretation of the photoelectric effect.
- The electron volt is a unit of energy that is useful when calculating properties of light and electrons.

$$1 \text{ eV} = 1.6 \times 10^{-19} \text{ J}$$

- When a photon hits an electron in a metal, it will transfer either all or none of its energy to the electron. This occurs within a time interval of typically 10^{-9} s of a beam of light striking a surface.
- Below a threshold frequency, f_0 , the emission of electrons does not occur regardless of the intensity of light.
- Planck's constant is $h = 6.63 \times 10^{-34} \text{ J s} = 4.14 \times 10^{-15} \text{ eV}$.
- The maximum kinetic energy of emitted electrons, $E_{k \text{ max}}$, is given by the equation $E_{k \text{ max}} = hf - \phi$, where f is the frequency of the light and ϕ is the work function of the material.
- The maximum kinetic energy of the electrons emitted because of the photoelectric effect can be determined by measuring the stopping voltage, V_0 .

$$E_{k \text{ max}} = qV_0$$

- The intensity of incident irradiation has no effect on the stopping voltage; it only has effects directly in proportion to the size of the photocurrent. A wave model for light cannot account for this, but a particle model of light can.
- A graph of the maximum kinetic energy of emitted electrons plotted against frequency gives a straight line. The gradient of the graph is Planck's constant, h . The y-intercept is the work function, ϕ , and the x-intercept is the threshold frequency, f_0 .
- The photoelectric effect is strong evidence for light consisting of a stream of particles.
- Photons also have momentum, p , given by the equation $p = \frac{h}{\lambda}$, where λ is the wavelength of the photon.



Resources



To access key concept summaries and past VCAA exam questions download and print the **studyON: Revision and past VCAA exam question booklet** (sonr-0060).

11.5.2 Key terms

An **electron gun** is a device to provide free electrons for a linear accelerator. It usually consists of a hot wire filament with a current supplied by a low-voltage source.

An **electron volt** is the quantity of energy acquired by an elementary charge ($q_e = 1.6 \times 10^{-19}$ C) passing through a potential difference of 1 V. Thus, 1.6×10^{-19} J = 1 eV.

Ionisation energy is the amount of energy required to be transferred to an electron to enable it to escape from a material.

Monochromatic describes light of a single frequency and, hence, very clearly defined colour.

The **photoelectric effect** is the release of electrons from a metal surface as a result of exposure to electromagnetic radiation.

A **photon** is a discrete bundle of electromagnetic radiation. Photons can be thought of as discrete packets of light energy with zero mass and zero electric charge.

A **quantum** is a small quantity of a fixed amount.

The **work function** is the minimum energy required to release an electron from the surface of a material.



Resources



Digital document Key terms glossary (doc-32261)

11.5.3 Practical work and investigations

Investigation 11.1

Producing and transmitting radio waves

Aim: To demonstrate the production and transmission of radio waves

Digital document: doc-32617



Resources



Digital document Practical investigation logbook (doc-32262)

11.5 Exercises

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

11.5 Exercise 1: Multiple choice questions

- Which phenomenon first required a shift from a wave model for light to a particle model for light?
 - Two slit interference
 - Single slit diffraction
 - Incandescent emission of light from hot objects
 - The constant speed of light
- Blue light has a frequency 7.0×10^{14} Hz. Determine which of the following is the energy of a photon having this frequency.
 - 4.6×10^{-19} J
 - 2.8×10^{-19} J
 - 4.6×10^{-18} J
 - 2.8×10^{-18} J
- A beam of light consists of photons each with momentum 1.66×10^{-27} N s. Determine which of the following is the energy of a single photon in this beam.
 - 5.0×10^{-35} J
 - 2.0×10^{-35} J
 - 3.0×10^{-18} J
 - 5.0×10^{-19} J
- In a typical photoelectric effect experiment, a beam of photons each with energy 4.7 eV strikes a photocell. The maximum energy of the emitted electrons is 2.9 eV. Determine which of the following is the work function ϕ of the photocell.
 - 7.6 eV
 - 2.8 eV
 - 1.8 eV
 - 3.1 eV
- Electrons emitted from a photocell have a maximum energy 4.8×10^{-18} J. These electrons are all stopped by a stopping voltage applied across the anode and cathode. Determine which of the following is the value of this stopping voltage.
 - 4.8 V
 - 3.0 V
 - 3.0 eV
 - 4.8 eV
- The stopping voltage for a specific photoelectric effect experiment is 2.50 V using a photocell with a work function 3.40 eV. Determine which of the following is the energy of the photons used to strike the photocell.
 - 9.44×10^{-19} J
 - 3.25×10^{-19} J
 - 6.73×10^{-19} J
 - 2.46×10^{-19} J
- A student is performing a typical photoelectric effect experiment and finds that, when she shines blue light on the photocell, a stopping voltage of 2.7 V is required. She then reduces the intensity of the light. Which of the following statements is correct?
 - The work function will be reduced.
 - The stopping voltage will be reduced.
 - The stopping voltage will be unchanged.
 - The photocurrent will be unchanged.

8. In another experiment, a student again shines blue light on the photocell and finds the stopping voltage again to be 2.7 V. This time he changes the light source to a UV source having the same intensity. Which statement is correct?
 - A. The work function will be increased.
 - B. The stopping voltage will be increased.
 - C. The stopping voltage will be unchanged.
 - D. The photocurrent will be increased.
9. The work function for a particular metal surface used as a photocell is 3.4 eV. Determine which of the following is the threshold frequency if this surface is used to investigate the photoelectric effect.
 - A. 3.8×10^{14} Hz
 - B. 4.7×10^{14} Hz
 - C. 6.9×10^{14} Hz
 - D. 8.2×10^{14} Hz
10. Which statement below is consistent with a wave model prediction for what should happen in the photoelectric effect?
 - A. No threshold frequency should exist for the emission of photoelectrons.
 - B. Light with greater intensity will produce photoelectrons with the same energy.
 - C. Light with greater intensity will have no effect on any time delay associated with light striking a photocell and the subsequent emission of photoelectrons.
 - D. Light with increased frequency incident on a photocell will produce photoelectrons having increased energy.

11.5 Exercise 2: Short answer questions

1. Red light has a wavelength 650 nm.
 - a. State the wavelength in metres.
 - b. Calculate the frequency of red light.
 - c. Determine both the energy and momentum of a photon in the red light.
2. A 1000 W radio transmitter emits photons with frequency 105.9 MHz. Calculate the number of photons emitted per second by the transmitter.
3. Incident on its surface, a photocell has light of frequency 6.8×10^{14} Hz. Electrons emitted from this cell have a maximum energy of 2.4×10^{-19} J.
 - a. Find the energy of a photon of light incident on the photocell. Give your answer in both the units of joule and electron volt.
 - b. Determine the work function of the photocell surface. Give your answer in both the units of joule and electron volt.
 - c. Determine the stopping voltage necessary to stop all photoelectrons.
4. The threshold frequency of a particular photocell is 3.50×10^{14} Hz.
 - a. Explain why light with frequency below this will not emit electrons from this photocell.
 - b. Determine the work function ϕ for this cell.
 - c. Calculate the energy of photoelectrons emitted from this photocell when light of frequency 5.10×10^{15} Hz is incident on the cell.
5. Students collect data using a photocell as part of an investigation. They find that, when light of frequency 4.1×10^{14} Hz is used, the stopping voltage is 0.72 V. When they use light of a higher frequency, 6.2×10^{14} Hz, the stopping voltage is increased to 1.60 V
 - a. Use this data to determine a value for Planck's constant in both eV s and J s.
 - b. Calculate the work function of this photocell.
6. Students have accurately measured and recorded the following information for a specific photoelectric effect experiment.

incident light frequency: $f = 5.2 \times 10^{12}$ Hz

stopping voltage: $V_0 = 1.10$ V

photocurrent when voltage is 0 V: 24 μ A

The following changes are then made:

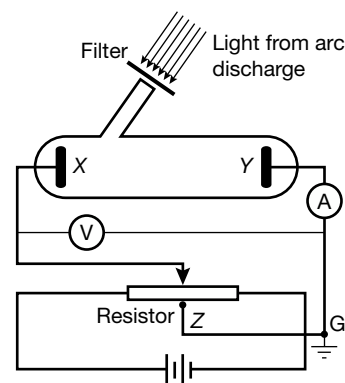
- The light is made more intense. State and explain what will happen to the stopping voltage and what will happen to the photocurrent in this situation.
 - The light is returned to its original intensity and a higher frequency is used. State and explain what will happen to the stopping voltage and what will happen to the photocurrent in this situation.
 - The light is returned to its original frequency and intensity, but this time a photocell having a smaller work function is used instead. State and explain what will happen to the stopping voltage and what will happen to the photocurrent in this situation.
7. Consider four observations made concerning the photoelectric effect. Give reasons why a particle model better explains each of these observations and also why a wave model for light is inadequate.

11.5 Exercise 3: Exam practice questions

Use the following information to answer Questions 1 through 4.

A student shines light of a single frequency onto a metallic surface causing electrons to be emitted in accordance with the well-known photoelectric effect. This is shown in the diagram at the right. Electrons are ejected from plate X and some of them are collected on plate Y. Plate Y is connected to the negative terminal of a variable power supply. The student increases the voltage of the power supply until the current in the ammeter decreases to zero. Then the stopping voltage V is recorded. An optical filter is removed and replaced with another one and the experiment repeated. In this way, the frequency of the light can be altered.

The following table shows some data collected by the student, who is studying aspects of the photoelectric effect.



wavelength of light used (nm)	frequency of light used $f \times 10^{14}$ (Hz)	photon energy of light used (eV)	Maximum energy of photoelectrons E_e (eV)
575			0.47
		3.33	1.60

Question 1 (7 marks)

- Complete the table. There are four blank cells to complete. 4 marks
- In each case using your completed table, determine the value of each of the following three quantities:
 - Planck's constant h in the unit of J s 1 mark
 - The threshold frequency f_0 for the metal surface in Hz 1 mark
 - The work function ϕ for the metal surface, in eV 1 mark

Question 2 (2 marks)

Using your values for h or either f_0 or ϕ , calculate the wavelength of light necessary to strike the metallic surface when the maximum energy of the electrons emitted from the surface is 1.34×10^{-19} J.

Question 3 (2 marks)

A new photocell is now used. It is found that when light of frequency 8.25×10^{14} Hz is used, a stopping voltage of 1.59 V is required to stop the most energetic electrons.

When the battery voltage is set to 0 V, the photocurrent is measured to be 18 μ A.

The intensity of the light is now doubled.

- a. What happens to the photocurrent with the battery voltage still set to 0 V when the light intensity is doubled? **1 mark**

The voltage is now increased and the photocurrent slowly reduces to 0 A as the stopping voltage is achieved.

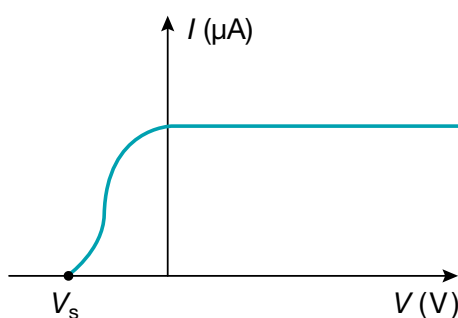
- b. What is the stopping voltage when the current first equals 0 A with the light intensity doubled? **1 mark**

Question 4 (3 marks)

Give two observations from the photoelectric effect experiment to illustrate that light has the capacity to behave as though it were a particle. Give a third observation that illustrates light behaving as though it were a wave.

Question 5 (2 marks)

Monochromatic light is shone onto a photocell, and a photocurrent I vs. voltage V graph is obtained. The graph is shown with the stopping voltage on the graph labelled V_s .



The photocell is now replaced with a different cell with a smaller work function ϕ . The same frequency light but of greater intensity is now shone onto the photocell and electrons are still emitted.

On a copy of the graph shown, sketch a curve to illustrate the expected photocurrent versus voltage.

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12 Light and matter

12.1 Overview

Numerous **videos** and **interactivities** are available just where you need them, at the point of learning, in your digital formats, learnON and eBookPLUS at www.jacplus.com.au.

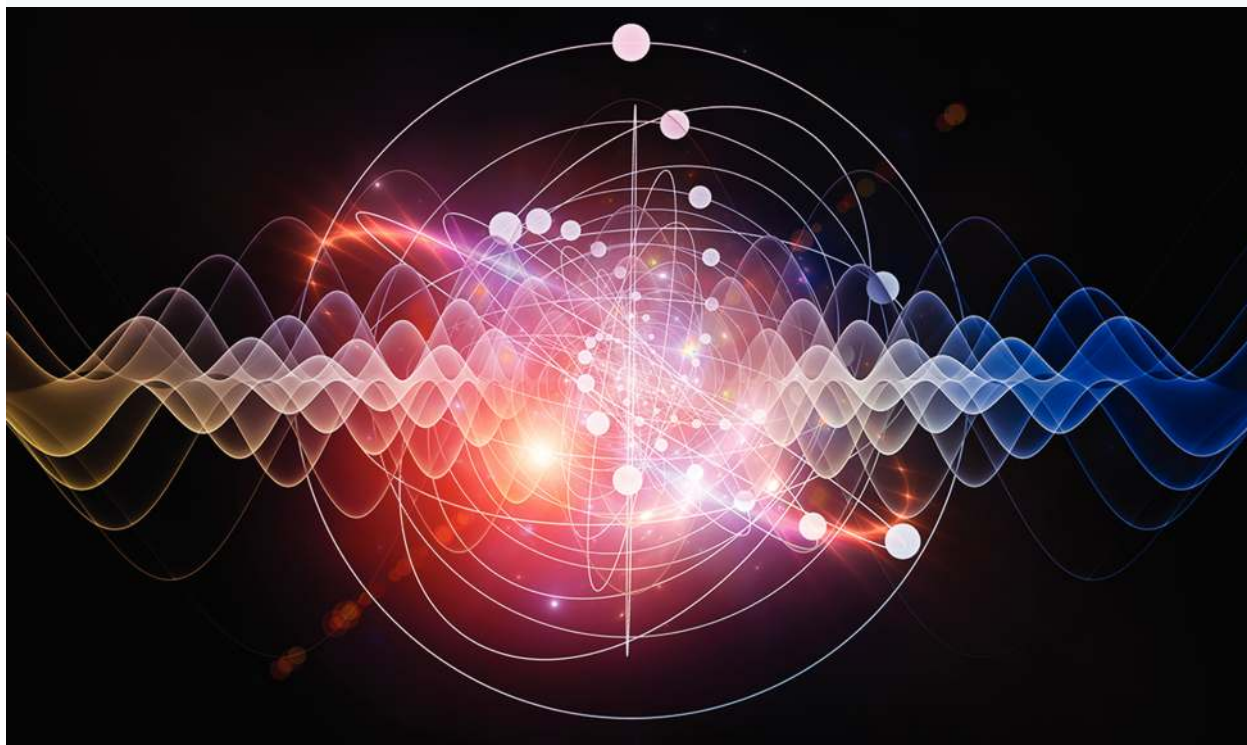
12.1.1 Introduction

Until the nineteenth century, most scientists thought that light was a type of wave, but later evidence pointed towards light behaving more like a stream of particles. In the twentieth century, physicists realised that neither description was sufficient for light. You've seen that light can behave both like a wave and like a particle. Can matter also behave like a particle at certain times and like a wave at other times? If so, how would its wavelength be found? What would a matter wave indicate and indeed what would it mean? What experiments should be attempted to test for the wave properties of matter?

In 1920, Louis de Broglie suggested a way to calculate the wavelength of a piece of matter, from its momentum. Later that decade, William Bragg showed that individual electrons could diffract when passing through narrow openings — the space between atoms in crystals. A wave model for electrons in atoms not only explains the diffraction of matter but also perfectly explains both discrete emission and absorption spectra; both a particle and wave model are required for matter as well.

One final question remains: Can light and matter sometimes behave like a wave propagating in all directions at once and sometimes like a particle moving in a single direction only? The answer is, it can! Welcome to the world of wave–particle duality, quantum mechanics and Heisenberg's uncertainty principle.

FIGURE 12.1 Do discoveries related to light behaving like a particle and a wave apply to electrons and matter?



12.1.2 What you will learn

KEY KNOWLEDGE

After completing this topic, you will be able to:

- interpret electron diffraction patterns as evidence for the wavelike nature of matter
- distinguish between the diffraction patterns produced by photons and electrons
- calculate the de Broglie wavelength of matter: $\lambda = \frac{h}{p}$
- compare the momentum of photons and of matter of the same wavelength including calculations using $p = \frac{h}{\lambda}$
- explain the production of atomic absorption and emission line spectra, including those from metal vapour lamps
- interpret spectra and calculate the energy of absorbed or emitted photons: $\Delta E = hf$
- analyse the absorption of photons by atoms, with reference to
 - the change in energy levels of the atom due to electrons changing state
 - the frequency and wavelength of emitted photons: $E = hf = \frac{h}{\lambda}$
- describe the quantised states of the atom with reference to electrons forming standing waves, and explain this as evidence for the dual nature of matter
- interpret the single photon/electron double-slit experiment as evidence for the dual nature of light and matter
- explain how diffraction from a single-slit experiment can be used to illustrate Heisenberg's uncertainty principle
- explain why classical laws of physics are not appropriate to model motion at very small scales
- compare the production of light in lasers, synchrotrons, LEDs and incandescent lights.

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PRACTICAL WORK AND INVESTIGATIONS

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

on Resources

-  **Digital documents** Key science skills — VCE Physics Units 1–4 (doc-32112)
Key terms glossary (doc-32297)
Practical investigation logbook (doc-32298)

studyon

To access key concept summaries and past VCAA exam questions download and print the **studyON: Revision and past VCAA exam question booklet** (sonr-0061).

12.2 Matter as particles or waves

KEY CONCEPTS

- Interpret electron diffraction patterns as evidence for the wavelike nature of matter
- Distinguish between the diffraction patterns produced by photons and electrons
- Calculate the de Broglie wavelength of matter: $\lambda = \frac{h}{p}$
- Compare the momentum of photons and of matter of the same wavelength including calculations using $p = \frac{h}{\lambda}$

12.2.1 The wave behaviour of electrons

By the end of the nineteenth century, it was clear that light exhibited wavelike properties and could be very well modelled as consisting of waves. At the time, it was also firmly established that matter could be modelled as consisting of particles. Early in the twentieth century, however, the photoelectric effect showed that it was necessary for light to also be modelled as a particle. Was it possible that electrons, too, could exhibit wave phenomena as well as demonstrating particle behaviour?

Even though Niels Bohr could calculate their energies, he could not explain why hydrogen electrons only occupied orbits whose energies were discrete. Why were they the only possible electron orbits? What was so special about them? How did atoms make sure they emitted the correct frequency to ensure they landed in another stationary state?

In fact, Rutherford wrote to Bohr:

Your ideas are very ingenious and seem to work out well . . . There seems to me to be one grave difficulty in your hypothesis . . . namely, how does an electron decide what frequency it is going to vibrate at when it passes from one stationary state into another? It seems to me that you would have to assume that the electron knows beforehand where it is going to stop.

In 1923 French nobleman Louis de Broglie (1892–1987) suggested that matter also had a wavelength associated with it. He was intrigued by the fact that light exhibited both wavelike and particle-like properties, and on this basis proposed that matter may also exhibit wavelike properties. This work was done as his PhD thesis. De Broglie proposed that the wavelength of a particle, λ , is related to its momentum, p , according to the following equation:

$$\lambda = \frac{h}{\vec{p}} = \frac{h}{m\vec{v}}$$

where: λ is the de Broglie wavelength of the particle, in m
 h is Planck's constant (6.63×10^{-34} J s)
 $\vec{p}$ is the momentum of the particle, in kg m s⁻¹ (or N s)
 m is the mass of the particle, in kg
 $\vec{v}$ is the velocity of the particle, in m s⁻¹

The constant h , Planck's constant, is related to the particle-like behaviour of light and has a value of 6.63×10^{-34} J s, or 4.14×10^{-15} eV s. The momentum of matter is given by the product of its mass and velocity.

It can be appreciated why the wave properties of matter are difficult to observe. For example, calculate the **de Broglie wavelength** of a 70 kg athlete running at a speed of 10 m s⁻¹.

$$\begin{aligned}
 \lambda &= \frac{h}{mv} \\
 &= \frac{6.63 \times 10^{-34} \text{ J s}}{70 \text{ kg} \times 10 \text{ m s}^{-1}} \\
 &= 9.5 \times 10^{-37} \text{ m}
 \end{aligned}$$

This wavelength is much too small for the ready observation of diffraction effects as an athlete runs through a narrow opening! However, for a particle with a small mass, such as an electron travelling at low speed, this is not the case. Electrons accelerated through a 100 V potential difference would have a speed of approximately $6.0 \times 10^6 \text{ m s}^{-1}$, and because the mass of an electron is $9.1 \times 10^{-31} \text{ kg}$, it would have a momentum of:

$$\begin{aligned}
 p &= mv \\
 &= 9.1 \times 10^{-31} \text{ kg} \times 6.0 \times 10^6 \text{ m s}^{-1} \\
 &= 5.5 \times 10^{-24} \text{ kg m s}^{-1}
 \end{aligned}$$

The de Broglie wavelength for these electrons is:

$$\begin{aligned}
 \lambda &= \frac{h}{p} \\
 &= \frac{6.63 \times 10^{-34} \text{ J s}}{5.5 \times 10^{-24} \text{ m s}^{-1}} \\
 &= 1.2 \times 10^{-10} \text{ m}
 \end{aligned}$$

This wavelength has the same order of magnitude as the spacing between atoms in many crystals. When the ratio of wavelength to slit width w , $\frac{\lambda}{w}$, is sufficiently large, say greater than $\frac{1}{10}$, then diffraction effects are readily observable.

The framework for testing to see if matter had an associated wavelength had now been constructed. Researchers could build an apparatus to fire a beam of electrons of specific energy and hence specific momentum and wavelength at a crystal and observe if any diffraction effects appeared.

SAMPLE PROBLEM 1

- Calculate the de Broglie wavelength of a 10.0 g snail whose speed is 0.100 mm s^{-1} .
- How fast would an electron have to travel to have a de Broglie wavelength of $1.0 \text{ } \mu\text{m}$?

THINK

- The de Broglie wavelength is given by the expression

$$\lambda = \frac{h}{p} = \frac{h}{mv},$$

keeping in mind that mass must be in kilograms and velocity in metres per second.

WRITE

$$\begin{aligned}
 \text{a. } \lambda &= \frac{h}{mv} \\
 &= \frac{6.63 \times 10^{-34}}{10 \times 10^{-3} \times 0.10 \times 10^{-3}} \\
 &= 6.6 \times 10^{-28} \text{ m}
 \end{aligned}$$

b. The expression $\lambda = \frac{h}{mv}$ can be transposed to make v the subject. The values for Planck's constant, the mass of an electron and the de Broglie wavelength can be substituted in.

$$\begin{aligned} \text{b. } v &= \frac{h}{m\lambda} \\ &= \frac{6.63 \times 10^{-34}}{9.1 \times 10^{-31} \times 1.0 \times 10^{-6}} \\ &= 7.3 \times 10^2 \text{ m s}^{-1} \text{ (to 2 significant figures)} \\ \text{The speed of the electron is } 7.3 \times 10^2 \text{ m s}^{-1}. \end{aligned}$$

PRACTICE PROBLEM 1

Which has the greater de Broglie wavelength: a proton ($m = 1.67 \times 10^{-27} \text{ kg}$) travelling at $2.0 \times 10^4 \text{ m s}^{-1}$ or an electron ($m = 9.1 \times 10^{-31} \text{ kg}$) travelling at $2.0 \times 10^5 \text{ m s}^{-1}$?

Finally, it is worth noting that the de Broglie wavelength associated with a piece of matter is inversely proportional to both the speed and mass. Hence, to create matter with large wavelengths necessary for wave properties to manifest themselves, matter has to travel slowly and have little mass. Since electrons have a mass that is approximately $\frac{1}{1800}$ that of a proton or neutron, it is easier to detect the wave properties of electrons over those of other fundamental particles such as protons and neutrons.

on Resources



Video eLessons De Broglie wavelength (med-0199)

The momentum of photons and matter (med-0423)



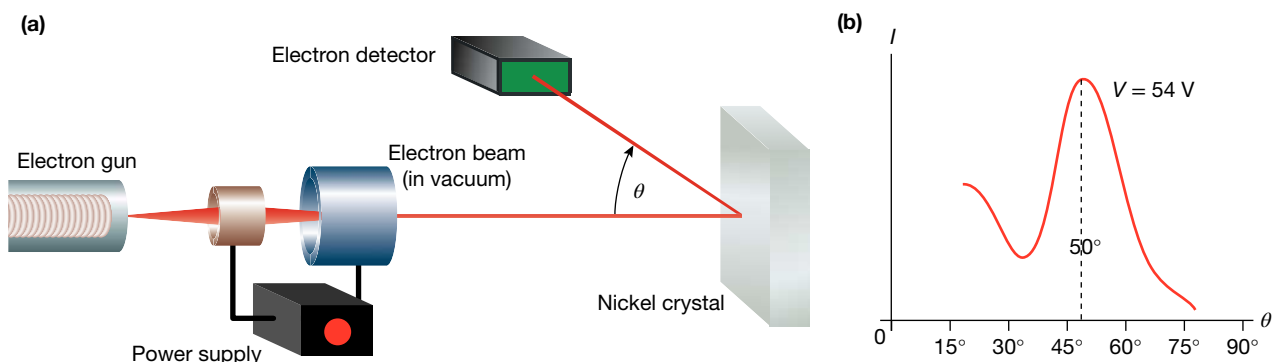
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The atomic lab: electron interference

12.2.2 Diffraction of electrons

De Broglie suggested conducting an experiment to confirm whether a beam of electrons could be diffracted from the surface of a crystal. The openings between atoms could be used as a diffraction grating in much the same way that X-rays were diffracted by thin crystals as suggested by Max von Laue in 1912. Clinton Davisson (1881–1958) and Lester Germer (1896–1971) directed a beam of electrons at a metal crystal in 1927, and the scattered electrons came off in regular peaks as shown in figure 12.2b. This pattern is indicative of diffraction taking place with individual electrons as they scattered off the crystal surface. The diffraction patterns produced by photons and electrons are indistinguishable when they are at the same wavelength. In fact, the wavelength determined from the diffraction experiments was exactly as predicted by the de Broglie wavelength formula. In this way, electrons were shown to have wavelike properties. Since then, protons, neutrons and, more recently, atoms have been shown to exhibit wavelike properties, but it begs the question: if matter can exhibit wave characteristics, what is it that is ‘waving’? More technically, the question is: what physical variable is it that has an amplitude and phase?

FIGURE 12.2 The Davisson and Germer experiment. (a) Electrons emitted from a heated filament are accelerated towards the crystal surface. The intensity of reflected electrons is recorded as the angle of the detector is changed. (b) Electron intensity as a function of angle.



SAMPLE PROBLEM 2

What would be the dimensions of the array of slits required to observe diffraction of 60 gram tennis balls travelling at 30 m s^{-1} ? What about electrons travelling at $3.0 \times 10^6 \text{ m s}^{-1}$?

Teacher-led video: SP2 (tlvd-0211)

THINK

1. To observe diffraction effects, the size of the opening needs to be of the same order of magnitude or smaller than the wavelength of the waves.

Calculate the de Broglie wavelength of the tennis ball and the electron, by substituting $h = 6.63 \times 10^{-34} \text{ J s}$, $m = 60 \text{ g} = 0.060 \text{ kg}$ and $v = 30 \text{ m s}^{-1}$ for the tennis ball, and $m = 9.1 \times 10^{-31} \text{ kg}$ and $v = 3.0 \times 10^6 \text{ m s}^{-1}$ for the electrons.

2. State the order of magnitude of the de Broglie wavelength of the tennis ball and the de Broglie wavelength of the electron.
3. Answer the question.

WRITE

The de Broglie wavelength of the tennis ball:

$$\begin{aligned}\lambda &= \frac{h}{mv} \\ &= \frac{6.63 \times 10^{-34}}{0.060 \times 30} \\ &= 3.7 \times 10^{-34} \text{ m}\end{aligned}$$

The de Broglie wavelength of the electron:

$$\begin{aligned}\lambda &= \frac{h}{mv} \\ &= \frac{6.63 \times 10^{-34}}{9.1 \times 10^{-31} \times 3.0 \times 10^6} \\ &= 2.4 \times 10^{-10} \text{ m}\end{aligned}$$

The de Broglie wavelength of the tennis ball is of the order of 10^{-34} m and that of the electron is of the order of 10^{-10} m .

The distances between atoms in a crystal are of the order of 10^{-10} m , so diffraction and interference can be observed when these electrons are scattered from a crystal. It is not surprising that diffraction and interference effects are never observed with tennis balls, due to the extremely small wavelength, 10^{-34} m , that they have.

PRACTICE PROBLEM 2

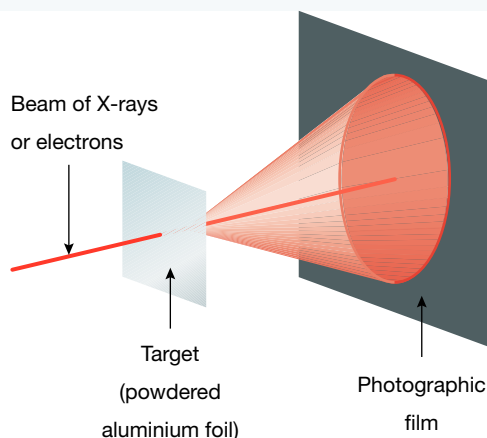
At what velocity would neutrons (mass = 1.67×10^{-27} kg) have to be moving for them to demonstrate diffraction effects when passing through an array of slits of width $1\mu\text{m}$?

12.2.3 Electrons through foils

Intense, creative interest in fundamental physics ran in the Thomson family. Remember, it was J.J. Thomson whose ingenious experiment yielded the measurement of the charge-to-mass ratio of the electron. At that time, there was no doubt that electrons were extremely well modelled as particles. However, G.P. Thomson, son of J.J., continued the exploration of the wave properties of electrons. He fired electrons through a thin polycrystalline metallic foil. The electrons had a much greater momentum than those used by Davisson and Germer. They were able to penetrate the foil and produce a pattern demonstrating diffraction of the electrons by the atoms of the foil — further evidence for wavelike behaviour of electrons. The polycrystalline nature of the foil results in a series of rings of high intensity. A single crystal would produce a pattern of spots. Thomson used identical analysis techniques to those used for diffraction of X-rays through foils, to confirm the de Broglie relationship.

Both Thomsons were awarded Nobel prizes — J.J. in 1897 for measuring a particle-like characteristic of electrons, and G.P. in 1937, together with C.J. Davisson, for demonstrating their wave properties.

FIGURE 12.3 Diffraction of X-rays and electrons by polycrystalline foils



Just as light requires a wave model and a particle model to interpret and explain how it behaves, so too does matter; it behaves like a particle in the sense that work can be done on it to increase its kinetic energy under the action of forces, but matter can also be made to diffract through sufficiently narrow openings and around obstacles. This requires a wave model and the de Broglie wavelength is used to determine the extent of matter's wave behaviour. It appears that both a particle and a wave model are needed for both light and matter. Electrons passed through a voltage, V , acquire a kinetic energy E_k equal to $q_e V$. Since they have kinetic energy, they also possess momentum and, according to de Broglie, a wavelength. A useful relationship can be determined between the de Broglie wavelength of an electron (λ) and the accelerating voltage (V) used.

By equating the kinetic energy of the electron (E_k) to the work done by an accelerating voltage acting on an electron ($q_e V$), the following relationship is obtained:

$$E_k = \frac{1}{2} m_e v^2 = q_e V$$
$$m_e v^2 = 2 q_e V$$

SAMPLE PROBLEM 3

What voltage is required to accelerate electrons to a velocity of $3.0 \times 10^6 \text{ m s}^{-1}$?

THINK

To accelerate electrons to a speed of $3.0 \times 10^6 \text{ m s}^{-1}$, the work done by a voltage V needs to be calculated.

$$\Delta E_{\text{k electron}} = \frac{1}{2} m_e v^2$$

$$\begin{aligned} \Delta E_{\text{k electron}} &= -\Delta E_{\text{p electron}} \\ &= q_e V \end{aligned}$$

$$\Rightarrow V = \frac{m_e v^2}{2q_e}$$

where q_e is the *magnitude* of the charge of the electron ($1.6 \times 10^{19} \text{ C}$).

WRITE

$$\begin{aligned} V &= \frac{m_e v^2}{2q_e} \\ &= \frac{9.1 \times 10^{-31} \times (3.0 \times 10^6)^2}{2 \times 1.6 \times 10^{-19}} \\ &= 26 \text{ V} \end{aligned}$$

So, only 26 V is required to accelerate an electron to $3.0 \times 10^6 \text{ m s}^{-1}$.

PRACTICE PROBLEM 3

Calculate the velocity of electrons accelerated from rest by an electron gun whose voltage is set at 13 V.

If we multiply both sides of the equation by the mass of an electron (m_e) seen earlier, we get:

$$(m_e)^2 v^2 = 2m_e q_e V$$

The left-hand side is just the square of the momentum of the electron, and hence by taking the square root of both sides:

$$p = \sqrt{2m_e q_e V}$$

or

$$p = \sqrt{2m_e E_k},$$

remembering that E_k is equal to $q_e V$.

Since the de Broglie wavelength λ is given by $\frac{h}{p}$, it follows that:

$$\lambda = \frac{h}{\sqrt{2m_e q_e V}} = \frac{h}{\sqrt{2m_e E_k}}$$

where: h is Planck's constant ($6.63 \times 10^{-31} \text{ J s}$)

m_e is the mass of an electron, in kg

q_e is the charge on one electron, in C

V is the accelerating voltage, in V

E_k is the kinetic energy of the electron, in J

SAMPLE PROBLEM 4

Some of the X-rays used in G.P. Thomson's experiment had a wavelength of 7.1×10^{-11} m. Confirm that the 600 eV electrons have a similar wavelength.

THINK

- Electrons of energy 600 eV have passed through a voltage equal to 600 V; thus, their energy is $1.6 \times 10^{-19} \times 600$ J. From this their de Broglie wavelength can be determined. Use the relationship:

$$\lambda = \frac{h}{\sqrt{2m_e E_k}}$$

- Answer the question.

WRITE

$$\begin{aligned}\lambda &= \frac{h}{\sqrt{2m_e E_k}} \\ &= \frac{6.63 \times 10^{-31}}{\sqrt{2 \times 9.1 \times 10^{-31} \times 1.6 \times 10^{-19} \times 600}} \\ &= 5.0 \times 10^{-11} \text{ m}\end{aligned}$$

The de Broglie wavelength of 5.0×10^{-11} m is a similar value to the 7.1×10^{-11} m wavelength of the X-rays.

PRACTICE PROBLEM 4

- X-rays of wavelength 0.053 nm are used to investigate the structure of a new plastic. If a beam of electrons is to be used instead of X-rays, what voltage should be used to accelerate these electrons?
- Which has a greater wavelength: a 100 eV photon or a 100 eV electron?

When examining the energy and momentum of photons and electrons, two useful energy–momentum relationships can be derived. The equations relating energy E and momentum $\vec{p}$ are different for photons compared to electrons.

Photons

Since $E = hf$ and $f = \frac{c}{\lambda}$, it follows that $E = \frac{hc}{\lambda}$. But since $\vec{p} = \frac{h}{\lambda}$, it also follows that $E = \vec{p}c$. The energy of a photon E is directly proportional to the momentum of a photon:

$$E = \vec{p}c$$

Electrons

Since $E = \frac{1}{2}m\vec{v}^2 = \frac{1}{2} \times \frac{m^2 \vec{v}^2}{m}$ and $\vec{p} = m\vec{v}$, it follows that $E = \frac{\vec{p}^2}{2m}$. The kinetic energy E of an electron is directly proportional to the square of the electron's momentum:

$$E = \frac{\vec{p}^2}{2m}$$

Therefore:

- Photons having the same momentum as an electron will have a different amount of energy.
- Photons having the same energy as an electron will have a different amount of momentum.

SAMPLE PROBLEM 5

Consider a photon and an electron that both have a wavelength of 2.0×10^{-10} m.

- Calculate the momentum of the photon and the electron. What do you notice?
- Calculate the energy of the photon and the electron. What do you notice?
- Summarise what you have found concerning the momentum and energy of a photon and an electron with the same wavelength.

 **Teacher-led video:** SP5 (tlvd-0214)

THINK

1. The momentum of the photon and the electron are governed by the same equation, namely $p = \frac{h}{\lambda}$. Hence, both the photon and the electron will have the same momentum because they have the same associated wavelength.

2. Write your observations.

1. To determine the energy of an object from its momentum, the question must be asked whether it is a photon or an object with mass. The relations are different. For the photon, $E = pc$. For the electron, however, $E = \frac{p^2}{2m}$.

2. Write your observations.

- Summarise your observations from parts a and b.

WRITE

$$\begin{aligned} \text{a. } p &= \frac{h}{\lambda} \\ &= \frac{6.63 \times 10^{-34}}{2.0 \times 10^{-10}} \\ &= 3.3 \times 10^{-24} \text{ N s} \end{aligned}$$

The photon and the electron have the same momentum.

- Energy of the photon:

$$\begin{aligned} E &= pc \\ &= 3.3 \times 10^{-24} \times 3.0 \times 10^8 \\ &= 9.9 \times 10^{-16} \text{ J or } 6.2 \text{ keV} \end{aligned}$$

Energy of the electron:

$$\begin{aligned} E &= \frac{p^2}{2m} \\ &= \frac{(3.3 \times 10^{-24})^2}{2 \times 9.1 \times 10^{-31}} \\ &= 6.0 \times 10^{-18} \text{ J or } 37 \text{ eV} \end{aligned}$$

The electron has substantially less kinetic energy than the photon, even though they have the same momentum.

- Light and matter with the same wavelength will have the same momentum, and vice versa. However, when photons and electrons have the same momentum, they will not necessarily have the same energy. In this problem, the photon has substantially more energy than the electron.

PRACTICE PROBLEM 5

Consider a photon and an electron that both have a wavelength of 1.0×10^{-10} m.

- Calculate the momentum of the photon and the electron. What do you notice?
- Calculate the energy of the photon and the electron. What do you notice?

12.2 EXERCISE

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

1. Calculate the de Broglie wavelength of the following particles.
 - (a) A proton ($m = 1.67 \times 10^{-27}$ kg) travelling at 3.0×10^7 m s⁻¹
 - (b) An electron accelerated by a voltage of 54 V, the voltage used by Davisson and Germer in their electron diffraction experiment
 - (c) A tennis ball ($m = 0.20$ kg) moving with a speed 50 m s⁻¹
2. In X-ray tubes, the electric potential energy of electrons is transformed into the energy of X-ray photons. Consider a beam of electrons accelerated through 5.0 kV from rest, which rapidly decelerate when they collide with the anode of the tube.
 - (a) What is the kinetic energy of these electrons as they reach the anode, in joules?
 - (b) If the entire energy of each electron is transformed into the energy of a single photon, what is the wavelength of the resulting X-rays?
3. Explain what William L. Bragg meant when he said, 'On Mondays, Wednesdays and Fridays light behaves like waves, on Tuesdays, Thursdays and Saturdays like particles, and like nothing at all on Sundays'. Is this a good description of the behaviour of light?
4. A beam consists of electrons with speed 2.5×10^6 m s⁻¹ inside an evacuated tube. The beam is directed towards a thin crystal of sodium chloride that can act as a diffraction grating. The spacing between atoms for this crystal is 2.8×10^{-10} m.
 - (a) Calculate the momentum and the de Broglie wavelength for electrons in the beam.
 - (b) By comparing the wavelength to the atomic spacing, discuss whether or not the electrons would diffract significantly.
5. Electrons may display wave properties and diffract when passed through narrow openings. In a particular experiment, a scientist uses an electron gun to direct a beam of electrons towards a crystal. It is thought that the spacing between the atoms in the crystal is about 5.0×10^{-10} m. He adjusts the accelerating voltage of the electron gun to 3.0 kV.
 - (a) Find the energy of electrons in the beam in eV and in J.
 - (b) Calculate the momentum and hence the de Broglie wavelength of the electrons.
 - (c) Determine whether or not the scientist should expect to observe significant diffraction effects.
 - (d) How should the scientist adjust the accelerating voltage to make electrons diffract significantly when passing through the crystal?He now decides to use photons to obtain the same diffraction pattern when passing a beam of photons through the same crystal.
 - (e) What wavelength and, hence, momentum photons should he use?
 - (f) What is the energy of these photons? Give your answer in eV and in J.
6. Calculate the speed of an electron that has the same de Broglie wavelength as a photon of red light whose frequency is 4.5×10^{14} Hz.
7. An electron and a proton are accelerated through the same potential difference.
 - (a) Which will have the greater de Broglie wavelength?
 - (b) Using a potential difference of 1000 V, calculate the de Broglie wavelength for both an electron and a proton.The mass of a proton is 1.67×10^{-27} kg.
8. Electrons can be accelerated with a potential difference in an electron gun. In order to make a beam of electrons whose de Broglie wavelength is 2.0×10^{-10} m, what potential difference must be used?
9. Which has the shorter wavelength, a 10 eV electron or a 10 eV photon?

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12.3 Emission and absorption spectra

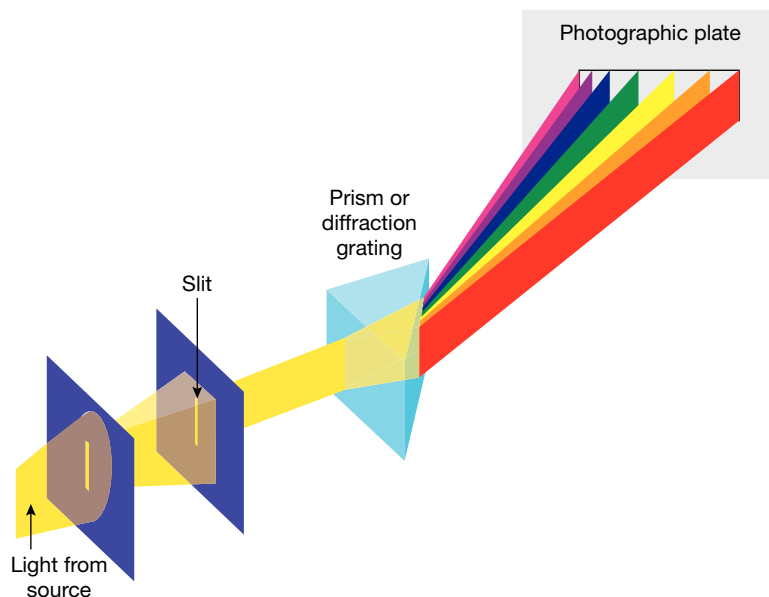
KEY CONCEPTS

- Explain the production of atomic absorption and emission line spectra, including those from metal vapour lamps
- Interpret spectra and calculate the energy of absorbed or emitted photons: $\Delta E = hf$
- Analyse the absorption of photons by atoms, with reference to
 - the change in energy levels of the atom due to electrons changing state
 - the frequency and wavelength of emitted photons: $E = hf = \frac{hc}{\lambda}$
- Describe the quantised states of the atom with reference to electrons forming standing waves, and explain this as evidence for the dual nature of matter.

12.3.1 Atoms emit photons

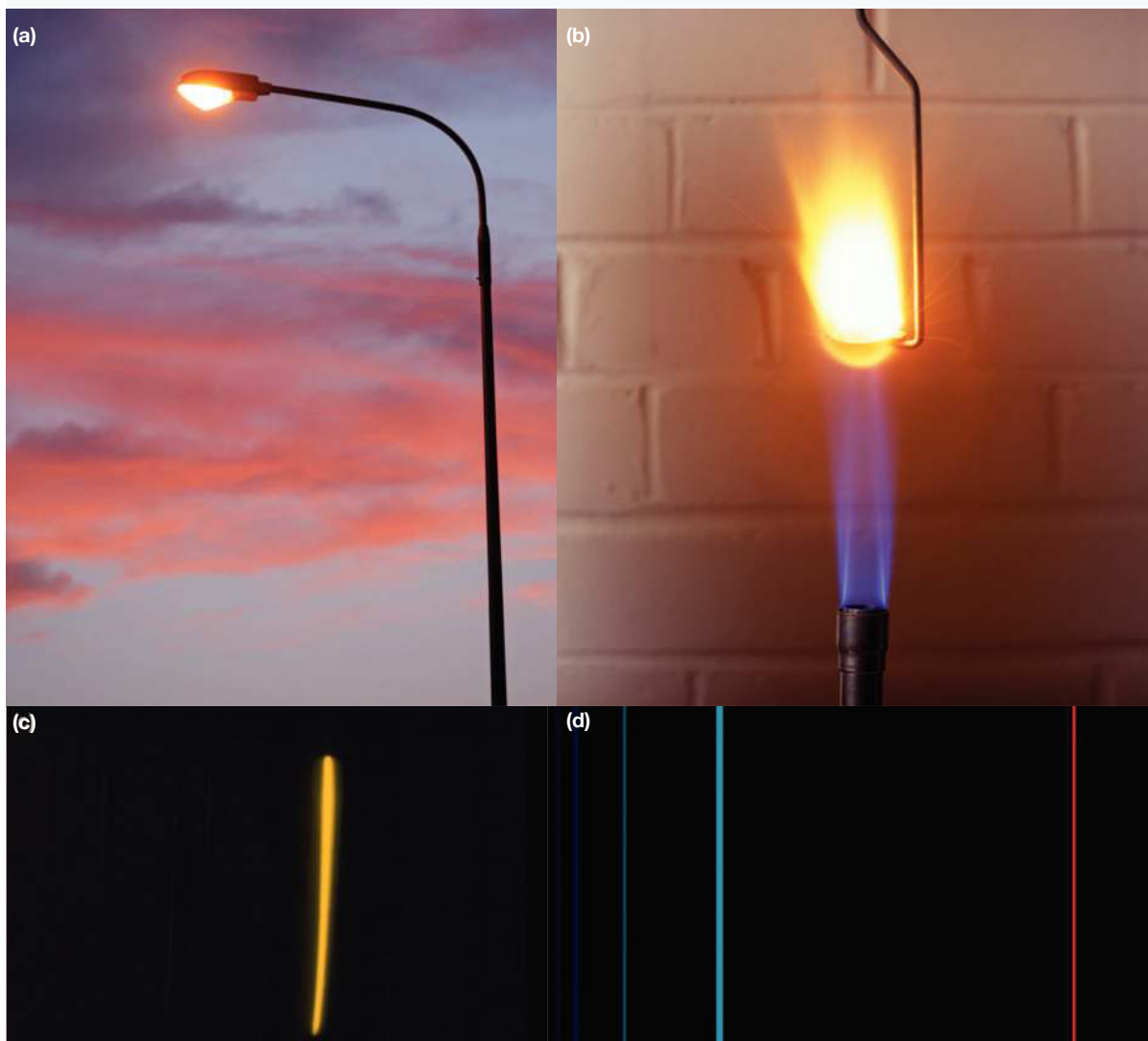
If you dip a loop of wire into a solution of common salt in water and then place the loop in the flame of a Bunsen burner, you will observe that, where the flame touches the loop, it is transformed from blue into glorious gold. If you then place two slits in a line to convert the light from the flame into a beam and use a prism to disperse the light from the beam and a telescope to take a good look at the results, you would be following in the steps of the scientists who developed the field of spectroscopy. You would have constructed a **spectrometer**, which could show you that spectra produced by solutions of sodium chloride and sodium carbonate both look like the spectrum shown in figure 12.4. Sodium atoms in the flame produce the spectrum, and it is identical to the spectrum observed when an electric current is passed through a container of sodium gas at low pressure. Spectrometers were used in the early 1860s to identify two new elements, rubidium and caesium, from unidentified colours in the spectrum of the vapour of mineral water.

FIGURE 12.4 A simple spectrometer



The colours in the spectrum produced by atoms in this way have become known as spectral lines because of the sharp lines they produce on the photographic plate in a spectrometer. These photographs are known as **emission spectra**.

FIGURE 12.5 (a) Sodium vapour street light, (b) characteristic colour of sodium flame, (c) visible line spectrum of sodium atoms, and (d) visible line spectrum of hydrogen atoms



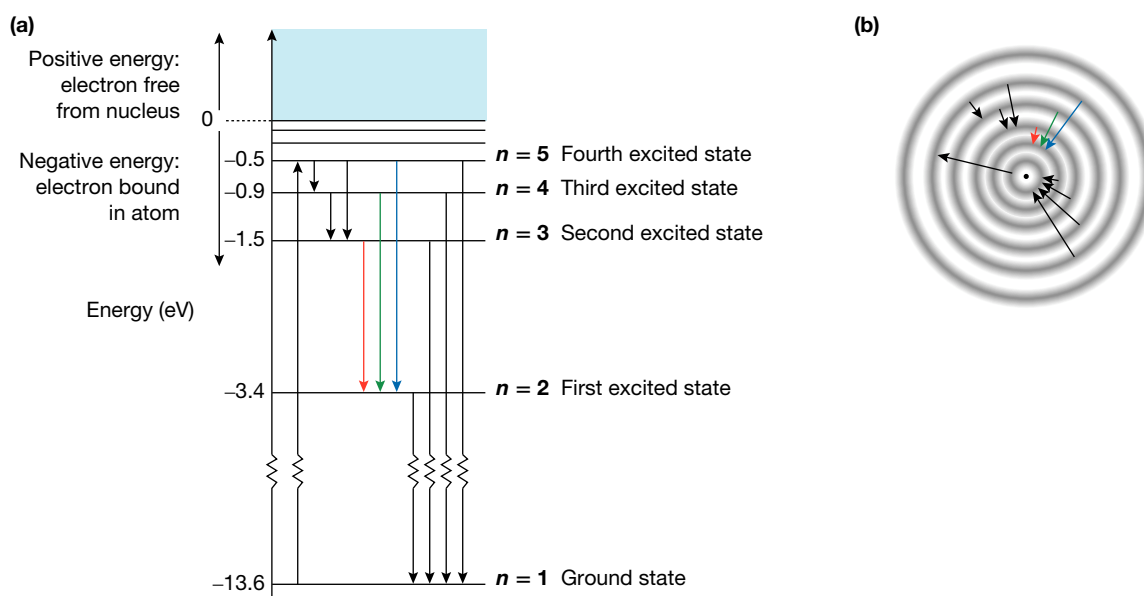
The fact that the spectrum of an element is its ‘fingerprint’ makes it possible to detect tiny traces of elements in complex mixtures, and for astronomers to use the light emitted by remote stars to identify elements in the stars. Of more interest here is the contribution that line spectra makes to developing the understanding of both the structure of matter and the behaviour of light. The key is the sharp line nature of the spectra. Sharp lines have precise wavelengths and, in the photon model for light, this indicates precise photon energies. So line spectra indicate that a particular type of atom emits light energy in quite specific fixed amounts. This behaviour is remarkably different to that of a hot filament and other incandescent light sources, which emit a continuous spectrum of light with a range of wavelengths.

Any model of atomic structure must be able to explain the behaviour of the atom leading to discrete emission spectra. In 1911, Ernest Rutherford, an eminent New Zealander who directed the Cavendish laboratory at Cambridge, established that electrons revolved around a nucleus, with most of the atom being empty space. Then in 1913, Niels Bohr, a Danish physicist, proposed what was then a revolutionary model for the behaviour of these atoms and electrons. His model provided the basis for the current understanding of atoms. The hydrogen atom — the simplest, with just a single electron revolving around a proton — was the initial testing ground for Bohr’s model. The discussion that follows focuses on the hydrogen atom.

Bohr's model had two main ideas.

1. Each atom has a number of possible stable states, each state having its own characteristic energy. In each atomic state, the electron is in a stable orbit around the nucleus. The electron obeys Newton's laws of mechanics but does not radiate electromagnetic waves as predicted by Faraday. (This idea of Bohr's was radical. Electromagnetic theory predicted that an orbiting electron would radiate electromagnetic radiation continuously, losing energy and spiralling into the nucleus.) The energy of these states may be imagined as the rungs on a ladder. The energy of the atom must lie exactly on a rung of the ladder, and never between. The energy levels are said to be discrete, or **quantised**. The energy ladder diagram for hydrogen is shown in figure 12.6a.

FIGURE 12.6 (a) Atomic energy level view of the spectral series of hydrogen (visible colours are shown as coloured arrows), and (b) electron orbit view of the spectral series of hydrogen as illustrated in (a). These lines are seen in the spectrum in figure 12.5d.



2. An atom can jump up or down from one state to another, corresponding to the transfer of the electron from one orbit to another. When the atom drops to a state having a lower energy, a photon is emitted whose energy is equal to the energy loss of the atom. Alternatively, an atom may absorb a photon, raising the energy of the atom in the process. The energy of the photon must exactly match the energy difference between the current state of the atom and one of the higher energy states it is allowed to jump to. The energy of the photon absorbed or emitted can be determined using Planck's equation for the energy of a photon:

$$\Delta E = hf = \frac{hc}{\lambda}$$

where: ΔE is the energy of the photon produced, in J

h is Planck's constant

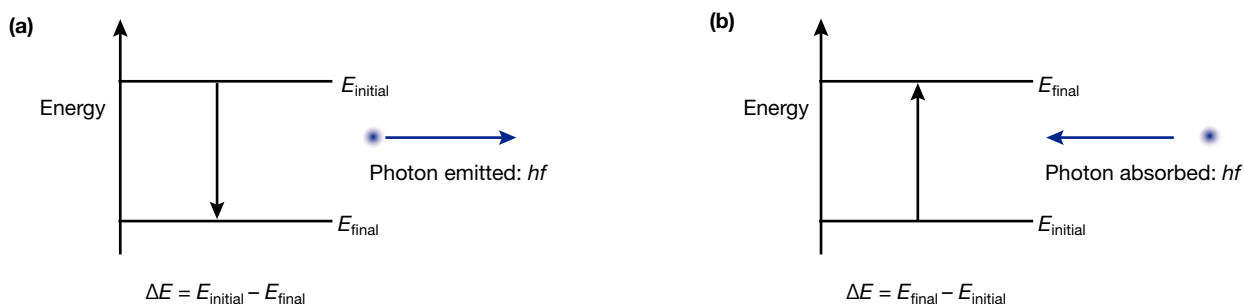
f is the frequency of the photon

c is the speed of light ($3.0 \times 10^8 \text{ m s}^{-1}$)

λ is the wavelength of the photon, in m

Emission and absorption of photons are illustrated in figures 12.7a and 12.7b respectively. The emission of light can be represented as $E_{\text{photon}} = hf = \Delta E = E_{\text{initial}} - E_{\text{final}}$, and the absorption of light can be represented as $E_{\text{photon}} = hf = \Delta E = E_{\text{final}} - E_{\text{initial}}$.

FIGURE 12.7 (a) Emission of light (b) Absorption of light



Atoms can gain energy in other ways. Absorption of energy can occur during a collision of an atom with an electron, in a discharge tube, or during a collision with an ion (as occurs in a flame).

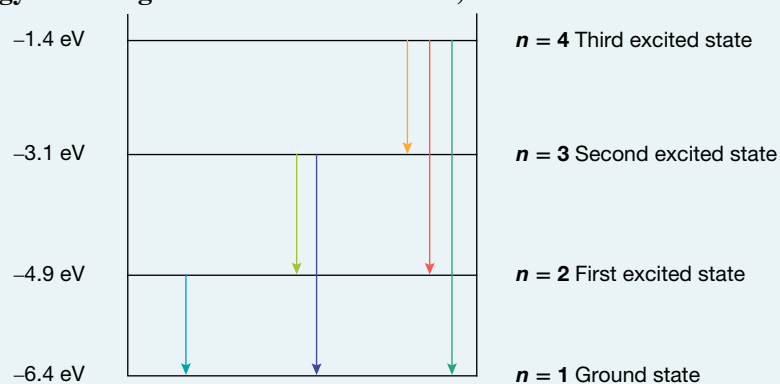
States of the atom are commonly labelled using the terms **ground state** for the lowest energy state (or the zero of energy), followed by the **excited states** at higher energy, often labelled first excited state, second excited state, and so on. The most common choice for the zero of energy is the energy of an electron and proton that are completely free from one another — that is, stationary, at an infinite separation. Using this scale, the energy of an electron bound to a proton in a hydrogen atom is negative. The system of a stationary proton and a separated, freely moving electron has a positive energy that is equal to the kinetic energy of the electron.

It's now time to examine how this explains the emission spectrum of hydrogen (seen earlier in figure 12.5d). Most hydrogen atoms at room temperature are in the ground state. In flames or discharge tubes, atoms are raised to excited states by collisions with other particles. For example, in figure 12.6a, the atom has first been excited into its fourth excited state where it has an energy of -0.5 eV. This is indicated by the upward arrow on the left-hand side of the diagram. Cascading transitions to the ground state are then possible, with a photon emitted during each transition. These are indicated by the downward arrows. Some of these downward arrows are shown in black as the emitted photons are not visible light so are not observed in an emission spectrum. Other photons are emitted as visible colours, which is what we observe in the spectrum. This model of atomic structure neatly accounted for emission spectra.

By collecting an emission spectrum containing many discrete spectral lines and establishing the photon energy associated with each line, it is possible to work backwards to construct an energy level diagram for an atom.

SAMPLE PROBLEM 6

Consider an energy level diagram for a fictitious atom, as shown.



Consider a large population of atoms all excited to the third excited state ($n = 4$), from which an emission spectra is obtainable, resulting in all atoms decaying to the ground state. Calculate all six possible energies in electron volts for photons emitted by the large population of atoms, and arrange them in ascending order.

THINK

- There are six possible transitions:
 - third excited state to ground state (teal arrow)
 - third to first (red arrow)
 - third to second (orange arrow)
 - second to ground (purple arrow)
 - second to first (green arrow)
 - first to ground (blue arrow)

The energy of the emitted photon is calculated by finding the difference between the energies of the states for each transition. The highest energy of any photons emitted by this atom occurs when transitioning from the 3rd excited state to the ground state.

- The remaining five possible photon energies can be calculated in the same way using

$$E_{\text{photon}} = E_{\text{initial}} - E_{\text{final}}$$

- Arrange the photon energies in ascending order.

WRITE

For the $n = 4$ to $n = 1$ transition:

$$\begin{aligned} E_{\text{photon}} &= E_{\text{initial}} - E_{\text{final}} \\ &= (-1.4 \text{ eV}) - (-6.4 \text{ eV}) \\ &= -1.4 \text{ eV} + 6.4 \text{ eV} \\ &= 5.0 \text{ eV} \end{aligned}$$

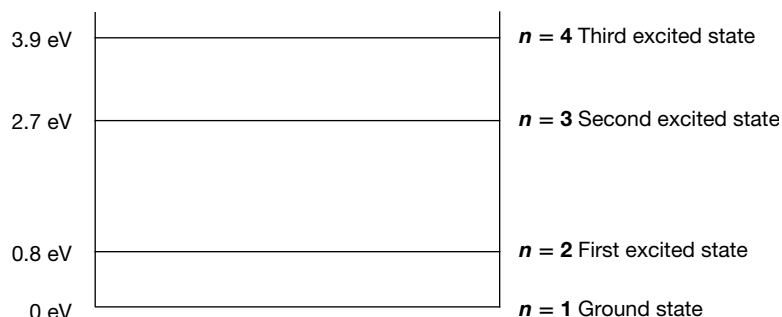
The remaining five calculations give energies of:

- 3.5 eV (third to first)
- 1.7 eV (third to second)
- 3.3 eV (second to ground state)
- 1.8 eV (second to first)
- 1.5 eV (first to ground state).

Arranged in ascending order, the six photon energies are 1.5 eV, 1.7 eV, 1.8 eV, 3.3 eV, 3.5 eV and 5.0 eV.

PRACTICE PROBLEM 6

Consider an energy level diagram for a fictitious atom, as shown.



- Complete the energy level diagram using arrows to show all the possible transitions.
- Calculate the highest energy and hence the frequency of a photon emitted by this atom in the $n = 4$ state.
- Calculate the lowest energy and hence the frequency of a photon emitted by this atom in the $n = 3$ state.

SAMPLE PROBLEM 7

The energies of states of the hydrogen atom are shown in the following table.

H atom state	Energy (eV)
Third excited state $n = 4$	-0.85
Second excited state $n = 3$	-1.51
First excited state $n = 2$	-3.40
Ground state $n = 1$	-13.61

What is the shortest wavelength of light emitted by hydrogen atoms that were initially excited into the third excited state?

 **Teacher-led video:** SP7 (tlvd-0216)

THINK

1. Light of the shortest wavelength is emitted when the photons have the greatest energy (when the atoms experience the greatest possible energy change). This will be the transition to the ground state. You need to calculate the energy in eV and convert into joules. Determine the energy of the photon.
2. Determine the wavelength using Planck's constant and the calculated energy change for the photon (in joules).

WRITE

For $n = 4$ to $n = 1$ transition:

$$\begin{aligned}
 E_{\text{photon}} &= E_{\text{initial}} - E_{\text{final}} \\
 &= (-0.85 \text{ eV}) - (-13.61 \text{ eV}) \\
 &= 12.76 \text{ eV} \\
 &= 12.76 \text{ eV} \times 1.6 \times 10^{-19} \text{ J eV}^{-1} \\
 &= 2.0 \times 10^{-18} \text{ J} \\
 \lambda_{\text{photon}} &= \frac{hc}{E_{\text{photon}}} \\
 &= \frac{6.63 \times 10^{-34} \times 3.0 \times 10^8}{2.0 \times 10^{-18}} \\
 &= 9.7 \times 10^{-8} \text{ m.}
 \end{aligned}$$

This is ultraviolet radiation.

PRACTICE PROBLEM 7

What is the lowest frequency and hence longest wavelength light emitted by hydrogen atoms that were initially excited to the third excited state? The energies of the states of the hydrogen atom are found in sample problem 7.

Resources

 **Video eLessons** The production of atomic spectra (med-0341)

 **Interactivities** Hydrogen emission spectra (int-0755)

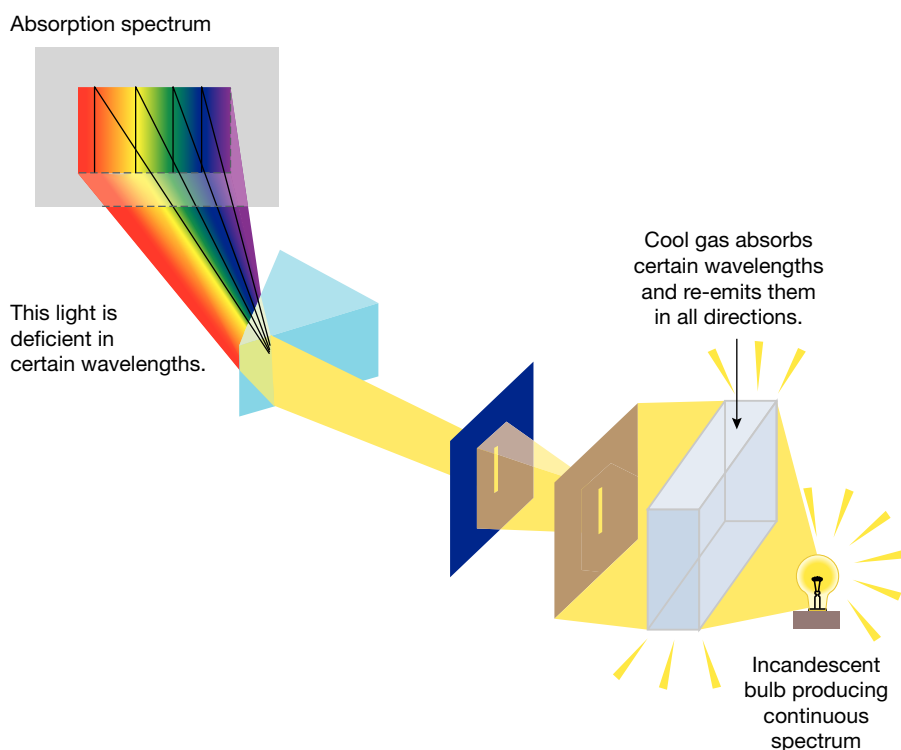
Photon emission by atoms (int-0122)

12.3.2 Atoms absorb photons

Atoms also absorb light. They absorb those particular wavelengths they would emit if the gas were excited. These are the frequencies that correspond to the differences in energy between the energy levels in the atoms. An **absorption spectrum** is a continuous spectrum with a series of dark lines indicating missing frequencies. Absorption spectra are produced by placing a sample of a gas in front of a **continuous spectrum** source, as shown in (figure 12.8).

The atoms making up the gas absorb particular wavelengths, raising electrons within the atoms into excited states. The electrons drop back to the ground state, emitting photons but now in all directions. This means that the original beam of light has very little of those absorbed colours. The continuous spectrum has dark bands. Generally, the dark bands in an absorption spectrum correspond to the bright lines in an emission spectrum of the same gas if it were hot.

FIGURE 12.8 Absorption spectra are produced by a cool gas absorbing particular wavelengths of light. The absorption spectrum consists of a series of dark lines corresponding to missing wavelengths.

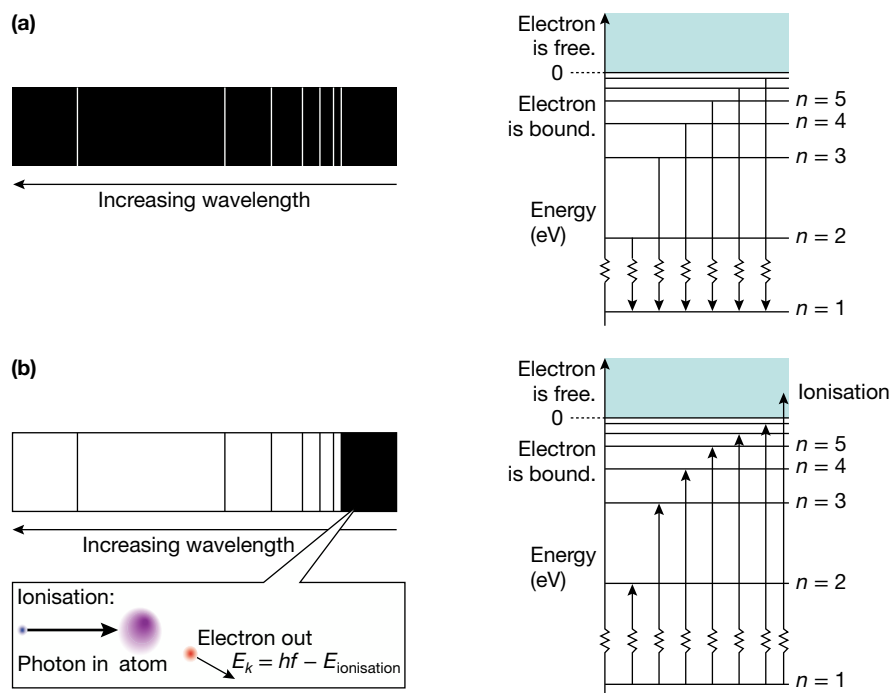


Comparing emission and absorption spectra

As they rely on the same energy level structure, the emission and absorption spectra often appear to be negatives of one another. However, there are differences.

The emission spectrum usually includes lines missing from the absorption spectrum of the same element. For example, the emission spectrum of the hydrogen atom includes lines for transitions to all states of the atom. The absorption spectrum of hydrogen atoms at room temperature, however, contains lines in the ultraviolet region only, each line linked to a transition beginning at the ground state. This is because virtually all atoms are in the ground state at room temperature — to begin with, only $\frac{1}{10^{171}}$ are not! The spectrum of hydrogen in the Sun is a different story. The surface temperature of 6000 K is hot enough for the proportion of atoms in the first excited state to rise to $\frac{1}{10^8}$. Not large, but large enough for their absorption spectrum to be detected.

FIGURE 12.9 (a) Part of the emission spectrum for hydrogen. The only region of the spectrum shown is that in which transitions to the ground state appear. (b) The absorption spectrum for hydrogen. The transfer of photon energy to eject an electron is labelled 'ionisation'. All wavelengths less than the limiting value (that is, photons with energy greater than the limiting value) can be absorbed.



Series of lines in an absorption spectrum converge on a particular wavelength. This wavelength corresponds to the photon energy equal to the ionisation energy of the electron. All light with shorter wavelengths than this limit, and therefore greater photon energy, can be absorbed, removing the electron from the atom completely. As there is no restriction on the energy of a free electron, all photons having energy above the ionisation energy can be absorbed so all light with wavelengths below the limit may be absorbed. This is another example of the photoelectric effect where a minimum photon energy must be reached before electrons will be ejected.

THE BOHR RADIUS AND DISTANCES BETWEEN PROTONS AND ELECTRONS

A hydrogen electron in a stable or stationary state does not move in a circular, or even an elliptical, orbit around the proton — its distance from the proton changes continuously.

In fact the words 'circular', 'elliptical' and 'distance' become inappropriate when an electron is considered not as a particle but as some type of wave phenomenon. To understand and account for emission and absorption spectra, it is better to think of an electron as having no specific location or path; instead, there is only a probability of locating it at various positions. This unpredictability is ultimately related to Heisenberg's uncertainty principle, which asserts that it is not possible to precisely measure both the location and the motion of any object at the same time. This realisation is the cornerstone of contemporary physics and the foundation of quantum mechanics.

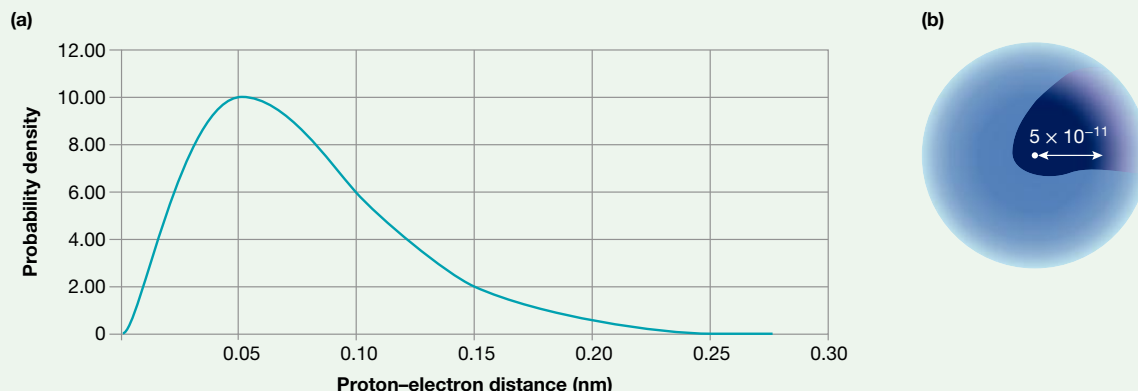
The most probable distance from proton to electron is 5.29×10^{-11} m, corresponding to the peak in the probability density curve.

This distance is called the Bohr radius and is often quoted as the 'radius' of the hydrogen atom. It can be useful to think of the hydrogen atom as having a spherical cloud of negative charge surrounding the proton, representing the unpredictable motion of the electron. The diminishing density of the cloud at large distances from the proton indicates that the electron is less likely to be there.

While the proton–electron distance is not fixed or predictable for a particular state of the atom, the total energy of the atom is predictable. As the electron weaves its intricate path around the proton, its kinetic energy changes, ►

being greater when the electron is closer to the nucleus. However, the total energy *does not* change. There is a transformation between the kinetic energy and electric potential energy. Electric potential energy increases as kinetic energy decreases, and vice versa, keeping the total energy constant.

FIGURE 12.10 (a) The probability of finding an electron a certain distance from the nucleus, and (b) the cloud picture of a hydrogen atom



on Resources

 **Digital document** Investigation 12.1 Spectroscopes (doc-32087)

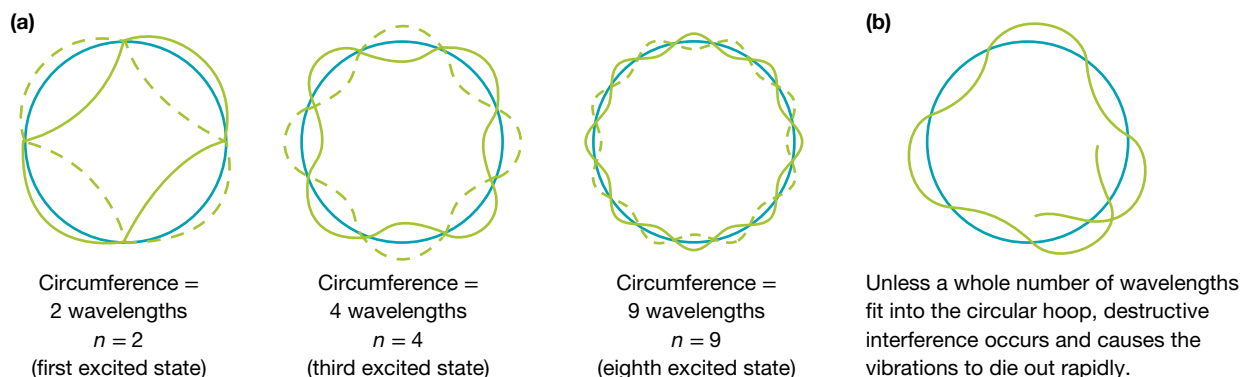
 **Teacher-led video** Investigation 12.1 Spectroscopes (tlvd-0254)

12.3.3 Electrons, atoms and standing waves

Individual electrons act like waves when they are diffracted by atoms in crystals. Do electrons in the atoms also exhibit wavelike properties? They certainly do! Thinking of electrons behaving like waves solved the puzzle of stationary states. This wave model for electrons that are bound within atoms also neatly explained why atoms absorb and emit photons of only particular frequencies, and provided the answers to Rutherford's questioning of the Bohr model of the atom. In essence, only waves whose de Broglie wavelength multiplied by an integer ($n\lambda$) set equal to the circumference of a traditional electron orbit are allowed to exist due to these waves being the only ones able to constructively interfere to produce a standing wave. De Broglie speculated about the electron in a hydrogen atom displaying wavelike behaviour in 1924. A complete description of the hydrogen atom awaited a more sophisticated mathematical treatment called quantum mechanics. The fundamentals of this model were developed by Erwin Schrödinger and Werner Heisenberg later in the 1920s.

Louis de Broglie pictured the electron in a hydrogen atom travelling along one of the allowed orbits around the nucleus, together with its associated wave. In de Broglie's mind, the circumference of each allowed orbit contained a *whole number* of wavelengths of the electron-wave so that it formed a standing wave around the orbit. Thus, $n\lambda = 2\pi r$ or $\lambda = \frac{2\pi r}{n}$ fixes the allowed wavelength. An electron-wave whose wavelength was slightly longer, or shorter, would not join onto itself smoothly. It would quickly collapse due to destructive interference. Only orbits corresponding to standing waves would survive. This is shown in figure 12.11. The concept is identical to the formation of standing waves on stringed instruments.

FIGURE 12.11 A model of the atom showing the electron as a standing wave



It is worth noting that the standing waves produced on a stringed instrument of length l have a series of possible wavelengths $\lambda_n = \frac{2l}{n}$ where n is a positive integer. This series of wavelengths is called a harmonic series. At this level of physics, which is only an introduction to the conceptual nature of quantum mechanics, the harmonic series provides for a series of associated momenta that are discrete in value. This in turn provides for a series of energy states that are also discrete. This connection is in complete agreement with the observation of emission and absorption spectra. When you pluck a guitar string, only certain frequencies are produced. Likewise, when you energise an atom, only certain energy levels are sustainable, resulting in the emission of well-defined frequencies of light in the form of individual photons.

In de Broglie's model of the atom, electrons are viewed as standing waves. It is this interpretation that provides a reasonable explanation for the emission spectra of atoms. It answers Rutherford's remark to Bohr. When a guitar string is plucked, how does it know what frequencies to vibrate at? The answer is the following: the frequencies that equate to the standing waves with wavelengths compatible with the length of the string.

Electrons viewed as standing waves can exist only in stable orbits with precise or discrete wavelengths. This implies that the electrons can only have discrete quantities of momentum. This in turn implies that the electrons can only have discrete amounts of energy. Energy transitions that are made by electrons occur in jumps from one high-energy standing wave to another standing wave of lower energy. In this way, the emission spectra and, hence, absorption spectra can be understood as arising from transitions between quantised energy levels due to electrons having a wavelike character.

It's a consistent story — light displays both wave and particle behaviour and so do electrons and all other forms of matter. The two models are complementary. You observe behaviour consistent with wave properties or particle properties, but not the two simultaneously. Remember how William Bragg expressed it: 'On Mondays, Wednesdays and Fridays light behaves like waves, on Tuesdays, Thursdays and Saturdays like particles, and like nothing at all on Sundays'. This delicate juggling of the two models by both light and matter is known as **wave-particle duality**.

There have been many conceptual hurdles for physicists in arriving at this amazingly consistent view of the interaction between light and matter. Their guiding questions always kept them probing for the evidence. Observations and careful analysis gave them the answers. Imagination, creativity and ingenuity were vital in their search for a more complete picture of light and matter.

It is now known that both light and matter can exhibit both wavelike and particle-like behaviour, depending on the types of experiments performed. For example, when light strikes a material object, it transfers energy as if it is a particle (the photoelectric effect), but when light passes through a narrow opening or a pair of slits, it acts as if it is a wave. Likewise, matter can have work done on it via well-understood forces accelerating it, but matter can also be diffracted when it passes through a crystal, producing diffraction patterns similar to those of X-rays. Also, the behaviour of electrons within atoms can only be understood by treating them as a type of wave phenomena.

A more detailed model for the seemingly paradoxical result of both wavelike and particle-like behaviour for both light and matter was developed in the 1910s and 1920s. The model is called quantum mechanics and, in it, wave and particle behaviour for both light and matter are unified.

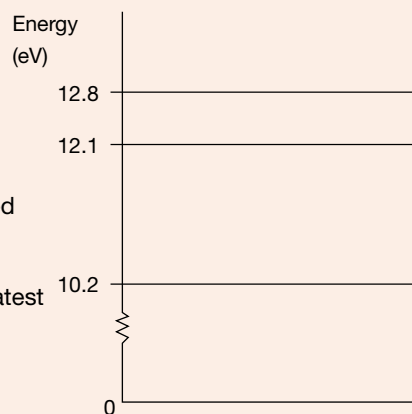
12.3 EXERCISE

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1. In what way is the reddish glow of light from a dying fire different from the reddish glow of a neon discharge tube?
2. Explain why spectral lines in the emission spectrum of an element correspond to absorption lines in an absorption spectrum for the same element.
3. A beam of red and green light appears yellow to a normal human. How could an experiment be devised to decide whether a beam of light that appeared yellow was in fact spectral yellow light or a mixture of red and green light?
4. There are two common ways of depicting the energy levels of an atom. In one method, the ground state is taken to be zero energy and, in the other method, the ionisation energy is taken to be zero. The first excited state of mercury atoms is known to be 4.9 eV above the ground state, the second excited state is 6.7 eV, the third excited state is 8.8 eV, and the ionisation energy is 10.4 eV above the ground state. Using the second method, where the ionisation energy is taken as 0 eV, give the energies of the ground state and the first three excited states. *Note:* Your values will be negative numbers, and a drawing of the energy level diagram will assist you.
5. Hydrogen is the name given to the atom consisting of the least number of particles — one proton and one electron.
 - (a) Explain what the word 'ground state' means when used to discuss atomic structure.
 - (b) Draw a diagram representing the first five energy levels (the ground state plus the first four excited states) in a hydrogen atom with the energy axis drawn to scale and each energy level given based on the ground state (taking the ground state as having zero energy). Use the electron volt as the energy unit. As a starting point, the ionisation energy of hydrogen is 13.6 eV, but you will need to find additional information via the internet or some other source.
 - (c) Conduct research to find out about the Balmer series, the name given to a group of lines that appears in the emission spectrum of hydrogen.
6. Fill in the gaps in the following table.

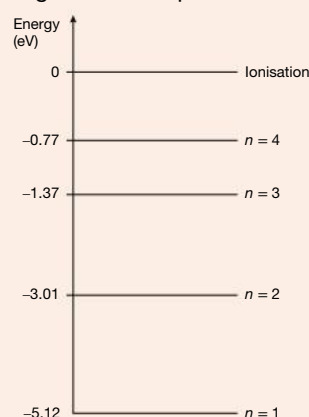
Element	λ (nm)	f (Hz)	E (J)	E (eV)	p (N s)
Red light			3.14×10^{-19}		
Electron				1.96	
Blue light	405				
Electron	405				

7. The ground state and the first three excited states of hydrogen are shown in the diagram at the right. An emission spectrum of hydrogen gas shows many different spectral lines.
 - (a) Copy the diagram and label the ground state and first three excited states.
 - (b) Draw arrows to represent all six possible transitions that may occur when hydrogen atoms in states lower than the fourth excited state emit a photon of light.
 - (c) Calculate the energy of each of the six possible photons.
 - (d) Determine the wavelength of the photon having the least and greatest energy in your answer to part (c).



8. Explain why there are dark lines in an absorption spectrum of a gaseous sample. Why are those particular colours missing from the otherwise continuous spectrum of light passed through a gaseous sample?
9. When sodium chloride (common salt) is placed in a flame, the flame glows bright gold. The diagram at the right shows some of the energy levels of a sodium atom.

- (a) On a copy of the diagram, label the ground state of the atom, and the first excited state.
- (b) Draw arrows to represent the change in energy of atoms in the ground state that absorb energy during collisions with other particles in the flame.
- (c) Calculate the wavelength of light emitted by these atoms as they return to the ground state in a single jump. Which energy change is responsible for the yellow glow?



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12.4 Making light

KEY CONCEPTS

- Compare the production of light in lasers, synchrotrons, LEDs and incandescent lights.

12.4.1 Accelerating charged particles

Accelerating charged particles emit electromagnetic radiation (the electromagnetic spectrum is shown in figure 12.13). Radio and television transmitters are examples of this. They generate radio waves by driving a high-frequency electric current up and down an aerial. In contrast, X-rays are generated when fast-moving electrons decelerate on striking a target — for example, in an X-ray machine or in a CRT television screen. In contrast yet again, a high-frequency oscillator generates microwaves by rapidly reversing the direction of an electric current — for example, in the magnetron of a microwave oven, the magnetron generates electromagnetic waves at the resonant frequency of water molecules. This makes the molecules vibrate faster and increases the temperature of the food.

FIGURE 12.12 The magnetron of a microwave oven

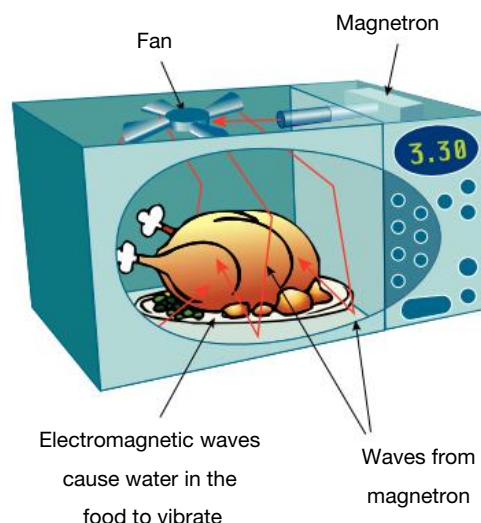
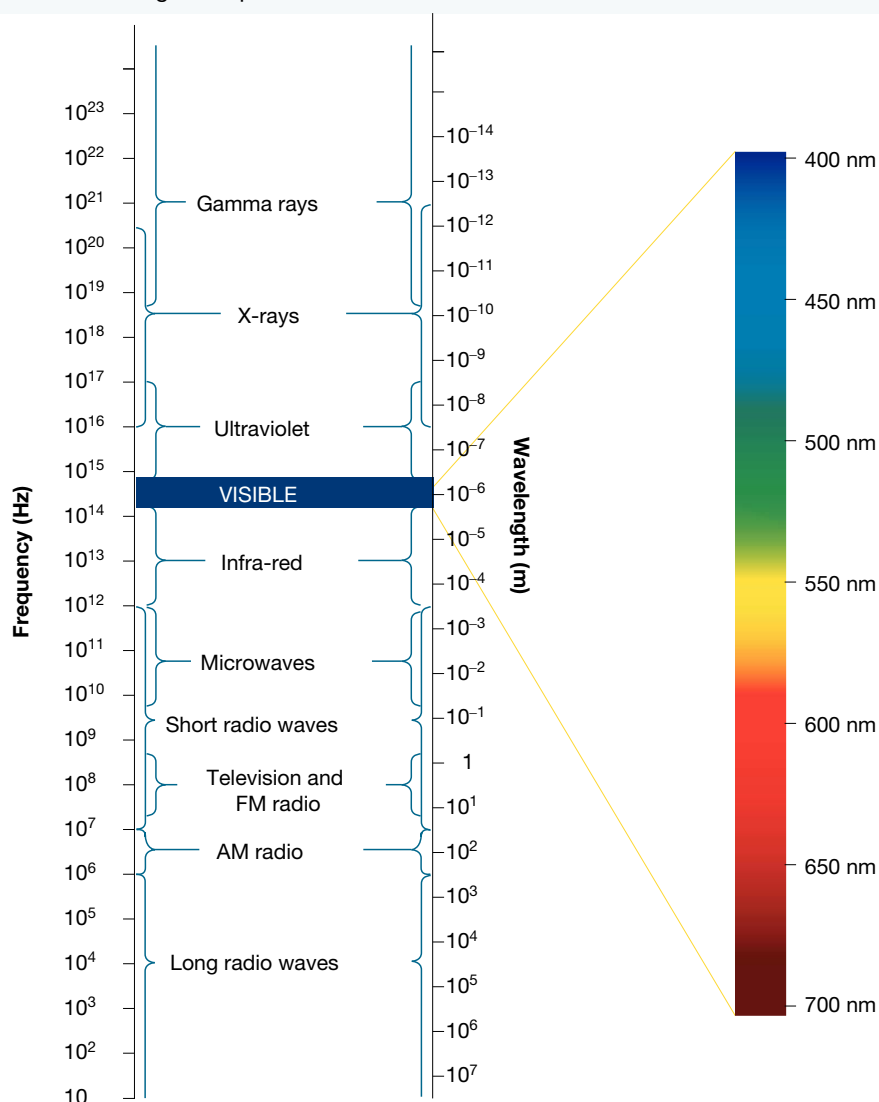


FIGURE 12.13 The electromagnetic spectrum



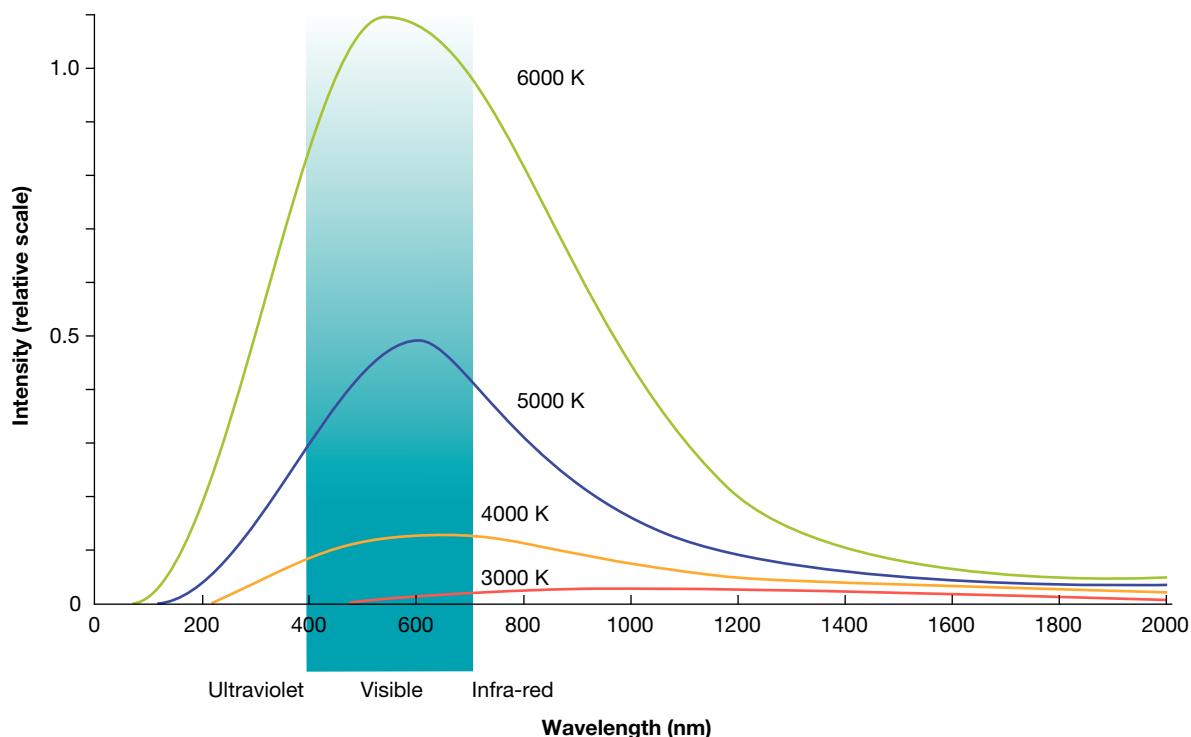
12.4.2 Thermal radiation — randomly accelerated charged particles

Thermal radiation is the range of radiation given off by an object due to its temperature. It results from the thermal movement of atoms and from collisions between the outer-shell electrons of adjacent atoms.

Whenever a force is applied to an electron, the electron will accelerate and emit a photon. Collisions between atoms can cause the outer-shell electrons to accelerate and thus emit photons. This is known as thermal radiation. The spectrum of thermal radiation depends on the distribution of speeds of the atoms in the material.

If a material is opaque (cannot be seen through), it radiates a continuous spectrum. This spectrum has a peak value at a wavelength that depends on the temperature of the material. As the temperature increases, the wavelength emitting the greatest number of photons decreases. Figure 12.14 shows how the intensity of radiation is distributed over a range of wavelengths for an ideal **black body** at different temperatures. Note that the overall intensity increases as the temperature increases, and that the wavelength with the peak intensity decreases as the temperature increases. The **thermal spectrum** of a black body is continuous. This is different to the **line emission spectrum** for individual atoms.

FIGURE 12.14 Thermal radiation for an ideal black body



12.4.3 Incandescent light sources

Incandescent light sources emit light because of their temperature. They are thermal sources. Stars, candles and light bulbs with filaments are all incandescent light sources.

As an iron rod is heated in a furnace, its temperature increases. At first it emits radiation only in the infra-red part of the electromagnetic spectrum. As it gets hotter, it starts to emit red light. It continues to heat up and emits more light in the visible region of the spectrum until it becomes white hot.

The colour of gases in a flame indicates the temperature of the flame. The blue part of a Bunsen burner flame is the hottest. Blue light has a shorter wavelength and more energy than red light. The light emitted by a candle is caused by the thermal motion of the atoms and molecules in the gases of the flame.

Incandescent light bulbs emit light by using an electric current to heat a tungsten filament. Tungsten is used because it is a metal and has a high melting point. The range of colours of light emitted depends on the temperature of the filament. The atoms in the filament vibrate violently when an electric current passes through it. Collisions between outer-shell electrons produce the light. Incandescent light bulbs are filled with an inert gas so that the metal in the filament will not be able to take part in chemical reactions and disintegrate. The filament reaches temperatures greater than 2800 K.

12.4.4 Fluorescent light sources

Fluorescence occurs when an atom is excited from one energy state to another by the absorption of a photon — it might then return to the ground state by making two or more jumps. This can occur only if there are two or more allowable energy states in between. At each jump, the atom may emit photons with a smaller energy and frequency than the absorbed photon. This process is known as fluorescence.

Many fluorescent light sources are used for indoor and outdoor lighting. Most of these produce visible light when an electrical current passes through a gas at a very low pressure. The gas is contained in a glass tube with electrodes at each end. The atoms or ions of the gas become excited when they collide with electrons emitted by the electrodes. This means that electrons in the atoms or ions are sent into a high energy level. When they fall to lower states, they emit photons of light (as seen in figure 12.15). Some of these photons are in the visible part of the electromagnetic spectrum. This process produces a line emission spectrum that is unique for each gas.

Examples of the gases used in discharge tubes include the noble gases (neon, argon and xenon), and metal gases such as sodium (used in streetlights) and mercury (found in household fluorescent tubes). Each gas produces characteristic colours that are determined by the colours present in the line spectra. This is why sodium streetlights are yellow and neon lights are red. Mercury gas discharge tubes mainly emit ultraviolet light.

Household fluorescent light tubes are filled with mercury vapour and argon gas at low pressures as shown in figure 12.17. The tubes are coated on the inside with phosphor particles. Phosphor particles absorb ultraviolet light and later re-radiate the energy as visible light by the process of fluorescence. You may have noticed that fluorescent lights keep glowing for several minutes after they are switched off. Fluorescent lights use less electrical power to produce the same amount of illumination as incandescent light bulbs; therefore, they cost less to run. Energy efficient lights are usually thin fluorescent light tubes bent into a compact shape and mounted so they can be fitted to the light sockets used for incandescent globes.

FIGURE 12.15 Fluorescence

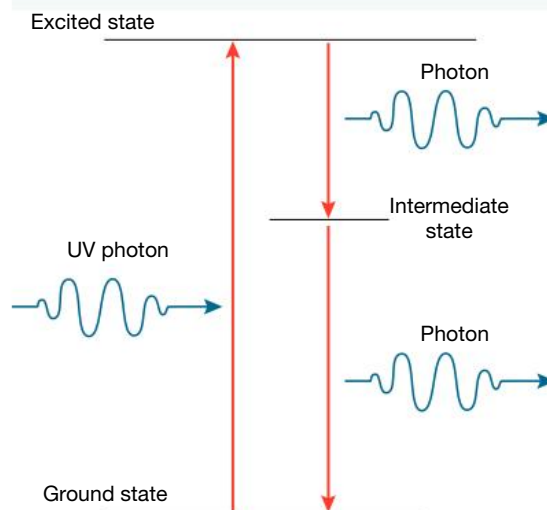


FIGURE 12.16 Gases excited by electrical discharge produce line emission spectra such as these for sodium, mercury and neon, shown from top to bottom respectively.

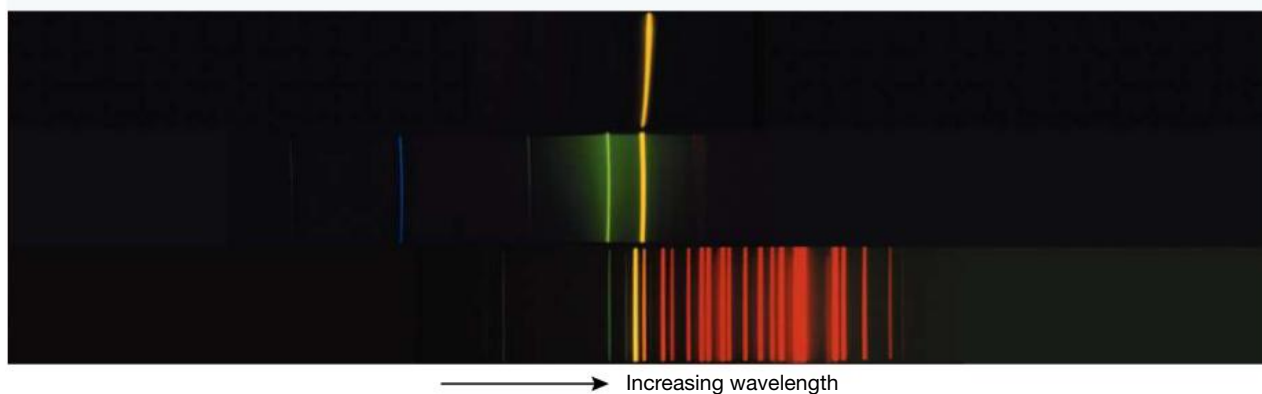


FIGURE 12.17 A household fluorescent light tube

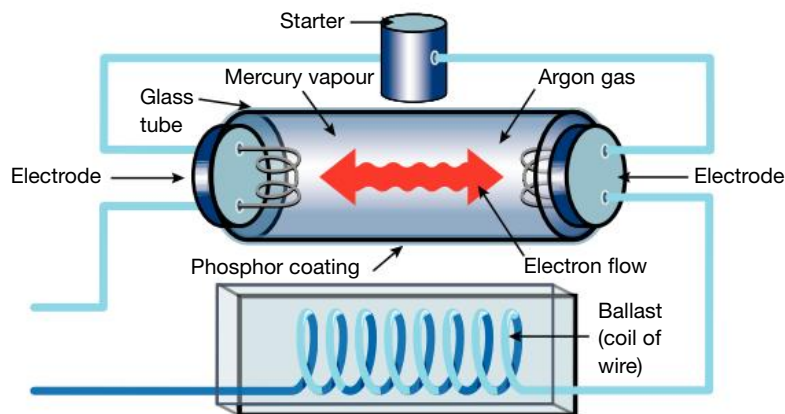
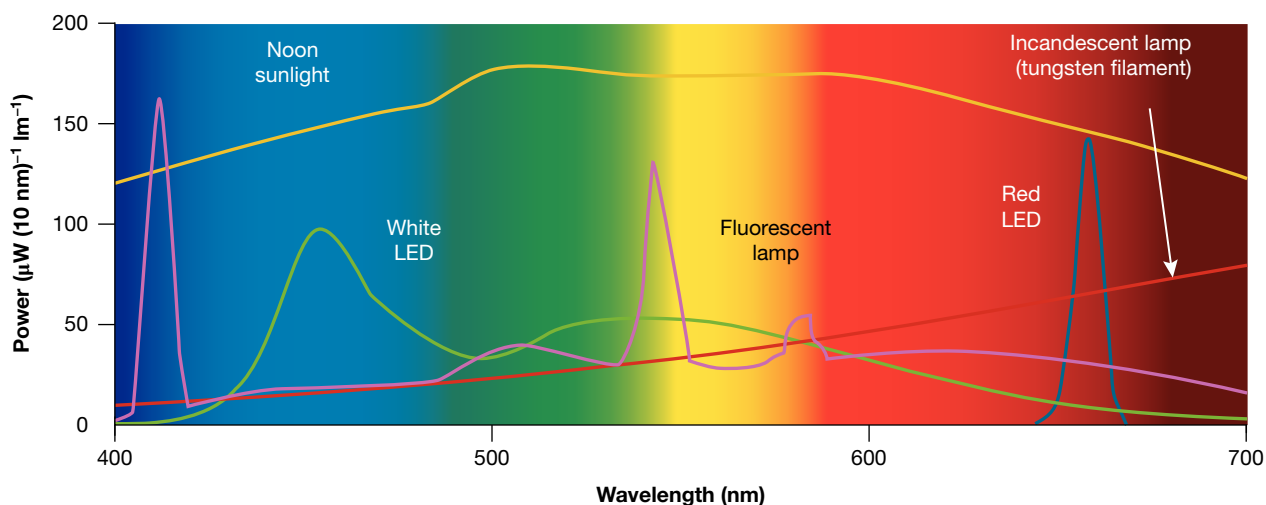


Figure 12.18 shows the spectra from some common light sources. The Sun and a tungsten filament lamp have the continuous spectrum of thermal emitters, whereas a mercury vapour lamp has the line spectrum of a fluorescent light source.

FIGURE 12.18 Spectra from some common sources of visible light



12.4.5 Light-emitting diodes

A **light-emitting diode (LED)** is a small semiconductor diode that emits light from its p–n junction when it is forward biased and a current passes through it. The p–n junction forms between two types of semiconductors — a positive side (p-type) and a negative type (n-type). **Semiconductors** are materials whose properties are midway between those of a good conductor and a good insulator. LEDs are used as light sources in optical-fibre systems. They can be made to emit any colour (red, green and yellow are the most common) by the choice of impurities added to the base semiconductor used in their construction. As electrons move across the p–n junction, they lose electrical potential energy ΔE (sometimes referred to as band gap energy), and the subsequent emission of a photon of frequency f results, such that $\Delta E = hf$. The larger the band gap, the greater the energy and, hence, the higher the frequency of the emitted photon. They can turn on and off rapidly, making them suitable for transmitting digital signals.

12.4.6 Lasers

The word laser is the acronym for ‘light amplification by stimulated emission of radiation’.

Lasers produce light in a fascinating way. Ordinary photon emission is called spontaneous emission, but the atoms in a laser undergo stimulated emission. When an atom or ion that is already in an excited state encounters a photon that matches its excitation energy, the atom or ion sometimes responds by dropping to the lower energy level, emitting a photon that is identical to the first photon, in energy, phase and direction. This process is called stimulated emission. As you might imagine, these two photons could stimulate the emission of two more photons, resulting in four identical photons, then, eight, sixteen and so on — like a nuclear chain reaction.

For the process to work, there must be a greater number of atoms in the upper state than in the lower state. Often a lamp is needed to *pump* the laser, providing photons to excite the atoms or ions into the upper energy level ready for stimulated emission. To increase the probability of a photon stimulating another photon emission, the laser cavity that contains the gas has mirrors on both ends, reflecting photons back and forth through the lasing material many times. The mirror at one end of the cavity is only partially reflecting. The photons passing through it form the laser beam. The distance between the mirrors is a whole number of half-wavelengths, so a standing wave is set up between them.

The colour of laser light is determined by the energy level structure of the atoms or, for some lasers, the ions, which emit the laser’s characteristic photons.

FIGURE 12.19 (a) The bright, intense light of a laser, and (b) operation of a laser

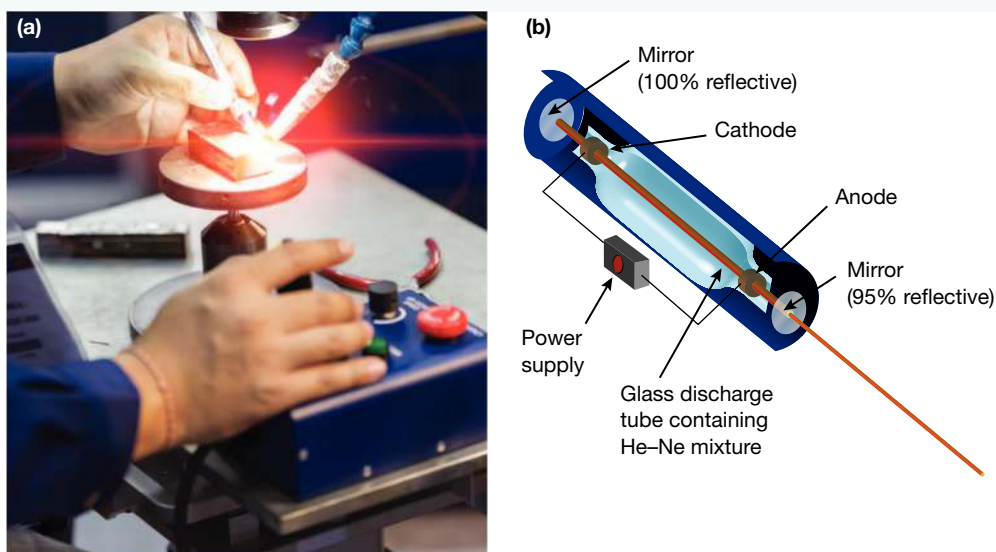
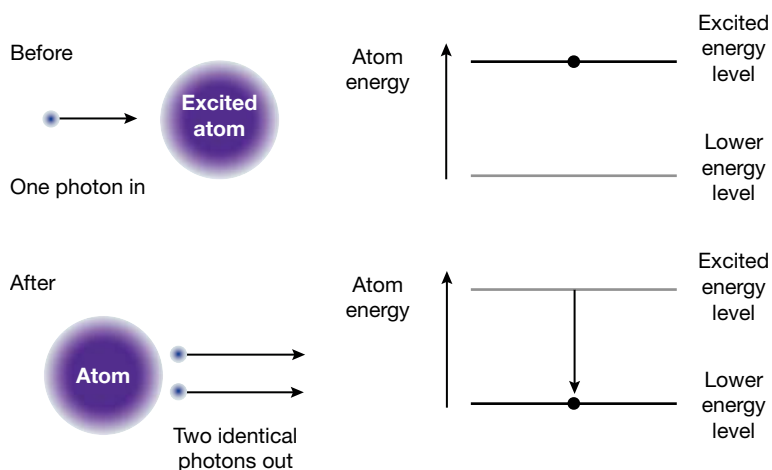
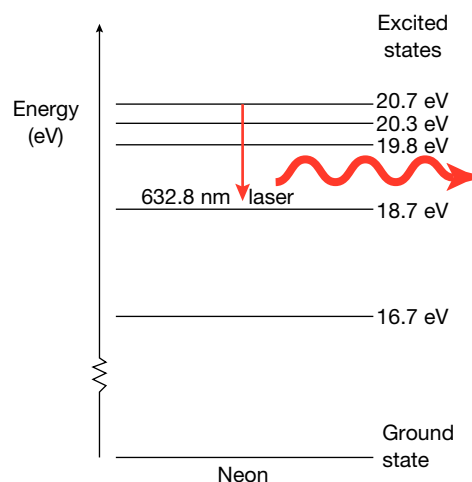


FIGURE 12.20 Stimulated emission produces identical photons.



The warning signs make it clear — lasers are dangerous. Do not look into the laser while it is on! Even though the power rating on a helium–neon laser found in a school laboratory is typically 1 mW compared to the 75 W of a conventional light bulb, the laser converts that energy into light much more efficiently. A laser also concentrates the photons it produces into a much smaller area, delivering a much greater intensity. Light emitted from a laser is said to be **coherent** because all the photons emitted are in phase. This coherence leads to particularly intense light due to constructive interference between in-phase photons.

FIGURE 12.21 The energy ladder for neon atoms in a helium–neon laser, showing the lasing transition.



12.4.7 Synchrotron radiation

Synchrotron storage rings are designed to produce synchrotron radiation, the electromagnetic radiation emitted when charged particles are accelerated, generally in circular motion such as at the Australian Synchrotron.

Synchrotron radiation is emitted as photons that form a narrow cone as they head towards the target. The main characteristics of synchrotron radiation are:

- **Divergence.** The beam of radiation spreads out like a cone as it travels down the beamline. Typically a beam cone would have a cone angle of a few microradians — that is, less than half of one thousandth of a degree, as seen in figure 12.22.
- **Brightness.** The intensity of the beam is hundreds of thousands times greater than that of conventional X-ray tubes. Brightness can be understood as the number of photons every second. It is more properly measured as the number of photons emitted per second per square millimetre of source size, per square milliradian of cone angle within a specific frequency range. Brightness can be as high as 10^{19} photon s^{-1} mm^{-2} mrad^{-2} .
- **Spectrum.** Synchrotron radiation is mostly in the form of X-rays, as they are the most useful. However, radiation across the electromagnetic spectrum, from infra-red upwards, can be produced. The spectrum is also continuous, which means there are no gaps or missing frequencies. Any frequency can be found in the range. The shorter the wavelength, the more energetic the photon, as seen in figure 12.26.

FIGURE 12.22 Cone of radiation showing cone angle. The size of the cone angle is a few microradians, which is less than half of one thousandth of a degree.

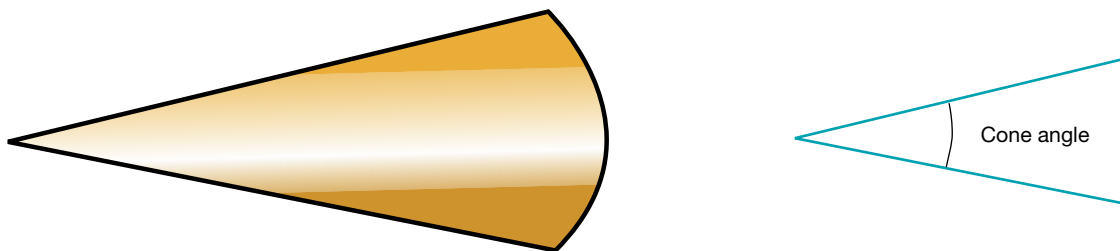


FIGURE 12.23 Brightness of different sources

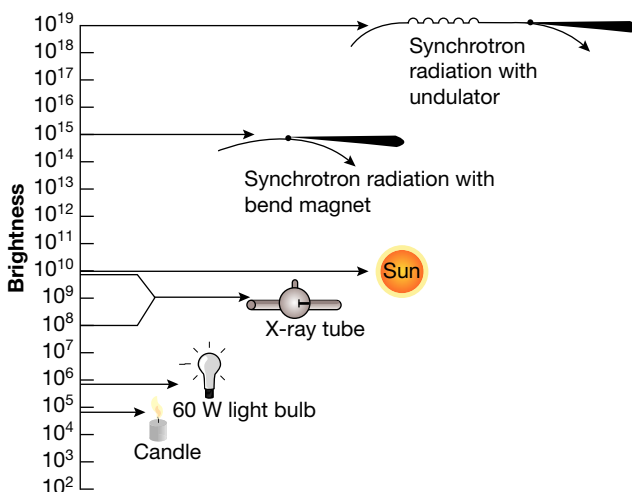
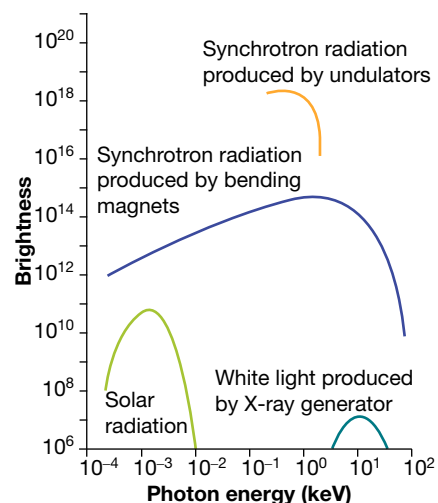
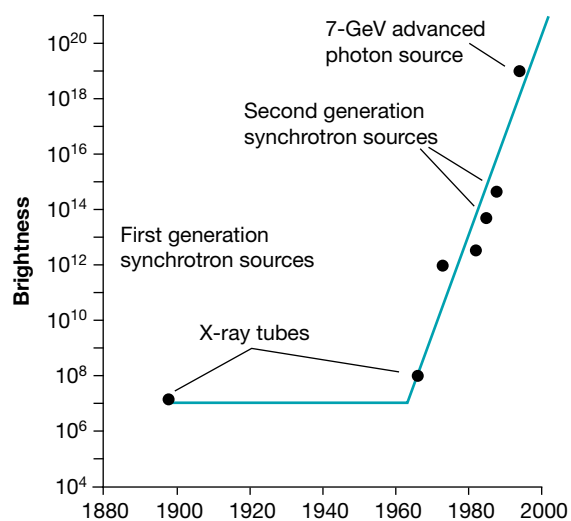


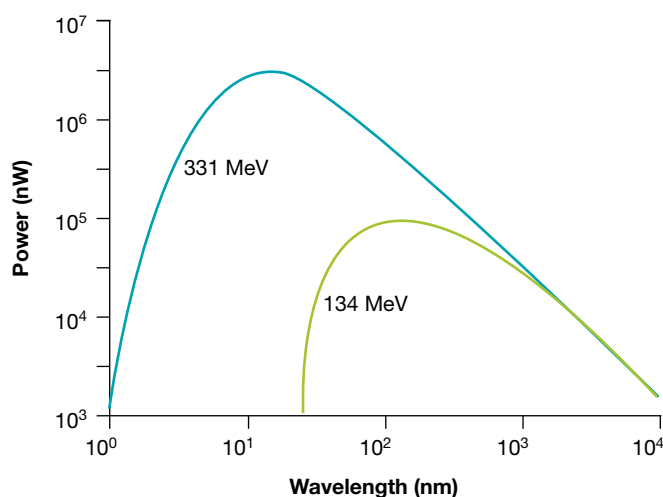
FIGURE 12.24 Brightness of different energy sources



Source: © Australian Nuclear Science and Technology Organisation. www.ansto.gov.au

FIGURE 12.25 Brightness of synchrotrons

Source: © Australian Nuclear Science and Technology Organisation. www.ansto.gov.au

FIGURE 12.26 Spectrum of synchrotron radiation

- **Polarisation.** The radiation from a synchrotron is polarised. That is, the X-rays consist of photons whose electric and magnetic fields all oscillate in one plane, not in any arbitrary plane as is the case for unpolarised radiation.
- **Duration.** Synchrotron radiation comes in pulses, typically lasting about one billionth of a second.

TABLE 12.1 Comparisons of radiation: a synchrotron, a laser and an X-ray tube

	Brightness	Spectrum	Divergence
Synchrotron	Extremely intense	Continuous and wide	Very narrow
Laser	Very intense	Single frequency	Narrow
X-ray tube	Intense	Narrow, continuous but not smooth	Wide

These features allow the X-rays to be used to investigate the fine structure of many materials — that is, to locate specific atoms in a molecule, even a large molecule such as haemoglobin, which is found in red blood cells. This information is of value to researchers across a range of fields, because it enables them to answer such questions as the following:

- What are the differences between malignant and non-malignant brain tumours?
- What is the structure of material, such as semiconductor **nanocrystals**, which may be used in the next generation of computers?
- What are the steps or dynamics of a chemical reaction, either an industrial situation or a biological one?

To get some idea of how X-rays can answer these questions, going back in time to their discovery is required.



Resources



Weblink Photonics resources for teachers

12.4 EXERCISE

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1. The light from a red light-emitting diode (LED) has a frequency of 4.59×10^{14} Hz. What is the energy change in electrons within atoms that produce this light?
2. Light of wavelength 420 nm is absorbed by gas consisting of helium atoms.
 - (a) Explain in terms of energy transfer to the atom why the light is absorbed.
 - (b) Calculate the increase in energy of an electron within a helium atom that has absorbed a photon of wavelength 420 nm.
3. Describe the main features of light emitted by the following objects, using these descriptors: continuous spectrum / discrete spectrum; temperature related / temperature independent; monochromatic / polychromatic; coherent/incoherent; and polarised/non-polarised.
 - (a) An incandescent light globe
 - (b) A candle
 - (c) The Sun
 - (d) A white-hot bar of iron
 - (e) A fluorescent light tube
 - (f) An LED
 - (g) A laser
4. Explain why different LEDs can emit different colours.
5. An LED emits light of wavelength 5.8×10^{-7} m. Calculate the band gap of the semiconductor material in the LED.
6. The band gap in an LED is 1.8 eV. Calculate the average wavelength of light emitted by this LED.
7. Explain what is meant by the word 'coherence' when applied to photons of light.

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12.5 Experiments exploring the duality of waves and particles

KEY CONCEPTS

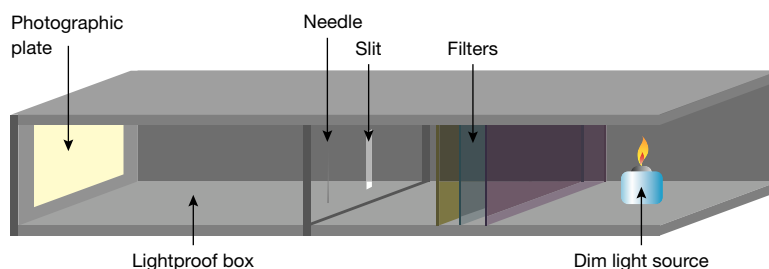
- Interpret the single photon/electron double-slit experiment as evidence for the dual nature of light and matter
- Explain how diffraction from a single-slit experiment can be used to illustrate Heisenberg's uncertainty principle
- Explain why classical laws of physics are not appropriate to model motion at very small scales.

12.5.1 Photons have wave properties too

A beam of light isn't required to observe wave effects — every single photon has wave properties. Geoffrey Taylor set out to demonstrate this in 1909, while he was a student at the University of Cambridge. Taylor photographed the diffraction pattern in the shadow of a needle, but his photograph took three months of light exposure to produce. He used an extremely dim source, a gas flame, together with several smoked glass screens, to illuminate the entrance slit of a light-tight box. Taylor measured the light intensity entering the box, and estimated that only 10^6 photons entered the box each second. This may not sound like a low intensity, but with a photon speed of 3.0×10^8 m s⁻¹, the average distance between photons was 300 m!

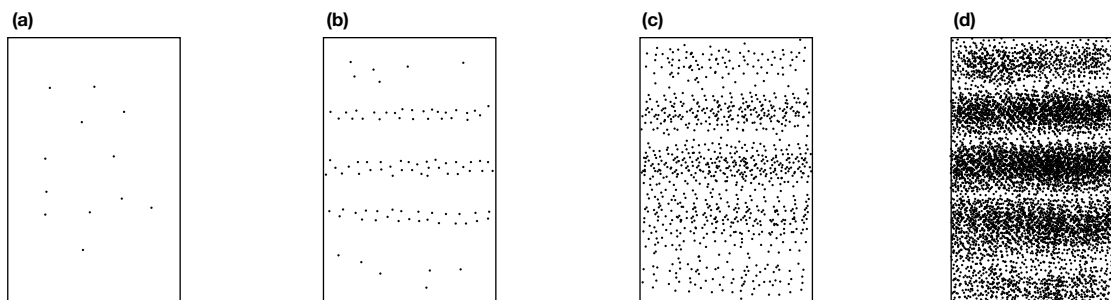
Using a box 1 m long, Taylor could be sure that rarely was there more than one photon travelling through it at any one time, so a vast majority of photons travelled through the box unaccompanied. An image appeared on the photographic plate after three months just as Taylor expected — a pattern of light and dark bands in the shadow of the needle. Taylor compared it to the pattern obtained in a short time with an intense light source and stated, ‘In no case was there any diminution in the sharpness of the pattern’. His experiment demonstrated that interference occurred photon by photon, and that the wave of a single photon filled the box, interfering with itself as it diffracted past the edges of the needle.

FIGURE 12.27 Taylor’s experiment



Taylor’s experiment invites one to imagine watching an interference pattern build up on the photographic plate. The first few photons would produce an apparently random sprinkling of spots, each spot due to a single photon changing the chemical state of an ion in the photographic film. As the spots accumulated, they would start to overlap and, gradually, a pattern would emerge from the randomness. During this process, you would never be able to predict precisely where the next photon would strike the plate. The pattern predicted by the wave nature of the light would allow only the prediction of the *probability* of a photon reaching a particular point. This pattern of probabilities would be clear only after many photons had made their mark.

FIGURE 12.28 Imagine the gradual build-up of photon spots into a double-slit interference pattern.



Taylor’s experiment is a beautiful demonstration of wave–particle duality. The wave and particle characteristics of light are entangled and cannot be separated. Both models are needed. In fact, even when light is travelling particle by particle, its wave characteristics are there at the same time, determining the outcome.

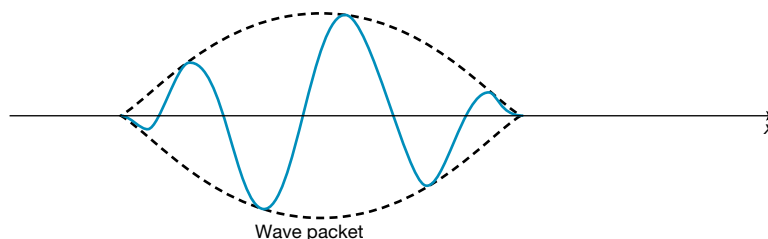
Similar experiments have been carried out with electrons and neutrons and, more recently, with large molecules. In all cases, the wavelike behaviour of these individual entities when passing through openings has demonstrated wave–particle duality in the form of diffraction effects. It seems that the entities pass through the opening and self-interfere in the process. Importantly, they do this one entity at a time. Over an extended period, a statistical distribution builds up of where these entities go, recorded by where they strike a screen. The distribution is consistent with a wave model analysis for coherent waves of the one wavelength passing through an opening, whether it is a single slit, a double slit or any complicated array of openings.

12.5.2 Heisenberg’s uncertainty principle

In the 1920s, as quantum mechanics was being developed, it became apparent that the exact location of an object, x , and the exact momentum of the object, p , were impossible to know simultaneously with complete precision. This applied to both light and matter. In essence, if you knew exactly where an object was, you would not know exactly what it was doing, and vice versa. Curiously this realisation is not unlike one of Zeno’s paradoxes, articulated over 2000 years ago, relating to the motion of an arrow. In modern terms, the uncertainty principle can be written in terms of the uncertainty in x , Δx , and the uncertainty in p_x , Δp_x , where x is the position and p_x is the momentum of an object parallel to the x -axis.

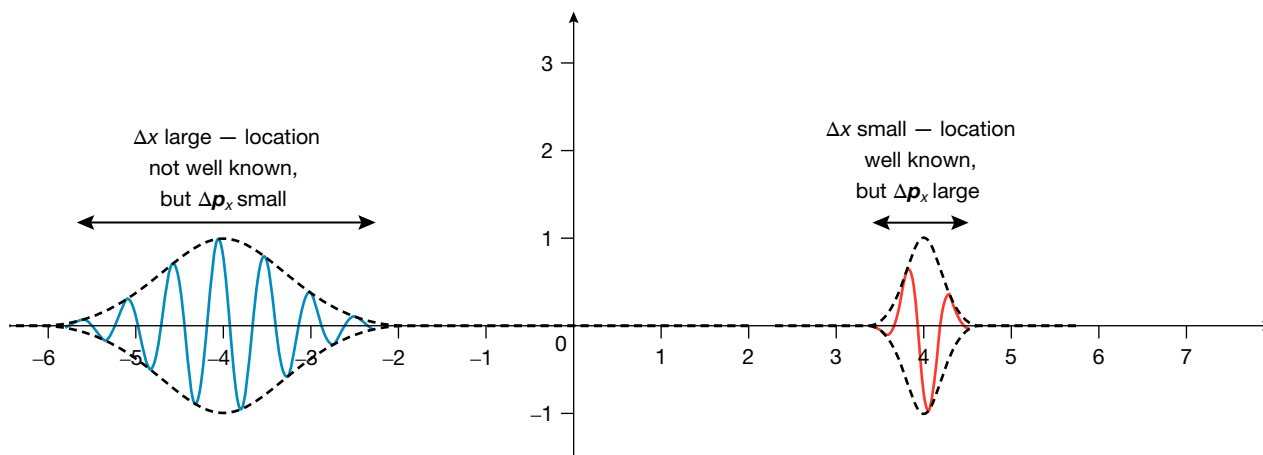
Before continuing, the concept of the ‘wave packet’ needs to be introduced. A wave packet is a mathematical entity that has two features. It is a periodic function and it has an amplitude that varies. From this function, the position of the entity can be recorded with some imprecision. The momentum of the entity can also be recorded, since the function has a wavelength, but this also is imprecise.

FIGURE 12.29 A wave packet



Recall that the momentum of an object is given by the equation $p = \frac{h}{\lambda}$. If the wavelength of an object cannot be precisely measured, then the momentum of that object is also uncertain. Figure 12.30 illustrates two wave packets.

FIGURE 12.30 Two wave packets — a packet with a large Δx (left), and a packet with a small Δx (right)



In figure 12.30, the wave packet on the left has a large uncertainty in location — Δx is large — but the packet contains enough information to precisely determine the wavelength and hence the momentum. In the wave packet on the right, however, Δx is small and, as a consequence, the wavelength cannot be as precisely determined. Hence, there is an intrinsic uncertainty, Δp_x , in being able to determine the object's momentum.

A common form of Heisenberg's uncertainty principle asserts that:

$$\Delta x \times \Delta p_x \geq \frac{h}{4\pi}$$

where: Δx is the uncertainty in the position

Δp_x is the uncertainty in the momentum

$h = 6.63 \times 10^{-34} \text{ J s}$

As an introductory example, say that the position of an electron along the x -axis is uncertain to the extent that $\Delta x = 1 \times 10^{-10} \text{ m}$. Using the inequality introduced in the preceding pink box, this would imply that the uncertainty in the momentum of the electron, Δp_x , was approximately $5 \times 10^{-25} \text{ N s}$.

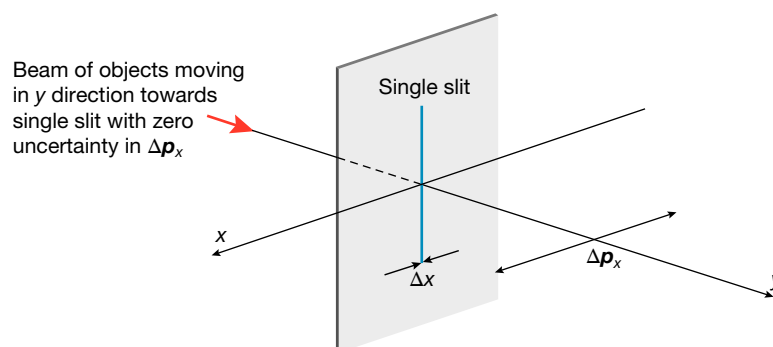
Importantly, it is not the position or momentum of an object that is being discussed, but rather the uncertainty or inherent error in these quantities. Decreasing the uncertainty in x would serve to increase the uncertainty in p_x , the momentum of the electron parallel to the x -axis. The more confined or well known that the electron's position is along the x -axis, the more uncertain its motion becomes along that axis, because its momentum becomes more uncertain. This concept can be used to appreciate why electrons in atoms are simultaneously delocalised and their motion unpredictable. But it also helps in the appreciation of the significance of single-slit diffraction, where a beam of objects spreads out after traversing an opening. Traditionally, these objects have been photons or subatomic particles such as electrons but, recently in Austria, a research team succeeded in demonstrating diffraction effects using very large molecules.

Now consider a beam of objects moving in a fixed direction at a steady rate but heading straight towards a single slit of width Δx . This opening defines not only the width of the beam as the objects move from one side of the slit to the other side (saying that the objects went through the slit is to be avoided) but also the extent of the uncertainty, Δx , in the direction perpendicular to the beam. Because of this confinement associated with the width of the slit, the objects will have an uncertainty of Δp_x associated with their movement on the far side of the slit: $\Delta p_x \geq \frac{h}{4\pi \Delta x}$. It is clear to see that, when the width of the slit is smaller, Δx is smaller and that the uncertainty in the momentum, Δp_x , is larger.

It should not be surprising to find objects leaving the slit with momentum directed either to the left or to the right of the slit, in apparent violation of the conservation of momentum. This is because objects passing through an opening may change direction due to the uncertainty principle. The smaller the opening is, the more likely that a change in the direction of an object in the beam will occur as it emerges from the slit.

From diffraction experiments it is known that reducing the width of the opening causes the diffraction pattern to spread out, and now an explanation exists for why this is the case. The spreading out is due to the uncertainty of the momentum of the beam of particles along the x -axis — the bigger the width of the single slit, the smaller the uncertainty in the momentum of the objects in the beam, and the higher the probability that they continue to travel in the same direction they were travelling in on the other side of the slit. This relationship is illustrated in figure 12.31, where a beam of objects is incident on a single slit of width Δx . The beam before the slit is directed along the y -axis with no momentum in the x -axis. The objects on the other side of the slit have an uncertainty in their momenta represented by the double-ended arrow parallel to the x -axis due to traversing the single slit. It is the presence of the single slit that creates an uncertainty in the position of an object in the beam parallel to the x -axis, which in turn is associated now with an uncertainty in the momentum of the beam along the x -axis according to the Heisenberg uncertainty principle.

FIGURE 12.31 A beam of objects moving in the y -direction towards a single slit with zero uncertainty in Δp_x



Again, it is important to avoid saying that the objects passed through the slit; it is simply that at one stage they were on one side of the slit and, later in time, they were on the other side of the slit. Using this language ensures that the problem associated with a similar double-slit experiment is avoided: that is, if an object, be it a photon or a piece of matter, is on one side of the pair of slits and then later on the other side, which opening did the object pass through? Also avoided is any problem with a beam of objects spreading out when traversing a narrow opening. In applying quantum mechanics to a double-slit type experiment, it is not helpful to ask the obvious question of which slit the object passed through. Experiments designed to measure which of the two slits an object passes through fail to simultaneously detect the interference pattern associated with a double slit when researchers measure which opening an object passes through — just as in a single-slit experiment researchers cannot simultaneously observe a diffraction pattern and where an object is as it passes through the single slit.

Heisenberg's principle can be understood on many levels, but a rigorous and sophisticated interpretation is beyond the current course due to its mathematical complexity. A simple explanation is more helpful at this stage.

In order for the wavelength of a wave to have a measurable value, the wave should consist of a least one cycle. The greater the number of complete cycles, the easier it is to ascertain a value for the wavelength. For a wave of less than one cycle, the error associated with any wavelength measurement would increase. This means that, for a small error assessment of an object's momentum, its associated wave should consist of many cycles: the more cycles, the smaller the error in momentum, due to a more accurate result for the wavelength. However, a wave pulse consisting of many cycles implies that the exact location of the object associated with the wave is more uncertain; the only thing known is that the object is likely to be found somewhere between the start and finish of the wave packet. Hence, to measure what an object is doing (via its momentum), knowing where it is located is forsaken, and vice versa.

This trade-off in knowledge, arising because both light and matter manifest both particle (localised) and wave (delocalised) behaviours, forms the basis of the Heisenberg uncertainty principle. The uncertainty principle spelled the end for determinism, a philosophical belief arising from Newtonian mechanics in which the universe is considered to be a machine fully explainable by forces alone.

PROBABILITY DENSITY FUNCTION

For the interested reader, it is worth mentioning that the variables x and p_x are, in fact, probability density functions indicating the probability of finding an object at a point or the probability of having a particular momentum. The quantity Δx is the standard deviation of x , giving information about the distribution in location of an object, and Δp_x is the standard deviation of p_x , giving information about the momentum distribution of an object in the x direction.

Finally, each of the two variables x and p is the Fourier transform of the other. The variables x and p are referred to as complementary variables, and a Fourier transform is a mathematical process for finding one complementary variable given the other, for example, finding p given x or vice versa. Another pair of complementary variables

is energy, E , and time, t . Not surprisingly, there is an uncertainty principle here as well: $\Delta E \times \Delta t \geq \frac{h}{4\pi}$. This

relationship can be interpreted as stating that energy conservation may be violated by an amount ΔE provided it is done within a time Δt consistent with the Heisenberg inequality, just as how momentum conservation may be violated by an amount Δp_x provided it is done within an interval of space Δx .

It is a significant intellectual breakthrough to not only have rules about nature but also have rules about how to break or violate those rules. You will learn more about this if you study physics at university.

SAMPLE PROBLEM 8

A research scientist is working with a beam of photons produced by a laser of wavelength 640 nm. The beam of photons is directed onto a single slit. A screen is positioned on the other side of the slit, and a single-slit diffraction pattern is observed. Consider one of the photons in the beam.

- Determine the momentum of this photon in the direction of the beam and state the momentum perpendicular to the beam before the photon reaches the slit.
- The photons are incident on a narrow single slit of width 3.2×10^{-7} m. Calculate the uncertainty in the momentum of the photon perpendicular to the beam when it appears on the other side of the single slit.
- Explain in terms of the Heisenberg uncertainty principle why a traditional diffraction pattern would be observed in terms of the momentum in the direction of the beam compared to the momentum uncertainty perpendicular to the beam.

 Teacher-led video: SP8 (tlvd-0217)

THINK

1. Use the relation $p = \frac{h}{\lambda}$ to calculate the momentum of the photon in the direction of the beam.
 2. Determine the momentum perpendicular to the beam before the photon reaches the slit.
- b. Use the relation $\Delta x \times \Delta p_x \geq \frac{h}{4\pi}$ with $\Delta x = 3.2 \times 10^{-7}$ and solve for Δp_x .

WRITE

$$\begin{aligned} \text{a. } p &= \frac{h}{\lambda} \\ &= \frac{6.63 \times 10^{-34}}{640 \times 10^{-9}} \\ &= 1.0 \times 10^{-27} \text{ N s in the direction of the beam} \end{aligned}$$

The momentum perpendicular to the beam is 0 N s before incidence on the single slit. This means that the uncertainty in the location of the photon in the beam is significant and is associated with the aperture of the laser.

$$\begin{aligned} \text{b. } \Delta p_x &\geq \frac{h}{4\pi\Delta x} \\ &\geq \frac{6.63 \times 10^{-34}}{4\pi \times 3.2 \times 10^{-7}} \\ &\geq 1.6 \times 10^{-28} \text{ N s.} \end{aligned}$$

On the other side of the slit, the photon has an uncertainty in its momentum perpendicular to the beam of at least 1.6×10^{-28} N s.

- c. Explain in terms of the Heisenberg uncertainty principle why a traditional diffraction pattern would be observed in terms of the momentum in the direction of the beam compared to the momentum uncertainty perpendicular to the beam.
- c. Before they reach the slit, photons have momentum parallel to the beam and zero momentum perpendicular to the beam. They all travel in a straight line towards the single slit. When they appear on the other side of the slit, they still have the same momentum in the direction of the beam, but they now have an uncertainty in their momentum perpendicular to the beam. Importantly, this uncertainty allows for the photons to have some motion either to the left or to the right of the slit. Momentum is a vector quantity and thus the photons will travel in a variety of directions, not necessarily parallel to the incident beam, due to the narrowness of the opening being associated with an increase in the uncertainty of perpendicular momentum. The uncertainty is $1.6 \times 10^{-28} \text{ N s}$, which is about $\frac{1}{6}$ of the momentum of a photon in the beam. As a result, diffraction will be readily observable.

PRACTICE PROBLEM 8

An experiment consists of a beam of electrons incident on an opening of order 10^{-10} m . What would be the order of magnitude of the uncertainty in the momentum of electrons parallel to the width of this opening?

12.5.3 Why classical laws of physics are unable to model motion at very small scales

It is now clear why classical laws of physics are unable to model motion at very small scales. For large-scale events, the uncertainty of position has an insignificant effect on the uncertainty of momentum and vice versa. This is because Planck's constant is too small to be of any consequence when dealing with large objects. For example, if the uncertainty in the position of a moving cricket ball is $1 \times 10^{-6} \text{ m}$, this leads to an uncertainty in the ball's momentum of approximately 10^{-28} N s . A moving cricket ball with mass $50 \text{ g} = 5.0 \times 10^{-2} \text{ kg}$ and speed 20 m s^{-1} has a momentum of 1 N s . The uncertainty in the ball's momentum compared to its actual momentum is negligible, in this case 10^{28} times smaller.

However, when objects are investigated on very small scales, Planck's constant becomes significant. If the uncertainty in the position of an electron in an atom is 10^{-10} m , then the uncertainty in its momentum is now of the order of 10^{-24} N s . An electron with energy 1 eV ($1.6 \times 10^{-19} \text{ J}$) has a momentum of $5.4 \times 10^{-25} \text{ N s}$ (using the equation $p = \sqrt{2mE_k}$). In this case, the uncertainty in the momentum of the electron is larger than the magnitude of the momentum of the electron. An experimental arrangement would be incapable of ascertaining with any degree of certainty what this individual electron was doing, if indeed such an experimental question could be resolved.

For a reader new to this area of physics, they might be inclined to state that, with better and more refined measuring equipment, the ability to measure either location or motion could be improved. But the uncertainty principle is not about refinements in measurements; rather, it is an assertion about what can and can't be known simultaneously and to what level of precision — an insignificant fact when observing day-to-day phenomena, but central to appreciating the motion of very small objects. The pathway to knowledge is never complete but, in modern physics, a significant achievement was established in the 1920s, when the limits to humanity's understanding were quantified by a simple relationship that united the contradictory modelling in terms of particles and waves simultaneously.

12.5 EXERCISE

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1. Explain each variable in the Heisenberg uncertainty inequality.
2. An electron is confined to be inside an atom of diameter 2.0×10^{-10} m. Use this size to estimate the uncertainty in the momentum of this electron.
3. It is known that electrons do not exist inside the nucleus of an atom.
 - (a) Taking the size of a nucleus to be 1.0×10^{-15} m and using this size as the uncertainty in the position of an electron potentially positioned inside a nucleus, calculate the uncertainty in the momentum of this electron.
 - (b) If electrons can have this amount of momentum due to uncertainty, calculate the kinetic energy that these electrons could have due to the uncertainty principle. Use the equation $E_k = \frac{p^2}{2m}$. Express your answer in joules and in electron volts.
 - (c) On the basis of your answer to part (b) and experimental evidence regarding electron energies, explain why electrons do not occupy the nucleus.
4. A student tells you that she is perfectly still with zero momentum. Use the uncertainty principle to explain why her position will have a relatively large uncertainty.
5. Use the concept from question 4 to argue why achieving absolute zero kelvin is unobtainable.
6. Why does a diffraction pattern spread out when the width of the single slit is reduced in size?
7. Why is significant diffraction not observable when a person walks through a doorway into a classroom? Estimate the momentum of a person and the width of a doorway to illustrate this point by comparing the momentum of the person with the uncertainty associated with sideways momentum due to the person passing through the doorway.
8. Why are the classical laws of physics insufficient to deal with motion at very small scales?

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12.6 Review

12.6.1 Summary

- The behaviour of electrons — in particular, their deflection by electric and magnetic fields, and their electric charge and mass — is strong evidence for the particle-like nature of electrons.
- In 1924, Louis de Broglie suggested that electrons may also exhibit wave properties under suitable conditions. He proposed a diffraction style experiment using a beam of electrons and a crystal to act as a diffraction grating.
- The de Broglie wavelength, λ , can be determined from the momentum, p , according to the equation
$$\lambda = \frac{h}{p}.$$

Remember also that the momentum of a particle is given by $p = mv$, where m is the mass and v is the velocity.

- Diffraction effects can be observed with waves when the wavelength is the size of a slit or greater. When the wavelength is small, diffraction effects are difficult to observe.
- In 1927, Clinton Davisson and Lester Germer established the wavelike behaviour of electrons when they performed a diffraction experiment. Not only did they observe diffraction effects, they also established that the wavelength of the electrons in the beam was consistent with Louis de Broglie's prediction.
- A useful equation to determine the de Broglie wavelength, λ , of an electron accelerated in an electron gun with accelerating voltage V is
$$\lambda = \frac{h}{\sqrt{2m_e V q_e}}$$
 where m_e and q_e are the mass and charge of an electron respectively.
- Atoms emit light of precise frequencies. This light, when passed through a spectrometer, is known as an emission spectrum. The spectrum consists of a series of discrete lines.
- All atoms of the same element emit the same spectrum. Different elements produce their own distinctive spectra.
- Absorption spectra consist of a continuous spectrum with dark lines corresponding to particular missing wavelengths. In general, these dark lines correspond to the bright lines of emission spectra for a particular gas.
- To account for emission spectra, Niels Bohr proposed a radical model where electrons within atoms have stable orbits but only discrete energy levels are allowed.
- When an atom jumps from a high energy level, E_{initial} , to a lower energy level, E_{final} , resulting in a difference, ΔE , a photon of light is emitted with frequency, f , according to the equation $hf = \Delta E$. Hence, the observation of emission spectra having precise frequencies is evidence for atoms having discrete energy levels.
- The best model for atoms having discrete energy levels is to interpret electrons in atoms as behaving as a standing wave. The allowable standing waves are known as orbitals.
- Both light and matter exhibit both particle-like and wavelike behaviours under the right circumstances.
- A hot solid or liquid material emits a continuous spectrum that is independent of composition. These sources are often referred to as incandescent light sources.
- Synchrotron radiation is produced when a charged particle accelerates. In the storage ring of a synchrotron, the charged particles move in circular paths and hence are accelerating; the radiation is very intense, comes in a narrow beam and covers a broad range of frequencies.
- LEDs produce light from spontaneous emission when electrons fall from high to low energy levels or bands within a semiconductor. The loss in electron energy equals the energy of the emitted photon.
- Lasers produce light by a process called stimulated emission. The radiation produced is monochromatic and coherent.

- Double-slit experiments provide evidence for the dual nature (particle and wave) of both light and matter under conditions where single photons or individual material objects such as electrons are used to illuminate the slits and form an interference pattern.
- Heisenberg's uncertainty principle asserts that it is not possible to simultaneously know both the position and the momentum of an object along a particular axis. The uncertainty in each variable, Δx and Δp_x respectively, is subject to the inequality $\Delta x \times \Delta p_x \geq \frac{h}{4\pi}$ where $h = 6.63 \times 10^{-34}$ J s.
- Heisenberg's uncertainty principle can be used to explain diffraction patterns produced by either beams of light or matter incident on a single slit.
- Classical laws of physics are not appropriate when investigating motion on very small scales, as the uncertainties associated with both position Δx and momentum Δp_x become sizeable in comparison to their values.

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12.6.2 Key terms

An **absorption spectrum** is a spectrum produced when light passes through a cool gas. It includes a series of dark lines that correspond to the frequencies of light absorbed by the gas.

A **black body** is an ideal absorber of energy. It absorbs all electromagnetic radiation that falls on it and does not reflect any.

Coherent emitted light is light in which all photons are emitted in phase, leading to intense light.

A **continuous spectrum** is a spectrum that has no gaps. There are no frequencies or wavelengths missing from the spectrum.

The **de Broglie wavelength** is the wavelength associated with a particle or discrete piece of matter.

Emission spectra are produced when light is emitted from an excited gas and passed through a spectrometer.

A spectrum includes a series of bright lines on a dark background. The bright lines correspond to the frequencies of light emitted by the gas.

An **excited state** is a state in which an electron has more energy than its ground state.

The **ground state** is the state of an electron in which it has the least possible amount of energy.

A **light-emitting diode (LED)** is a small semiconductor diode that emits light when a current passes through it.

A **line emission spectrum** shows the discrete frequencies or wavelengths produced by an excited material.

A **nanocrystal** is a very small crystal with only a few hundred to a thousand atoms.

Quantised describes quantities that cannot be divided or broken up into smaller parts.

A **semiconductor** is a material that has a resistivity between that of conductors and insulators.

A **spectrometer** is a device used to disperse light into its spectrum.

A **thermal spectrum** is the spectrum produced by a body due to its temperature.

Wave-particle duality describes light as having characteristics of both waves and particles. This duality means that neither the wave model nor the particle model adequately explains the properties of light on its own.

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 **Digital document** Key terms glossary (doc-32297)

12.6.3 Practical work and investigations

Investigation 12.1

Spectroscopes

Aim: To use a spectroscope to observe the spectrum of a light source

Digital document: doc-32087

Teacher-led video: tlvd-0254



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 **Digital document** Practical Investigation logbook (doc-32298)

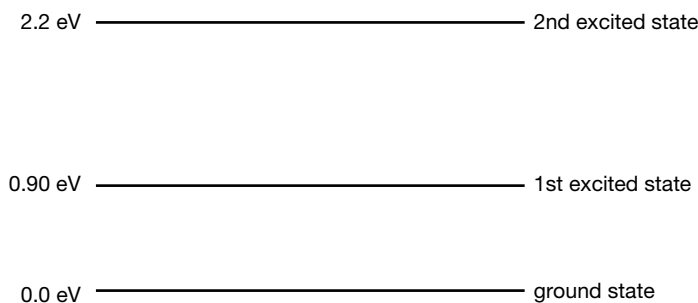
12.6 Exercises

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12.6 Exercise 1: Multiple choice questions

- Sometimes electrons behave like particles and sometimes they behave more like waves. Which one of the following statements is correct concerning the movement of electrons?
 - The movement of electrons in a vacuum through an electric field is well modelled by considering the electron to be a wave, but through a crystal it diffracts like a particle.
 - The movement of electrons in a vacuum through an electric field is well modelled by considering the electron to be a particle, but through a crystal it diffracts like a wave.
 - The movement of electrons in a vacuum through an electric field is well modelled by considering the electron to be a wave, and through a crystal it also diffracts like a wave.
 - The movement of electrons in a vacuum through an electric field is well modelled by considering the electron to be a particle, and through a crystal it also diffracts like a particle.
- A tennis ball of mass 0.10 kg travelling with speed 80 m s^{-1} is passing over the top of a tennis net. Which of the following is the de Broglie wavelength of the tennis ball?
 - $4.1 \times 10^{-35} \text{ m}$
 - $8.3 \times 10^{-34} \text{ m}$
 - $4.1 \times 10^{-34} \text{ m}$
 - $8.3 \times 10^{-35} \text{ m}$
- Consider a beam of electrons accelerated in an electron gun with voltage 60 V . The electrons are fired at a crystal and a diffraction pattern is produced. Which of the following is the de Broglie wavelength of an electron in the beam?
 - $3.3 \times 10^{-18} \text{ m}$
 - $6.5 \times 10^{-7} \text{ m}$
 - $1.6 \times 10^{-10} \text{ m}$
 - $4.3 \times 10^{-12} \text{ m}$
- An electron and a photon both have the same momentum. Which one of the following statements is correct?
 - To compare the wavelength of the two particles, you also need to know the energy.
 - The de Broglie wavelength of the electron is the same as the wavelength of the photon.
 - The de Broglie wavelength of the electron is greater than the wavelength of the photon.
 - The de Broglie wavelength of the electron is less than the wavelength of the photon.

5. The emission spectrum from a mercury lamp is different to the emission spectrum of a camp fire. Which one of the following statements best describes that difference?
- Light from a mercury lamp consists of a small number of specific colours whereas light from a camp fire displays a continuous spectrum.
 - Light from a mercury lamp consists of polarised photons whereas light from a camp fire is unpolarised.
 - Light from a mercury lamp consists of a continuous spectrum whereas light from a camp fire displays a small number of specific colours.
 - Light from a mercury lamp consists of unpolarised photons whereas light from a camp fire consists of polarised photons.
6. An electron in an atom makes a transition from the fourth excited state ($E = -7.6 \text{ eV}$) to the second excited state ($E = -10.7 \text{ eV}$). The atom emits a single photon. Determine which of the following is the energy of the emitted photon.
- 18.3 eV
 - 4.1 eV
 - 3.1 eV
 - 8.7 eV
7. The discrete emission spectrum obtained from a mercury lamp gives strong evidence for the nature of electrons in atoms. Which one of the following statements is best?
- The evidence supports a particle model for electrons confined to atoms. In this model, electrons behave much like a standing wave.
 - The evidence supports a particle model for electrons confined to atoms. In this model, electrons behave much like particles in circular orbits about the nucleus.
 - The evidence supports a wave model for electrons confined to atoms. In this model, electrons move in circular orbits about the nucleus.
 - The evidence supports a wave model for electrons confined to atoms. In this model, electrons behave much like a standing wave.
8. A collection of atoms that are all in their ground state are bombarded by a beam of photons such that all the atoms are excited into their third excited state. Which of the following is the number of different photon energies in the emission spectrum?
- 4
 - 5
 - 6
 - 7
9. Consider the partial energy level diagram of a particular atom X:



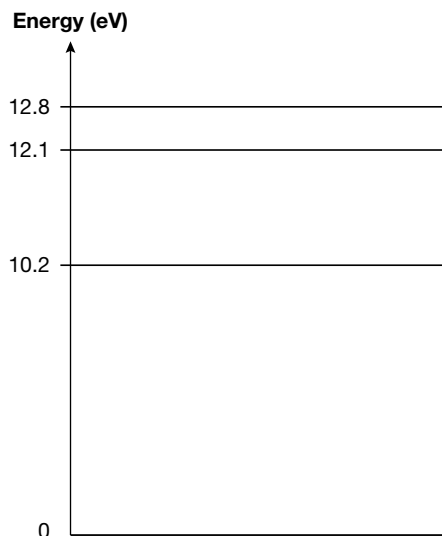
A beam of monochromatic photons with energy 1.8 eV is incident on a gas entirely made up of atom X. Determine which of the following statements is correct.

- The gas will emit only photons of energy 0.90 eV.
- The gas will emit photons with energy 0.90 eV and photons with energy 1.3 eV.
- The gas will emit photons with energy 0.90 eV and photons with energy 2.2 eV.
- The gas will not emit any photons.

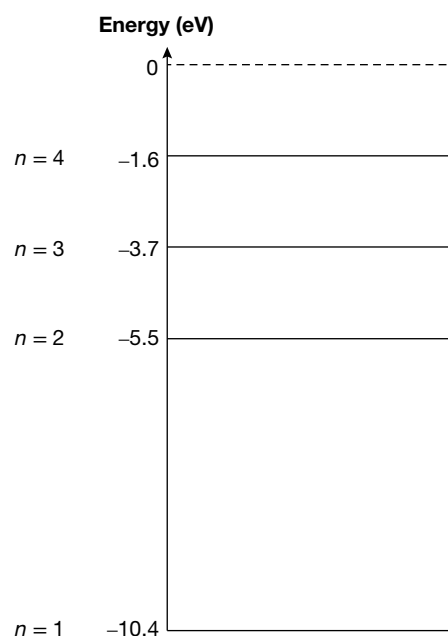
10. Consider an electron in a hydrogen atom with an uncertainty in its position Δx and another electron in a larger helium atom with a larger uncertainty $2\Delta x$. Determine which one of the following statements is correct.
- Both electrons would have the same uncertainty in their momentum.
 - The uncertainty in the momentum of the electron in the hydrogen atom is greater than the uncertainty in the momentum of the electron in the helium atom.
 - The uncertainty in the momentum of the electron in the hydrogen atom is less than the uncertainty in the momentum of the electron in the helium atom.
 - There is insufficient information.

12.6 Exercise 2: Short answer questions

- Consider both an electron and a photon. The photon has a frequency of 5.2×10^{14} Hz and the electron has a velocity of 2.8×10^6 m s⁻¹.
 - Calculate the wavelength of the photon and the de Broglie wavelength of the electron. Which has the greater value?
 - Determine the momentum of the photon and the electron. Which has the greater value?
 - Find the kinetic energy of the photon and the electron. Which has the greater value?
- A photon and an electron both have the same energy, namely 3.0 eV (4.8×10^{-19} J).
 - Calculate the momentum of both the photon and the electron. Which is greater in value?
 - Calculate the wavelength of the photon and the de Broglie wavelength of the electron. Which is greater in value?
 - If the energy of both the electron and the photon increases, what happens to the momentum of the photon and the electron? What happens to their respective wavelengths?
- What important piece of evidence does the diffraction of electrons provide for?
- Explain the difference between an emission and absorption spectrum as it relates to a gas of identical atoms.
- A beam of electrons accelerated by an electron gun is required for studying the structure of a new molecule. The de Broglie wavelength required is 1.0×10^{-11} m. Calculate the voltage required to accelerate the electrons so they have the required de Broglie wavelength.
- In what way is the light emitted from an incandescent light source different in nature to the light emitted from a neon discharge lamp?
- An LED emits light when electrons undergo an energy loss of 1.7 eV in the diode. Calculate the wavelength of the emitted photons.
- Some LEDs emit red light while others emit green light. Describe the essential difference in the LEDs that cause the different colours.
- Why are X-rays produced by a synchrotron useful in scientific research?
- The following figure is a partial energy level diagram for a hydrogen atom showing the ground state and the first three excited states.
 - Copy the diagram and draw arrows to represent all six transitions that may occur when a population of hydrogen atoms is excited into the third excited state.
 - Calculate the energy of each of the six possible photons that may be emitted.
 - Determine the wavelength of the photon having the least energy.



11. Consider the energy level diagram for a gas Q, shown in the following figure.
- Determine the energy of the photon emitted when an electron in the state $n = 3$ undergoes a transition to the state $n = 2$.
 - Determine the frequency and wavelength of this photon.
 - Determine the wavelength of the photon absorbed by this gas when an electron undergoes a transition from the state $n = 1$ to the state $n = 4$.
12. A beam of electrons with fixed momentum is used in a single-slit diffraction experiment designed to show the wavelike nature of matter. The electrons move from one side of the slit to the other and a diffraction pattern is produced. Use the Heisenberg uncertainty principle to explain what happens to the diffraction pattern when the width of the single slit is decreased.

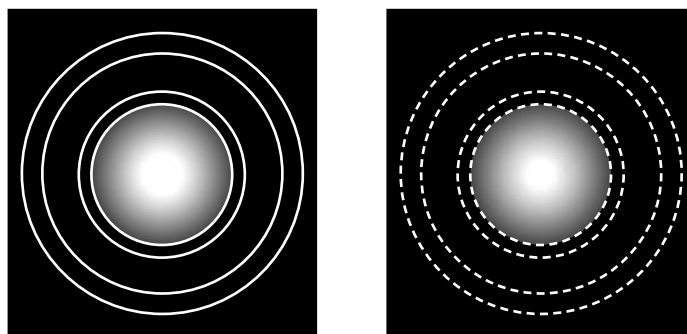


12.6 Exercise 3: Exam practice questions

Question 1 (4 marks)

The diffraction pattern shown in image (a) is made by passing X-rays through a thin layer of sodium chloride crystal. The diffraction pattern shown in image (b) is made by using a beam of electrons passing through the same crystal. The two images have circular rings of the same diameter. The X-rays have a frequency $f = 8.0 \times 10^{16}$ Hz.

- What does the pattern tell you about the nature of both X-rays and electrons when they pass through thin layers of crystal? **1 mark**
- What do the rings of equal diameter tell you about the X-rays and the electrons? **2 marks**
- Calculate the de Broglie wavelength of the electrons. **1 mark**



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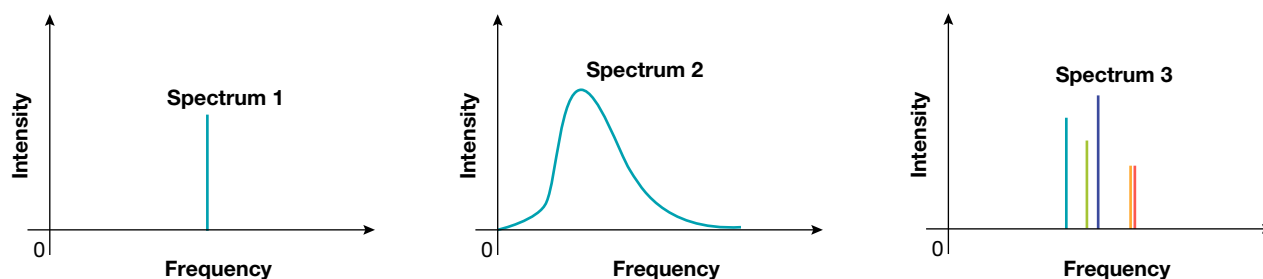
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Question 2 (2 marks)

Consider two single-slit diffraction experiments both using a beam of electrons. In the first experiment, electrons in the beam travel towards the slit with speed $1.0 \times 10^6 \text{ m s}^{-1}$. In the second experiment, electrons in the beam travel towards the slit with speed $2.0 \times 10^6 \text{ m s}^{-1}$. Describe and explain the differences in the diffraction pattern produced in each experiment.

Question 3 (1 mark)

The unidentified spectra produced by three light sources A, B and C are shown in the following figure. Light source A is a helium–neon laser, light source B is a mercury discharge tube, and light source C is an incandescent light globe.



Complete each of the three sentences.

Spectrum 1 is produced by source ____.

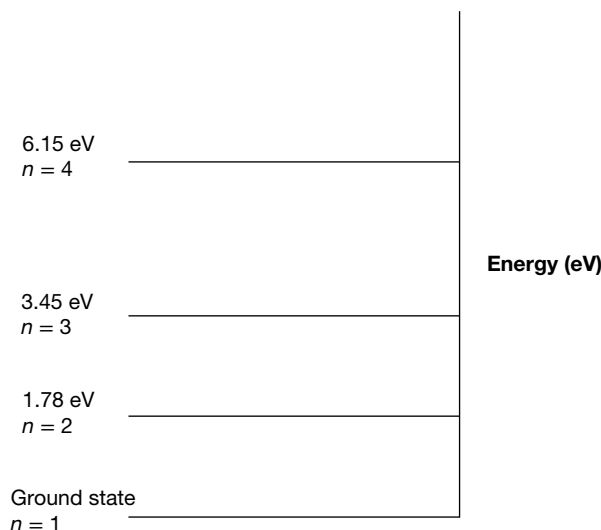
Spectrum 2 is produced by source ____.

Spectrum 3 is produced by source ____.

Question 4 (4 marks)

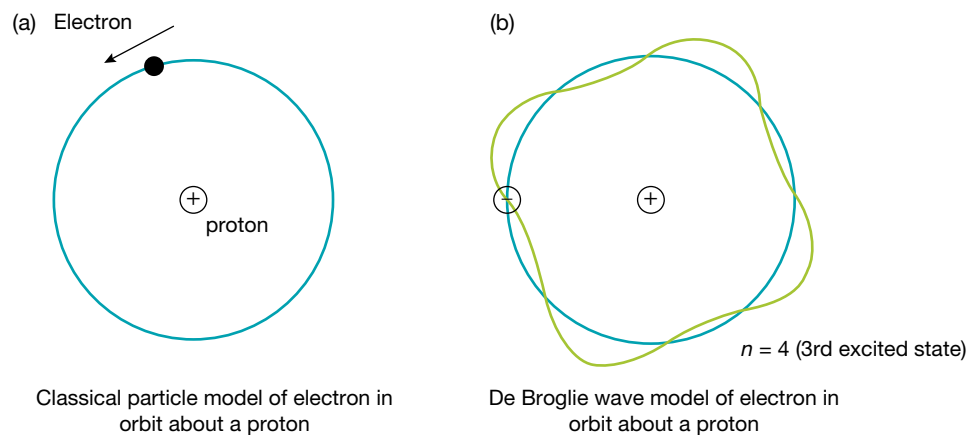
It is known that atoms may be excited into one of many energy levels. They subsequently change back to their ground state by emitting one or more photons. The energy level diagram for a particular element, X, is shown in the diagram.

- Onto a copy of the diagram, draw arrows to represent all three transitions that may occur when atoms of this element change from the $n = 3$ excited state back to the ground state. **1 mark**
- An atom of element X absorbs a photon and is excited into the second excited state. Calculate the frequency of the absorbed photon. **1 mark**
- An atom of element X is in the third excited state and decays to the first excited state. Calculate the wavelength of the emitted photon. **2 marks**



Question 5 (2 marks)

The following two diagrams illustrate models of the hydrogen atom.



The first model is a satellite model where an electron is envisaged as a particle in a stable circular orbit about the nucleus. The second model depicts an electron in the third excited state as a standing wave on the circumference of a circle. Discuss the reason why the first model fails to predict atomic behaviour whereas the second model is consistent with the observation of discrete emission spectra.

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UNIT 4 | AREA OF STUDY 2 REVIEW

AREA OF STUDY 2 How are light and matter similar?

OUTCOME 2

Provide evidence for the nature of light and matter, and analyse the data from experiments that supports this evidence.

PRACTICE EXAMINATION

STRUCTURE OF PRACTICE EXAMINATION		
Section	Number of questions	Number of marks
A	20	20
B	4	20
Total		40

Duration: 50 minutes

Information:

- This practice examination consists of two parts. You must answer all question sections.
- Pens, pencils, highlighters, erasers, rulers and a scientific calculator are permitted.
- You may use the VCAA Physics formula sheet for this task.



Resources



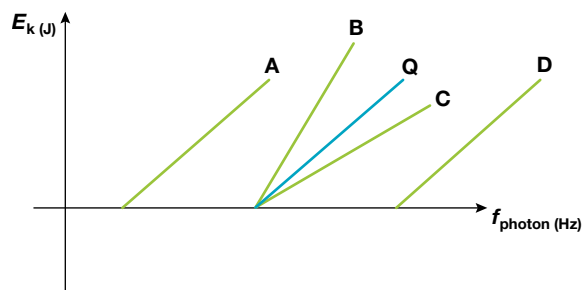
Weblink VCAA Physics formula sheet

SECTION A — Multiple choice questions

All correct answers are worth 1 mark each; an incorrect answer is worth 0.

1. Viruses such as the influenza virus have a particle size less than 200 nm across. They cannot be distinguished clearly by visible light microscopes with the highest magnifications. Which is the best explanation for this?
 - A. Visible light diffracts significantly at this length scale, resulting in blurry images.
 - B. Visible light has insufficient intensity to light up objects at this length scale.
 - C. Visible light frequencies are too high to be able to distinguish the edges of objects at this length scale.
 - D. Visible light wavelengths are too small to be able to distinguish the edges of objects at this length scale.
2. In the study of the DNA structure, X-rays were used to discern the double-helix configuration of the DNA. Which is the best reason for the ability of X-rays to do this?
 - A. The wavelengths of X-rays are smaller than the scale of the DNA molecule.
 - B. The intensity of the X-rays is sufficient to light up the DNA molecule.
 - C. X-ray frequencies are low enough to distinguish the edges of the DNA molecule.
 - D. X-ray wavelengths are long enough to distinguish the edges of the DNA molecule.

3. Experiments with photoelectrons provided the key evidence for the particle-like nature of light. If light had behaved in a wavelike manner, all the following experimental observations would have been made, with the exception of:
- A higher intensity light source would produce photoelectrons with higher kinetic energy; thus, a higher stopping voltage would be required.
 - A lower frequency light source would still produce photoelectrons, but with a time delay.
 - A higher frequency light source would produce photoelectrons with higher kinetic energy; thus, a higher stopping voltage would be required.
 - Photoelectrons would be produced at all frequencies.
4. The following 'Photoelectron kinetic energy vs Photon frequency' graph (E_k vs f_{photon}) shows the relationship for sodium metal, indicated by the line labelled Q. The relationship for another metal, which has a higher work function, ϕ , is indicated by which line, A, B, C or D?



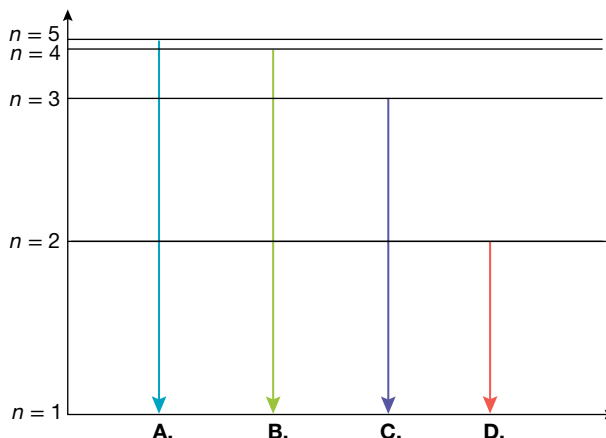
5. The photoelectron experiment resulted in the following observations being made that pointed to the particle-like nature of light, except for one. Identify the one that wouldn't have been made.
- A photocurrent was produced even at a low frequency.
 - Increasing the intensity of the light increased the photocurrent.
 - A higher frequency of light required a higher stopping voltage.
 - There is a cut-off frequency below which no photocurrent was produced.
6. Light with a frequency of 7.30×10^{14} Hz is incident on a metal with a work function of 1.23 eV. The expected kinetic energy of the photoelectrons is closest to:
- 1.79 eV
 - 3.02 eV
 - 4.25 eV
 - 4.87 eV
7. A photoelectron experiment determined that the cut-off frequency of a metal is 5.56×10^{14} Hz. What is the work function of that metal?
- 8.0×10^{-20} J
 - 1.2×10^{-19} J
 - 2.3×10^{-19} J
 - 3.7×10^{-19} J
8. A diffraction pattern produced by X-rays has exactly the same spacing between fringes as a diffraction pattern produced by electrons. Which of the following statements is correct concerning the X-rays and the electrons?
- The frequency of the X-rays matches the frequency of the electrons.
 - The photon energy of the X-rays matches the kinetic energy of the electrons.
 - The momentum of the X-rays matches the momentum of the electrons.
 - The intensity of the X-rays matches the intensity of the electrons.
9. The de Broglie wavelength of a golf ball ($m = 0.046$ kg, $d = 0.043$ m) travelling at 70 m s^{-1} is closest to:
- 2.1×10^{-34} m
 - 3.4×10^{-31} m
 - 6.7×10^{-31} m
 - There is no de Broglie wavelength as the golf ball cannot diffract.

10. An experiment with carbon buckyballs ($m = 1.20 \times 10^{-24}$ kg) demonstrated diffraction that is consistent with a de Broglie wavelength of 2.5×10^{-12} mm. What is the velocity of the buckyballs?
- $2.2 \times 10^1 \text{ m s}^{-1}$
 - $2.2 \times 10^2 \text{ m s}^{-1}$
 - $2.2 \times 10^3 \text{ m s}^{-1}$
 - $2.2 \times 10^4 \text{ m s}^{-1}$

Use the following information to answer questions 11 and 12:

An atom's electron energy levels are shown in the diagram in question 11. The arrows represent electrons transitioning between the energy levels.

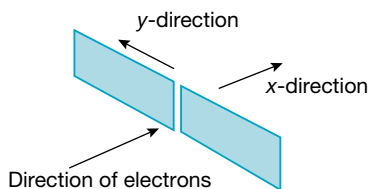
11. Which of the arrows corresponds to the emission of photons with the longest wavelength?



12. Choose the best explanation for the observation that photons are emitted when electrons transition between energy levels.
- Electrons behave as light waves that emit photons when transitioning between energy levels.
 - Electrons transition between behaving like light and behaving like matter between energy levels.
 - Electrons behave as matter waves that emit photons when transitioning between energy levels.
 - Electrons transition between behaving like particles and behaving like waves between energy levels.
13. The emission spectrum of an atom shows a peak at the frequency of 7.1×10^{14} Hz. What is the difference between the energy levels of the electron transition?
- 4.7×10^{-19} J
 - 9.3×10^{-19} J
 - 1.1×10^{-18} J
 - 2.94 J
14. Electrons transition between energy levels with a difference of 2.78 eV. What is the expected frequency of the photons absorbed or emitted during the transition?
- 1.5×10^{14} Hz
 - 2.1×10^{14} Hz
 - 4.2×10^{14} Hz
 - 6.7×10^{14} Hz

Use the following information to answer questions 15 and 16:

The single-slit electron diffraction experiment demonstrates that matter may sometimes behave like waves. The following diagram represents the set-up for one such experiment, where the electrons have been accelerated by an electric field towards the single slit.



15. Which of the following is the best description for the behaviour of the electrons in the experiment?
- A. The electrons behave like particles when accelerated, and also like particles when passing through the single slit.
 - B. The electrons behave like particles when accelerated, but like waves when passing through the single slit.
 - C. The electrons behave like waves when accelerated, and also like waves when passing through the single slit.
 - D. The electrons behave like waves when accelerated, but like particles when passing through the single slit.
16. Heisenberg's uncertainty principle may be used to explain electron diffraction. Which of the following is the best explanation for the behaviour of the electrons?
- A. The uncertainty of the electrons' momentum in the x-direction is larger than the uncertainty of the electrons' position in the x-direction.
 - B. The uncertainty of the electrons' momentum in the x-direction is larger than the uncertainty of the electrons' position in the y-direction.
 - C. The uncertainty of the electrons' momentum in the y-direction is larger than the uncertainty of the electrons' position in the x-direction.
 - D. The uncertainty of the electrons' momentum in the y-direction is larger than the uncertainty of the electrons' position in the y-direction.

Use the following description key to answer questions 17 and 18:

- I. Continuous spectrum
 - II. Discrete spectrum
 - III. Single frequency
 - IV. Multiple frequencies
 - V. Coherent
 - VI. Incoherent
17. Which of the following options best describes light produced by the synchrotron?
- A. I, III and V
 - B. II, IV and VI
 - C. I, IV and VI
 - D. I, III and VI
18. Which of the following options best describes light produced by a green laser?
- A. I, III and V
 - B. II, IV and VI
 - C. II, IV and V
 - D. II, III and V
19. Which of the following statements about producing electromagnetic waves is the most correct?
- A. Electromagnetic waves can only be produced by accelerating electric charges.
 - B. Electron energy-level transitions can produce electromagnetic waves.
 - C. All electromagnetic waves are produced by electron energy-level transitions.
 - D. Electromagnetic waves cannot be produced by accelerating electric charges.
20. Which of the following is not an example of incandescence?
- A. A Bunsen burner flame
 - B. A hot electric iron
 - C. The star Alpha Centauri
 - D. Lava flowing from a volcano

SECTION B — Short answer questions

Question 1 (3 marks)

A beam of light has a frequency of 4.8×10^{14} Hz.

- a. What is the wavelength for a single photon? 1 mark
- b. What is the energy for a single photon? Give your answer in electron volts. 1 mark
- c. What is the momentum for a single photon? 1 mark

Question 2 (8 marks)

In a photoelectric experiment, a group of students measured the threshold frequency of the metal electrode to be 4.3×10^{14} Hz.

- a. Determine the work function for the metal. Give your answer in joules. **1 mark**

Light of frequency 5.7×10^{14} Hz now strikes the photocell.

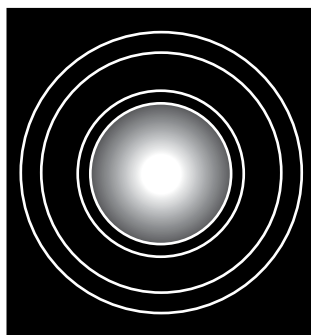
- b. Calculate the maximum energy of emitted electrons, in joules. **2 marks**

- c. What is the stopping voltage for the photoelectrons? **2 marks**

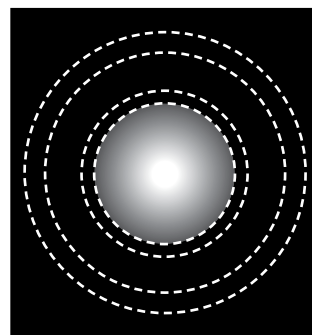
- d. Discuss the effects on the size of the photocurrent and the stopping voltage when the light intensity is increased. **3 marks**

Question 3 (6 marks)

X-rays with energy of 2.45×10^4 eV generate a diffraction pattern with fringe spacing that matches the diffraction pattern using a stream of accelerated electrons, as shown in the following images.



X-ray diffraction pattern

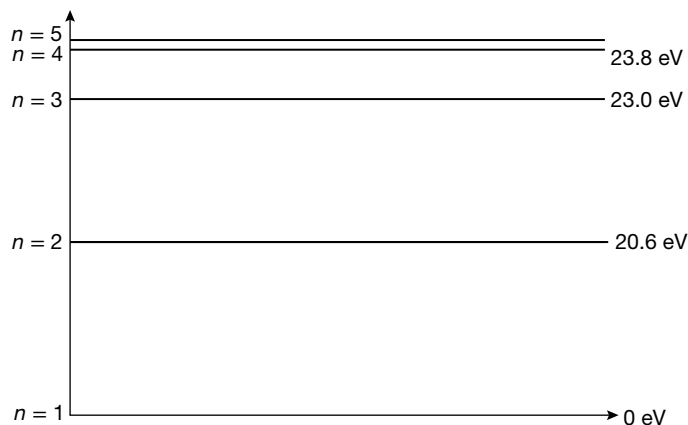


Electron diffraction pattern

- a. Determine the wavelength of the X-rays used. **1 mark**
b. State the de Broglie wavelength of the electrons used to generate the same diffraction pattern. **1 mark**
c. Calculate the kinetic energy imparted to the electrons if they start from rest. **2 marks**
d. What is the accelerating voltage of the electric field used if the electrons start from rest? **2 marks**

Question 4 (3 marks)

Electrons at the ground state ($n = 1$) of an atom may absorb energy and transition to higher energy levels. They transition back to the ground state, directly or via an intermediate energy level, by emitting photons.



- a. In one experiment, an electron transitions from $n = 1$ to $n = 3$. On the diagram provided, draw arrows to represent all the possible transitions for an electron at $n = 3$ back to the ground state. **1 mark**
b. An electron at $n = 4$ transitions to $n = 2$. What is the expected frequency of the photon emitted in this transition? **2 marks**

ASSESSMENT TASK — DATA ANALYSIS

In this task, you will be required to respond to the provided stimulus material and analyse data to provide evidence for the nature of light and matter.

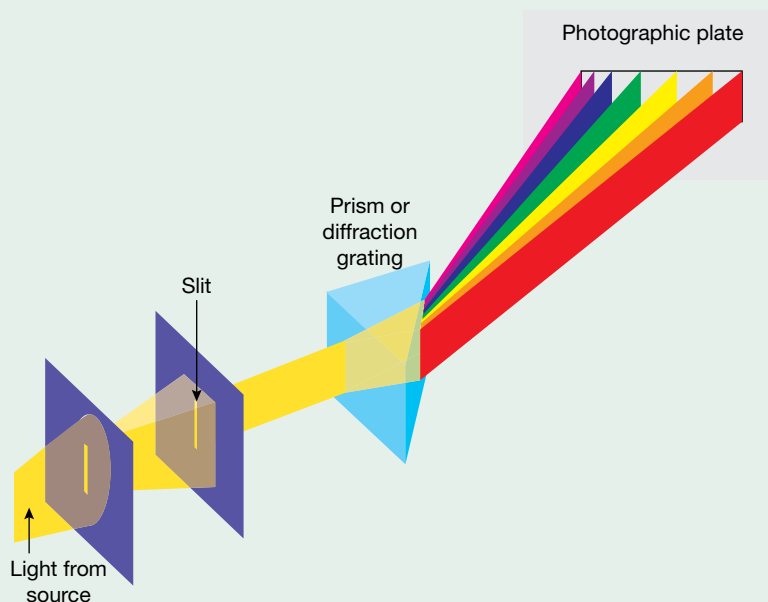
- This practice SAC requires you to respond to the provided stimulus material and analyse data.
- You may use the VCAA Physics formula sheet and a scientific calculator for this task.

Total time: 55 minutes (5 minutes reading, 50 minutes writing)

Total marks: 35 marks

ANALYSING LIGHT EMISSION SPECTRUM DATA

When a gas of atoms of a single element is struck by white light, the gas emits a series of discrete colours. The emitted light can be passed through a spectrometer to produce what is commonly known as an emission spectrum. The following diagram illustrates how the light emitted by the gas is collected, to produce an emission spectrum.



From the emission spectrum, the energy level diagram for the atom can be deduced. In one particular experiment, the wavelengths of six different colours were established from an emission spectrum. The frequency and energy of the photons for each of the six wavelengths were then determined. The data is shown in the provided table.

Wavelength (nm)	Frequency (GHz)	Energy (eV)
182	1.65×10^3	6.8
247	1.21×10^3	5.0
335	8.94×10^2	3.7
402	7.45×10^2	3.1
689	4.35×10^2	1.8
955	3.14×10^2	1.3

Answer the following questions, clearly referencing the stimulus material and the data provided.

1. Using the wavelength 182 nm, show clearly how the frequency presented in the table is calculated.
2. Using the frequency 1.65×10^3 GHz, explain how the energy 6.8 eV is determined.
3. Using your value for the highest energy photon emitted, convert that value from eV into J.

4. Using your value for the highest energy photon emitted, determine the momentum of that photon.
5. Briefly outline what an emission spectrum is and describe how it is used to provide an energy level diagram for an atom.
6. Assuming there are six different wavelengths in the emission spectrum, give an explanation as to why only the first three excited states of atoms making up the gas have been populated.
7. One of the photons emitted is in the infra-red region while three of the emitted photons are in the ultraviolet region of the electromagnetic spectrum. The remaining two are in the visible spectrum. State which wavelength is in the infra-red region and which three are in the ultraviolet region.
8. Using the information in the third column of your table, construct an energy level diagram for this element, where the ground state has an energy of 0 eV. Your energy level diagram should consist of the ground state and the first three excited states. (The ionisation level for this element is 11.5 eV above the ground state, and it should also be shown on your diagram.)

In some instances, energy level diagrams have levels that are negative in value. In these cases, the ionisation level is set at 0 eV and the excited states and ground state are referenced relative to this level.

9. Redraw the energy level diagram for this element, but this time with the ionisation level set at 0 eV.

In a subsequent experiment, the gas of atoms is illuminated by a beam of photons having energy 3.1 eV.

10. State which wavelengths would now appear in the emission spectrum.

In a follow-up experiment, the gas of atoms is now illuminated by a beam of photons having energy 3.5 eV.

11. Explain why there are no visible lines in the spectrum collected this time.
12. An absorption spectrum can also be produced. Explain how an absorption spectrum is produced.
13. When an absorption spectrum is made for this particular element, only three of the wavelengths that appear in the previous table are present. Which three wavelengths are they and why don't the other three wavelengths appear in the absorption spectrum?

In a contemporary model of the atom, electrons are said to be in orbitals where their precise location and momentum are not known. The Heisenberg uncertainty principle relates the uncertainty in position and momentum.

14. In an atom, electrons are confined to a space where their location is uncertain by an amount $\Delta x = 10^{-10}$ m.
 - a. If this uncertainty in location increases to 2×10^{-10} m, describe what would happen to the uncertainty in the momentum of an electron.
 - b. Does this match the expectation of Heisenberg's uncertainty principle in the diffraction from the single-slit experiment through slits of increasing width? Justify your response.



Resources



Digital document School-assessed coursework (doc-32303)

Numerous **videos** and **interactivities** are available just where you need them, at the point of learning, in your digital formats, learnON and eBookPLUS at www.jacplus.com.au.

As part of Area of Study 3, Unit 4, you will conduct a practical investigation exploring content you have covered in physics. The practical investigation allows you to follow your own interests and passions, through exploring the answers to questions that are important to you. Reflect on what it means to be ‘scientific’, and the characteristics of scientific ways of doing things compared to non-scientific ways. You will improve your ability to solve problems, use resources and communicate ideas using appropriate physics terminology. These attributes are useful in everyday life and highly valued in the workplace. Being scientific means making use of observations, experiments and logical thinking to test ideas.

A female student with long brown hair in a ponytail, wearing a black and white striped long-sleeved shirt and blue jeans, is working in a physics laboratory. She is standing at a grey lab bench, looking down at a laptop screen. The laptop is open, displaying a graph. On the bench, there is a digital scale with a white platform, a blue and red spring constant apparatus, a blue and white pendulum setup, and a blue and white spring. A notebook with a diagram is open in front of the laptop. In the background, there is a large window with a view of a building and a sink with a white faucet.

13.1.2 What you will learn

KEY KNOWLEDGE

After completing this topic, you will be able to apply the following to practical investigations:

- independent, dependent and controlled variables
- the physics concepts specific to the investigation, and their significance, including definitions of key terms, and physics representations
- the characteristics of scientific research methodologies and techniques of primary qualitative and quantitative data collection relevant to the selected investigation, including experiments (gravity, magnetism, electricity, Newton's laws of motion, waves) and/or the construction and evaluation of a device; precision, accuracy, reliability and validity of data; and the identification of, and distinction between, uncertainty and error
- identification and application of relevant health and safety guidelines
- methods of organising, analysing and evaluating primary data to identify patterns and relationships, including sources of uncertainty and error, and limitations of data and methodologies
- models and theories, and their use in organising and understanding observed phenomena and physics concepts, including their limitations
- the nature of evidence that supports or refutes a hypothesis, model or theory
- the key findings of the selected investigation and their relationship to concepts associated with waves, fields and/or motion
- the conventions of scientific report writing and scientific poster presentation, including physics terminology and representations, symbols, equations and formulas, units of measurement, significant figures, standard abbreviations and acknowledgement of references.

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on Resources

-  **Digital documents** Key science skills — VCE Physics Units 1–4 (doc-32112)
Key terms glossary (doc-32299)

13.2 Key science skills in Physics

KEY SCIENCE SKILLS

- Develop aims and questions, formulate hypotheses and make predictions
- Plan and undertake investigations
- Conduct investigations to collect and record data.

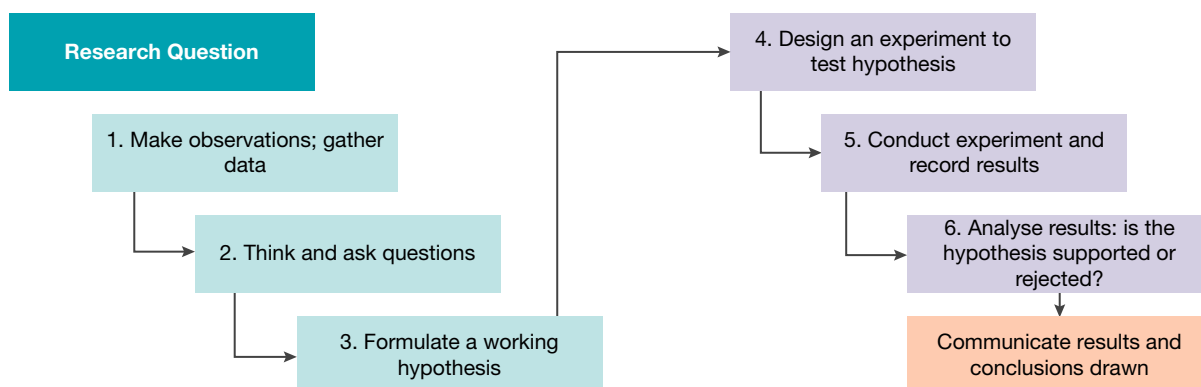
13.2.1 The scientific method — why are investigations conducted?

Physics relies on formulating and answering questions followed by communicating the findings in order to progress. Scientists work through a series of steps to advance their knowledge as part of this procedure. Experimental and other investigative work is central to this.

Figure 13.2 summarises this process for practical investigations and the scientific method.

Your investigation will draw upon a number of key skills that you have been developing in Units 1 and 2, and so far in Units 3 and 4, as well as the key knowledge that is specified for Unit 4, Area of Study 3 of the study design. You will be required to produce a report in the format of a scientific poster.

In this practical investigation, you will again investigate the effect of varying two independent variables but, this time, both variables must be continuous. This increases the amount of data collection, and the opportunities for data analysis and identification of mathematical relationships between your dependent variables and both independent variables.

FIGURE 13.2 The scientific method

In this investigation, there is more responsibility on you to plan and carry out the task. It gives you the opportunity to show your skill and imagination in experimental design, commitment to a task and your communication ability in explaining your **results**.

The investigation will require a significant amount of class time. Your teacher will set aside two to three weeks for the investigation. However, you will need to spend some extra time planning and organising your investigation in order to achieve a personally satisfying outcome. Table 13.1 will assist with your planning. The timeline may be different depending on your school. Your teacher may also set checkpoints regarding when you are required to submit work and what specific components need to be included.

TABLE 13.1 Investigation planning with sample schedule

Task	Due date
Your teacher spends some class time introducing the task, explaining what is expected of you, suggesting some possible topics or brainstorming other topics with the class. They will also outline the timeline for the investigation with the key due dates.	About two weeks before formal experimentation begins
Return a list of possible topics for approval by your teacher, who then provides feedback, recommendations and finally, approval.	A few days later
Submit a detailed research proposal for your approved topic. (Your teacher may decide to make this a formal task, done under test conditions in class and assessed, but with feedback provided afterwards on aspects that might need to be addressed before you begin.)	At the beginning of the week before your experiment begins
Submit your completed and signed Risk Assessment.	By the end of the week before your experiment begins
Requested equipment is assembled by the teacher and lab technician.	By the end of the week before your experiment begins
Investigation begins. - Set up equipment. - Collect preliminary data. - Troubleshoot any issues with equipment and finetune your procedure. - Collect data and measurements, graph your results and evaluate trends. - Adjust and refine method.	Week 1

(continued)

TABLE 13.1 Investigation planning with sample schedule (*continued*)

Task	Due date
- Continue the cycle of measurements and data analysis, leading to a review of progress and, further, more detailed measurements. - Move on to investigating the second continuous independent variable.	Week 2
- Finalise the investigation of the second variable. - Begin preparing your overview of the investigation: summarising your procedure, what you have found out, what difficulties you had and how you addressed them.	Week 3
- Finalise writing the sections of your report and paste them into a poster template. - Submit your logbook and poster.	Beginning of week 4

Remember, the practical investigation is part of the study design, so it is examinable. While questions about your specific investigation will not be asked, general questions around scientific investigation may be asked. This can include questions on the following:

- Identifying variables
- Using the **scientific method** to design an experiment
- Analysing data and determining the correct way to represent it
- Evaluating graphical information for patterns and trends
- Determining the accuracy, precision, validity and reliability of an experiment.

13.2.2 Using a logbook

As part of your practical investigation (as well as all practical experiments throughout the year), it is a requirement to keep a logbook.

Usually this logbook is a bound exercise book (however your teacher may request a digital logbook instead). It is vital to show all aspects of your scientific investigation within your logbook, using the scientific approach.

This logbook will be assessed by your teacher and is a compulsory requirement of your assessment. You must date all the work that is completed in your logbook to show when it was completed. Doing so will assist in validating your work.

FIGURE 13.3 All observations should be recorded in a logbook.**TABLE 13.2** Components in a logbook

Chosen question	Information about your topic and how you chose it, and the question you have selected
Introductory material	Background data on your topic, diagrams, notes and tables, information about key terms and past investigations that are similar to your investigation
Hypothesis and aim	A clear hypothesis and aim should be recorded. Relevant information is found late in this topic.
Methodology	Show all the equipment you plan to use and a clear method you plan to follow, with detailed steps that could be reproduced by someone else.
Results	Observe and record results in an appropriate form — tables are particularly useful for this.

(*continued*)

TABLE 13.2 Components in a logbook (*continued*)

Discussion	Refer to your results and carefully evaluate them, referring back to your hypothesis and questions. You may have set discussion questions to help scaffold your thoughts and ideas. You should also show further patterns and trends in the data using graphs, and refer to any appropriate equations.
Thoughts and questions	Note any concerns or questions you have about your investigation, and research the possible answers. It may be a question about a particular phenomenon.

13.2.3 Developing aims and questions

Coming up with a topic

Your practical investigation will focus on in one area of one of these topics: electric and magnetic fields, gravitational fields, forces and energy of motion, electromagnetism, and the properties of waves and light.

Choosing a topic is not an immediate process — it takes time and careful consideration. It is important you don't just pick a topic that sounds interesting. It's better to pick one that is reasonable to complete in the provided timeframe and using the available resources.

The topic of your investigation can come from any of the content you have been studying this year, so it may be useful to go back what you have covered and use this to form some ideas.

A good suggestion is to brainstorm a variety of topics as a group. A good way to do this is to draw a grid on a large sheet of paper with headings across the top such as (i) Hobbies and interests, (ii) Sports, (iii) Science in the news, (iv) Investigations you did in previous years, and (v) Course topics. Down the side, list types of investigations such as: (i) Investigating the operation of a device or technology, (ii) Solving a technological problem, and (iii) Investigating a physical phenomenon. Brainstorm as many ideas as you can then narrow this down to topics that you want to explore further.

Some topic examples are listed below, and a document that contains weblinks and many more additional topics can be found in your eBookPLUS. You should check through these lists and see what sparks your interest because choosing a topic that intrigues you will ensure a high level of commitment and a sense of pride in the finished work.

Topics

Here are some sample topics to get you thinking:

- The sweet spot of a tennis racket
- Bat (or club) and ball impacts
- The changeover from sliding to rolling
- Flight of a shuttlecock
- Surface tension of a liquid
- Performance of a parachute
- Effect of spikes on running shoes (figure 13.4)
- The performance of a water-driven rocket
- The impact force on and the energy lost by bouncing ball
- Flight of a table tennis ball
- The energy delivered by a catapult
- Dry sand is soft, wet sand is hard, wetter sand is soft again: investigate
- Factors affecting the design of a good paddle wheel
- The physics of a bicep curl
- The thrust of a propeller (in air or in water)
- The drag on spheres in an airstream

FIGURE 13.4 Effect of spikes on running shoes

- The motion of spheres in a viscous medium
- The effect of changing the size or shape of the wings of a glider
- The flight of a magnus glider
- The physics of the long jump (figure 13.5)
- Effect of the blocks on a sprint start
- Modelling the impact of the head with the dashboard in a car crash
- Electric force between charged plates
- Magnetic force between two magnets
- Strength of an electromagnet
- Interaction between two glider-mounted magnets
- The performance of a homopolar motor
- Efficiency of a DC motor used as a generator
- Efficiency of a bicycle dynamo
- Refractive index of a sugar solution
- Polarisation and optically active substances
- The resolution of a microscope (figure 13.6)
- Measuring the thickness of a soap film by interference.

FIGURE 13.5 Long jump



FIGURE 13.6 Microscopes can vary in resolution.



Creating a question

Turning the topic into a question focuses your mind on what you want to find out.

The question needs to be:

- one that can be investigated through the scientific method
- practicable, given your knowledge, time and the school resources
- asked in a way that indicates what you will do.

Example of formulating a question from a topic:

Topic: The sweet spot of a tennis racket

Question:

Where on a tennis racket should a ball be hit in order to strike with the greatest force?

OR

Can an individual return a tennis ball faster if they hit it at a specific spot on a tennis racket?

There are many ways of formulating a question from a topic. Just make sure it is something that can be measured, explored and answered in the scope of your practical investigation.

Developing an aim

Often, developing the **aim** of an investigation is done at the same time as formulating a question from your topic. The aim outlines the purpose or key objective of the investigation and should include what you are trying to achieve in order to answer your question.

There are two different ways that you can format your aim.

1. To [determine/investigate/compare] how the **dependent variable** is affected by the **independent variable**
2. To [determine/investigate/compare] how the **independent** variable affects the **dependent variable**

Your aim must:

- be short and succinct
- be directly linked to your question
- link the independent and dependent variables (variables are discussed further in subtopic 13.3).

Examples of aims include:

- To investigate the effects of electric field strength on the acceleration of a charged particle
- To investigate how the length of a pendulum affects the number of oscillations over a fixed period of time
- To compare gravitational and electric fields about a positive charge.

on Resources

 **Digital documents** Investigation topics (doc-19893)

13.2.4 Formulating hypotheses and making predictions

Formulating a **hypothesis** is an important step in the scientific method.

FIGURE 13.7 Hypotheses are testable explanations for a concept.

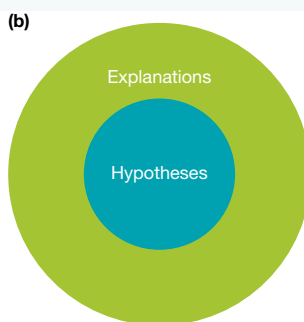
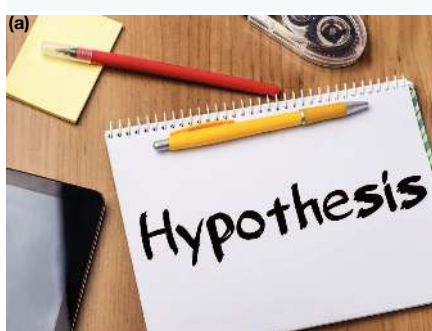
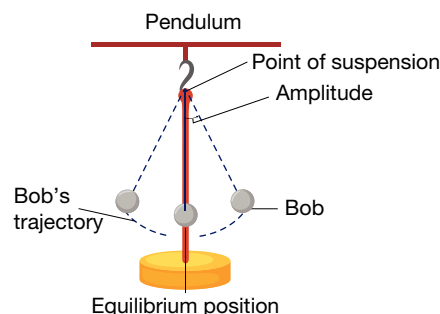


FIGURE 13.8 Table 13.3 shows a hypothesis for this investigation.



A hypothesis is a tentative, testable and falsifiable statement for an observed phenomenon, which predicts the relationship between two variables or predicts the outcome of an investigation.

Testable means that a hypothesis can be easily tested by observations and/or experiments.

Falsifiable means that there has to be a way to prove the hypothesis wrong.

A hypothesis usually predicts the relationship between two kinds of variables: an independent and a dependent variable. Variables will be explored further in subtopic 13.3.

To write a hypothesis, a good tip is to use the following format:

If (statement involving independent variable), then (prediction involving dependent variable) when (change in the independent variable occurs).

Typically, a scientific hypothesis starts with the tentative explanation and includes a prediction by which the hypothesis may be tested. Often, a hypothesis includes a tentative explanation or reasons for the prediction.

TABLE 13.3 Examples of a well-constructed hypothesis

IF	THEN	WHEN
IF the number of oscillations of a pendulum is inversely proportional to the pendulum length	THEN the number of oscillations of a pendulum with a longer string will be less than the number for one with a shorter string	WHEN a steeper incline is used.
IF the thickness of a wire affects the current flowing through it	THEN the resistance will decrease in a circuit	WHEN a thicker wire is used due to an increased area for electrons to flow.

Now consider the following statements and decide if each is an example of a well-formatted hypothesis:

Statement 1: ‘The heavier the object, the faster it will fall.’

No. This is simply a testable prediction. It does not include a tentative explanation.

Statement 2: ‘If an object has a greater mass, then it will fall faster than smaller objects.’

No. This does not identify a tentative explanation. The statement is a method followed by a predicted outcome. It also assumes that smaller objects don’t have a large mass, which is not correct.

Statement 3: ‘If an object with a greater mass causes an increased acceleration, then it will fall faster than an object with a smaller mass when they are both dropped at the same time.’

Yes. This identifies a tentative hypothesis (explanation) and a predicted outcome by which the hypothesis can be tested.

It is important to note that many different writing styles are used for hypotheses. The way you write your hypothesis will be dependent on the investigation you are conducting.

SAMPLE PROBLEM 1

Polly is putting the kettle on. Polly is very curious about science and wants to see how she can change the speed the water boils. She has heard rumours that salt causes water to boil faster. She has four different types of salt in her house: table salt, sea salt, Himalayan pink salt and chicken salt.

Write an appropriate research question, aim and hypothesis for the scenario listed above:

 **Teacher-led video:** SP1 (tlvd-0107)

THINK

1. Determine the variables to help write an aim, hypothesis and research question.

The factor that Polly is manipulating, the independent variable (IV), is the type of salt.

The factor that Polly is measuring, the dependent variable (DV), is the time it takes for the water to boil.

2. Create a research question based on Polly’s problem. Make sure that the question is one that is testable and clearly outlines what is occurring in the investigation.
3. Write an aim clearly outlining the purpose of the investigation. Be sure to link the IV and DV.
4. Write a hypothesis in the ‘IF ... THEN’ format. Remember, a hypothesis needs to link the IV and DV. Your hypothesis may not be correct, but it must be testable.
(You may also specify which salt you think would do this best.)

WRITE

The IV is the salt type.

The DV is the time it takes for the water to boil.

Does the type of salt added to water impact the time it takes for water to boil?

To determine if different types of salt impact the time it takes for water to boil.

If table salt, sea salt, Himalayan pink salt or chicken salt is added to water, then the time taken for the water to boil will decrease when salt is added, with pure table salt causing the largest decrease in time.

PRACTICE PROBLEM 1

Jack wants to know if changing the material of the clothing Jill is wearing will impact the speed at which she rolls down the hill.

Write an appropriate research question, aim and hypothesis for the scenario.

Resources

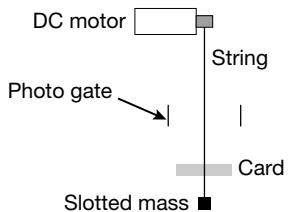
 **Interactivity** Formatting a hypothesis (int-7732)

13.2.5 Planning and undertaking experiments

Planning experiments

Once your teacher has approved your topic, and you have written a question, aim and hypothesis, the next step of the process begins. One way that planning may begin is through the use of a practical investigation proposal.

FIGURE 13.9 A sample practical investigation proposal

Practical investigation proposal	
Name:	Jill
Partner's name: <i>(optional)</i>	Jac
Title of your investigation:	The efficiency of a DC motor
Briefly describe its purpose: <i>(A brief sentence, but needs to be precise)</i>	To investigate how efficiently a DC motor converts electrical energy into gravitational potential energy by raising a mass
Write down three starting questions you want to answer. <i>(These are to help focus your planning.)</i>	What is the most efficient voltage for a given mass? How does this voltage vary with the mass? For a given voltage is there a mass the motor cannot lift? Is the mass raised at a constant speed?
List independent variables, indicating which are continuous and which are discrete, as well as dependent variables. <i>(Enables your teacher to see if you have thought of all the obvious variables.)</i>	Independent: voltage supplied to the DC motor, the mass being raised, the diameter of the spindle about which the string from the mass is wrapped, the type of DC motor (discrete) Dependent: The efficiency of the DC motor, the energy supplied to the DC motor, the time for the mass to travel a measured distance, gain in gravitational potential energy
List the physics concepts and relationships that you expect to use in your investigation. <i>(To give your teacher an indication of the extent of your understanding of the topic)</i>	Electric energy consumption, $W = VIt$ Gain in gravitational potential energy = $mg\Delta h$ Efficiency = $\frac{mg\Delta h}{VIt}$
List the equipment and measuring instruments that you plan to use. <i>(For your teacher to see whether you have the right tools for the task.)</i>	DC motor with spindle on the shaft Masses — either slotted masses and/or plasticine Light, thin string, possibly with a small card of known length attached near the bottom to trigger a photo gate Variable power supply, voltmeter and ammeter, switch Ruler and balance Timer, preferably electronic, e.g. a photo gate
Sketch your experimental set up. <i>(This will make your first day of investigating smoother, and your teacher may be able to suggest refinements.)</i>	
List the steps in your experimental design. <i>(This is an important stage in your planning and it will enable your teacher to see if there is anything you have forgotten.)</i>	1. Connect the circuit and attach a mass to the string. Set to a low voltage and turn on the power supply. Adjust arrangement of equipment and voltage and mass values to get a safe set-up that is capable of producing data without damaging the motor. 2. Adjust timer, card and photo gate set-up to produce consistent readings. 3. Set the mass at a known value, set the voltage at a low value, and measure the current at least five times. 4. Increase the voltage settings in increments of 1 V and repeat the measurements. Use a voltage divider circuit if in-between voltage values would be useful. 5. Increase the mass progressively and repeat steps 3 and 4 each time. 6. Check for possible intermediate mass values to identify maximum efficiency.
Any special requests <i>(E.g. equipment may need to be left set up between classes, or access at lunchtime or after school may be needed.)</i>	None

It is important that your investigation is able to:

- produce results that are reliable, accurate, precise and valid
- clearly show the link between dependent and independent variables
- include control variables that are not being tested
- minimise uncertainties and errors where possible
- allow the use of equipment and skills that are cost and time effective
- where possible, have a **control group** (not exposed to an independent variable to compare as a baseline) and numerous **experimental groups** (exposed to the independent variable).

An example of control and experimental groups may occur in a practical investigation exploring the impact of spikes on running shoes. Control groups provide a point of comparison of results when the independent variable is not applied. The experimental groups would be shoes with spikes (you might be testing different types or different number of spikes). The control group would be shoes without spikes.

At the end of your planning, you should be able to produce three written documents (these should be in your logbook). The last two however may be provided together as a detailed practical proposal:

- a risk analysis based on the hazards that you have identified (refer to section 13.6.2 for detail on risk assessments)
- a detailed list of equipment required, along with quantities (refer to section 13.5.3 for detail about different equipment used in physics)
- an explicit, step-by-step method that takes all of your planning into consideration, including diagrams where relevant.

Conducting investigations

When conducting investigations, it is vital to:

- follow all health and safety protocols.
- ensure you know how to use any chosen equipment correctly to minimise errors.
- carefully follow your methods; if any changes are required, note these down in your logbook.
- ensure you are controlling variables outside your independent variable to keep your results accurate and precise
- clearly record any results obtained, along with the date. This includes any results that did not go according to plan and any results concerning both the control and experimental groups.
- make sure that you are carefully packing up equipment after use. If equipment is required to be set up for a few days, make sure it will be in a location where it cannot be impacted by other individuals or environmental factors.
- repeat your experiment, if time allows, to improve accuracy and reliability.

13.2 EXERCISE

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

1. Using the following topics, create a testable question that could be used for a practical investigation:
 - (a) The type of tennis court surface and the impact on ball bounce
 - (b) Using different numbers of resistors in an electric circuit
 - (c) Examining differences in magnetic fields created by iron and nickel.
2. What is the purpose of a logbook in practical investigations?
3. Which of the following is an acceptable hypothesis?
 - A. As you heat a substance, it melts.
 - B. If the temperature of water increases and particles gain energy, then the water will change state from liquid to gas.
 - C. If the temperature of water increases, then particles will gain energy.
 - D. Heat causes particles to move faster.
4. List the main steps required in planning an investigation.

5. A student has made three parachutes with the same paper but has cut them into three different shapes: a circle, a square and a triangle. The student wants to see which stays in the air the longest when dropped from a height of 20 metres.
- Provide an aim for this investigation.
 - Provide a hypothesis for this investigation.

Fully worked solutions and sample responses are available in your digital formats.

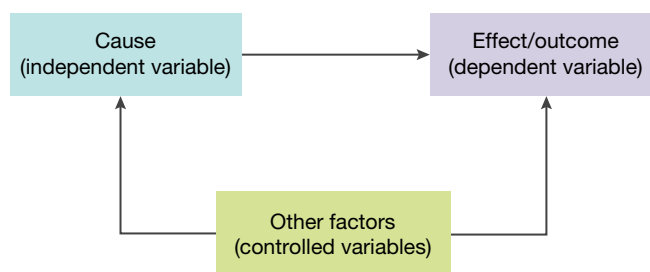
13.3 Variables

KEY CONCEPT

- Independent, dependent and controlled variables.

In an experiment, a variable is any factor that the researcher can control or change or measure. Three kinds of variables are commonly recognised (see figure 13.10). For some variables, you will set the value at the start of each experiment; others will be determined by your experiment; and sometimes there may be variables that you calculate using your measurements.

FIGURE 13.10 Diagram showing the relationships between variables in an experiment



- An **independent variable** is a factor that is deliberately manipulated by the investigator and affects the dependent variable. For example, you may be running a simple test to compare different types of materials and their resistance. The independent variable is the type of material. When graphing results of the independent and dependent variables, the independent variable is usually placed on the horizontal axis.
- A **dependent variable** is the factor that the investigator measures. The dependent variable is affected by the independent variable. In the investigation mentioned earlier, the dependent variable would be the recorded resistance. The dependent variable is usually placed on the vertical axis of a graph.
- Controlled variables** are all the factors that the investigator must maintain at constant values through the course of an experiment. If these factors are not kept constant, they can cause confusion in the interpretation of experimental results because they can cause changes in the dependent variable. For example, if you don't control the amount of liquid used when examining the boiling point of different liquids, the data will be hard to interpret. (You won't know whether it was the different volume or the different liquid type that caused the observed result.) In the investigation just mentioned, controlled variables would include the voltage from the power pack, the length of wires, the size of the material and the tool used to measure resistance. Often, controlled variables also include environmental factors such as temperature and humidity, but these are harder to control.

Example of types of variables

Allira and Hunter are investigating the effect of different starting blocks on a sprint start. They are trying different types of blocks to explore if a specific type of block allows for the greatest acceleration.

- **Independent variable:** The factor that is being manipulated is *the type of block*.
- **Dependent variable:** The factor that is being measured is the *acceleration* during a sprint start.
- **Controlled variables:** (i) The same runner is used to test each block, (ii) the same type of running shoes are used in each test, (iii) the same weather and surface conditions are used in each trial.

Variables can also be considered as numerical (quantitative) or categorical (qualitative). Refer to section 13.5.2 for further detail on this.

FIGURE 13.11 The use of starting blocks by a sprinter



on Resources

Interactivity Variables (int-7731)

13.3 EXERCISE

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

1. Describe the difference between a dependent and an independent variable.
2. Why is it important to control variables in an investigation?
3. Belinda and Paul plan to investigate the sweet spot of a cricket bat. The variables they are considering are: (i) the position on the bat where the ball hits, (ii) the speed of the ball at impact, (iii) the mass of the bat, (iv) the shape of the bat, (v) the angle that the ball is hit, (vi) whether the handle is fixed or whether the handle is free to move.
 - (a) Describe how you know these variables are independent.
 - (b) Determine for each of these variables if they are numerical (quantities) or categorical (qualities).
 - (c) List as many dependent variables as you can think of that Belinda and Paul might consider for their investigation, including ones that can be calculated from others.
4. Here are two topics with some variables identified. Complete the table for three others.

	Independent variables		Dependent variables
	Numerical	Categorical	
Bouncing basketball	i. Drop height ii. Pressure of the ball	Surface that the ball lands on, ball type	Rebound height, impact time, energy loss, change in momentum, average force of impact
Efficiency of a DC motor	i. Voltage drop across motor ii. Mass being raised iii. Diameter of spindle	Type of DC motor	Current through motor, time to travel fixed distance, power supplied, efficiency
(a) Performance of a parachute			
(b) The temperature inside cars			
(c) Movement of a ball down a hill			

Fully worked solutions and sample responses are available in your digital formats.

13.4 Concepts specific to investigations (key terms and representations)

KEY CONCEPT

- The physics concepts specific to the investigation and their significance, including definitions of key terms, and physics representations.

KEY SCIENCE SKILL

- Communicate and explain scientific ideas.

13.4.1 Concepts specific to investigations

As part of an investigation, it is vital to link key physics concepts that are relevant and clearly explain their significance. This shows a clear link between your understanding of practical application and your understanding of theory.

Background knowledge

Concepts should be researched prior to commencing your investigation, recorded in your logbook (and referenced). This background information will also form part of your introduction in your poster.

Concepts that are relevant to your investigation include:

- explanations of key formulas
- definitions of key terms
- detail about the theories being examined
- information about other practical investigations exploring similar concepts.

An example of this may be an exploration of Young's double-slit experiment. In your background information, it would be important to explain what this experiment is, its findings from the past, information about its use, the wavelike nature of light and a description of key formulas relevant to the investigation (such as $\Delta x = \frac{\lambda L}{d}$).

You should also clearly link concepts to theory from your background knowledge in your **discussion** section of the investigation.

13.4.2 Key terms

It is vital in practical investigations to define any key terminology.

This can be done in two ways:

- Within a report itself
- As part of an appendix or glossary at the end of the report.

Read the following excerpt of an introduction from a scientific report written by a student. The report concerns an investigation of photons and matter of the same wavelength.

Photons are discrete packets of electromagnetic energy with zero mass and zero electric charge. Matter, on the other hand, has mass and can have an electric charge.

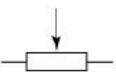
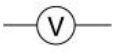
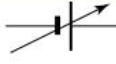
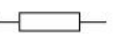
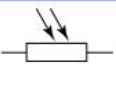
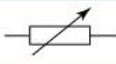
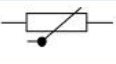
In this investigation, the momentum of photons and matter of the same wavelength will be explored. This will be calculated using the formula $p = \frac{h}{\lambda}$, in which λ is the wavelength, p is the momentum of a particle and h being the Planck constant (6.63×10^{-34} J s), which is the energy carried by a photon relative to its frequency.

This student has clearly defined key terms as part of their introduction within their report itself. What terms have they defined?

Electrical circuit representations

Many different symbols can be used in electric circuits to show the various components.

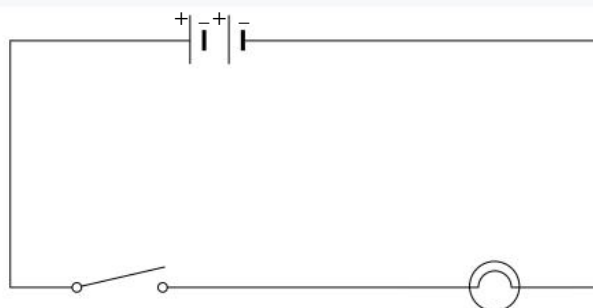
TABLE 13.4 Some representations of electric circuit components

Circuit component	Symbol	Circuit component	Symbol
Connection between conductors	•	Resistor with sliding contact to give a variable resistance	
Terminal	○	Semiconductor diode*	 or 
Conductors not connected*	 or 	Single pole switch (open)	
Conductors connected*	 or 	Button switch (open)	
Earth*	 or 	Voltmeter	
Battery		Ammeter	
Variable power supply*	 or 	Incandescent lamp*	 or 
Resistor	 or 	Light-dependent resistor (LDR)	
Variable resistor*	 or 	Heat-dependent resistor (Thermistor)	

*The first of the two alternative symbols is used in this book.

In sketches or diagrams of these models, it is clear what component each of these symbols represents, as seen in figure 13.14.

FIGURE 13.14 Representation of a simple electric circuit



Scientific notation

Very large and very small quantities can be more conveniently expressed in scientific notation. In scientific notation, a quantity is expressed as a number between 1 and 10, multiplied by a power of 10.

To write in scientific notation, follow the form $N \times 10^a$, where N is a real number between 1 and 10, and a is an integer (positive or negative).

When converting numbers into scientific notation, these steps should be followed:

1. Determine where the decimal point needs to go so that N is between 1 and 10.
2. Count the number of places the decimal point is moved to determine a (the power of 10 or the exponent). If the decimal point is moved to the left, a will be positive; if it is moved to the right, a will be negative.
3. Write the number in scientific notation.

For example, the average distance between the Earth and the Moon is 380 000 000 m. This is more conveniently expressed in scientific notation as 3.8×10^8 m.

In physics, scientific notation is generally used for numbers less than 0.01 and greater than 1000.

Quantities in scientific notation can be entered into your calculator using the EXP, 10^x or $^$ button (depending on the type of calculator you use).

SAMPLE PROBLEM 2

- a. The average distance between the Earth and the Sun is 149 600 000 kilometres. Write this in scientific notation.
- b. The mass of a proton is 0.000 000 000 000 000 000 001 67 g. Write this in scientific notation.

 **Teacher-led video:** SP2 (tlvd-0103)

THINK

- a. 1. Determine the position that a decimal needs to be placed in for the number to be between 1 and 10, and remove any 0s that are not between non-zero digits.

The decimal place would need to go between 1 and 4 to form 1.496.

2. Determine the exponent by establishing the number of times the decimal place was moved.

If the decimal was moved to the left to convert to scientific notation, the exponent should be positive; if the number was moved to the right, the exponent should be negative. The decimal was moved 8 spots to the left so the exponent is 8.

3. Place the number in scientific notation.

- b. 1. Determine the position that a decimal needs to be placed in for the number to be between 1 and 10 and remove any 0s that are not between non-zero digits.

The decimal place would need to go between 1 and 6 to form 1.67.

2. Determine the exponent by establishing the number of times the decimal place was moved.

If the decimal was moved to the left to convert to scientific notation, the exponent should be positive; if the number was moved to the right, the exponent should be negative. The decimal was moved 24 spots to the right so the exponent is -24 .

3. Place the number in scientific notation.

WRITE

a. 1.496

10^8

1.496×10^8 km

b. 1.67

10^{-24}

1.67×10^{-24} g

PRACTICE PROBLEM 2

Express the following quantities in scientific notation:

- the radius of the Earth, 6 370 000 m
- the speed of light in a vacuum, 300 000 000 m s⁻¹
- the diameter of a typical atom, 0.000 000 000 3 m.

13.4 EXERCISE

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

- Explain two ways by which key terms can be defined in your report.
- Why are representations useful in scientific reporting?
- Draw a simple circuit using the information in table 13.4 and in figure 13.14. Your circuit should contain wires, a single cell battery, a resistor, a light globe and a voltmeter.
- Express the following quantities in scientific notation:
 - the radius of Jupiter, 71 500 km
 - the number of kilometres in a light year, 9 460 730 472 580 km
 - the size of the influenza virus particle, 0.000 000 08 m.
- A student is writing a simple report about the addition of two vectors (vector A and vector B):
Vector A is 8 cm long and goes to the right. Vector B is 6 cm long and also goes to the right. Adding these vectors gives the vector, named C. This relationship can be expressed as $A + B = C$.
Rewrite this relationship using appropriate representations for the vectors, and draw a diagram to represent the addition of the two vectors.

Fully worked solutions and sample responses are available in your digital formats.

13.5 Scientific research methodologies and techniques

KEY CONCEPT

- The characteristics of scientific research methodologies and techniques of primary qualitative and quantitative data collection relevant to the selected investigation, including experiments (gravity, magnetism, electricity, Newton's laws of motion, waves) and/or the construction and evaluation of a device; the precision, accuracy, reliability and validity of data, and the identification of, and distinction between, uncertainty and error.

KEY SCIENCE SKILLS

- Conduct investigations to collect and record data.
- Analyse and evaluate data, methods and scientific models.

13.5.1 Characteristics of scientific research methodologies

It is important to carefully follow **scientific research methodology** in conducting practical investigations, to ensure that your results are as precise, accurate, reliable and valid. This includes minimising errors and uncertainties in data in order to draw **conclusions** in relation to your question.

Each type of research method has its specific purposes, procedures, advantages and limitations. The researcher's choice depends on which method is most appropriate for the specific topic of research interest and hypothesis being tested.

There are different types of scientific inquiry and research methods that can be used, as shown in table 13.5.

In all scientific inquiries, various processes are followed. These include the following:

- Formulating a question and hypothesis to be tested
- Controlling variables
- Using control groups and experimental groups
- Completing a logbook outlining the introduction, methodology, results, discussion and conclusion of an investigation
- Ensuring that methods are being taken to allow for validity, accuracy, precision and reliability
- Ensuring that methods are being used that reduce uncertainties and errors
- Collecting data accurately in an appropriate form that best suits the question being investigated.

TABLE 13.5 Types of scientific inquiry

Method	Use
Controlled experiment	Determining the relationship between an independent and dependent variable. All other variables are controlled. For example, testing how the size of a parachute affects the rate it falls to the ground.
Single-variable investigation	Exploring how a variable changes over time and understanding causes of the observations and how other factors impact it. For example, investigating how electric fields change over time.
Identification	Investigating if objects or events belong to specific sets or are parts of new sets. For example, exploring if gravity is a contact or non-contact force.
Designing	Designing a device using scientific knowledge. For example, designing, constructing, testing and evaluating a motor.
Investigating models	Exploring everyday phenomena and collecting evidence to test the model. For example, devising an investigation to test Newton's First Law of Motion.

13.5.2 Techniques of primary qualitative and quantitative data collection

Data is a set of facts that are collected, observed or generated. Data that you gather may come from **primary sources** or from **secondary sources**. Typically, data that you collect is raw data that must later be analysed and interpreted to produce useful information.

- Primary sources of data provide direct or firsthand evidence about some phenomenon, as, for example, a research investigation. Your completed logbook will be a primary source of data about pursuing an investigation concerning your research question.
- Secondary sources of data are comments on or summaries and interpretations of primary data. Sources of secondary data include review articles in scientific journals, books, newspapers and popular science magazines as summaries and/or comments on the research of others.

FIGURE 13.15 Recording data is vital in investigations.



Qualitative and quantitative data

Qualitative data (or **categorical data**) is usually expressed in words. It is descriptive and not numerical and can be easily observed but not measured. Bar graphs or pie graphs are often used to display the frequencies of categorical variables (graphs will be explored later, in section 13.7.1).

There are two types of categorical data:

- *Ordinal data* can be ordered or ranked, for example ionisation energies (1st, 2nd, 3rd) or opinion polls (strongly agree, agree, disagree, strongly disagree)
- *Nominal data* cannot be organised in a logical sequence — for example types of sub-atomic particles (proton, neutron or electron) or the type of surface a ball rolls down.

Quantitative data (or **numerical data**) can be precisely measured and have values that are expressed in numbers. Line graphs or scatter plots are often used to display the frequencies of numerical variables.

There are two types of numerical data:

- *Continuous data* can take any numerical value, such as the release height of a parachute or the temperature of an object.
- *Discrete data* can only take on set values, which can be counted, such as the number of protons in an atom or the number of electron shells.

Table 13.6 shows examples of how some attributes can be expressed both qualitatively and quantitatively.

TABLE 13.6 Examples of data types

Attribute	Qualitative	Quantitative
Length of pendulum	Long	52 cm
Colour	Green	520 nm
Sound	Loud	85 decibels
Speed	Fast	120 km h ⁻¹
Temperature	Hot	100 °C
Gravitational force (acceleration)	Strong	9.8 m s ⁻²

When collecting data, it is vital to consider what is most appropriate for your investigation. Normally, the best evidence is primary quantitative data and, for most of your investigations, this is what should be collected and recorded as a minimum. However, sometimes an investigation only allows for the collection of qualitative data. Qualitative data can be subjective — if you record the speed as fast, what does that mean? Be clear and detailed in the data collected, particularly qualitative data.

In terms of primary data collection, it is important that results are carefully checked to make sure that recorded data is correct. Many people interpret measurements slightly differently, or use the wrong units, so make sure you are double-checking data. All your collected data should be recorded in your logbook — note down all observations (usually in a table). You may find noting down both the qualitative and quantitative data gives the clearest detail for your investigation.

13.5.3 Choosing techniques relevant to an investigation

It is important to select techniques that will best suit your investigation.

When selecting appropriate techniques, it is important to ensure that the:

- technique can be performed in an appropriate timeframe
- technique is appropriate to your investigation and serves a purpose to answering the question and supporting or rejected your hypothesis
- data is easily recorded, measured and interpreted, with a particular emphasis on quantitative data
- technique can be safely performed — this is particularly important in a school where health and safety restrictions are closely regulated
- equipment used in the technique is available and cost effective — if it is not available in a school, can it be used with permission at other locations?
- technique allows for the control of other variables — if there are too many factors that cannot be controlled and will impact results, the technique isn't a great choice for an investigation.

Selecting your measuring instruments

You should also consider the most appropriate equipment to use for a particular purpose.

Your school will have a range of measuring instruments. They will vary in precision and ease of use.

You won't always need to use the most accurate instrument. A simple instrument that allows for quick measurements will be enough more often than not. Sometimes a simple stopwatch is just as good as an electronic timer, and a beam balance may compare well to a very accurate top-loading balance.

Some instruments that you might consider are shown in the following list, based on what they measure. There are many more devices you may choose to use for your investigation.

FIGURE 13.16 Different types of measuring equipment vary in precision.



Mass

- Slotted masses of known mass (figure 13.17). Simple to use; accurate; comes only in multiples of a set weight, for example, 50 g.
- Beam balance (figure 13.18). Accurate with a large range of values; can be time consuming to measure several masses.

FIGURE 13.17 Slotted masses



FIGURE 13.18 Beam balance



- Spring balance (figure 13.19). Quick to use; covers a large range of masses; not very accurate.
- Top-loading balance (figure 13.20). Very accurate; very good for small masses; simple to use. With equipment set up above the balance, it can be used to measure small variations in attractive and repulsive forces such as magnetic force, electric force and surface tension. If the balance sits on a laboratory jack, force against distance can be easily measured.

FIGURE 13.19 Spring balance



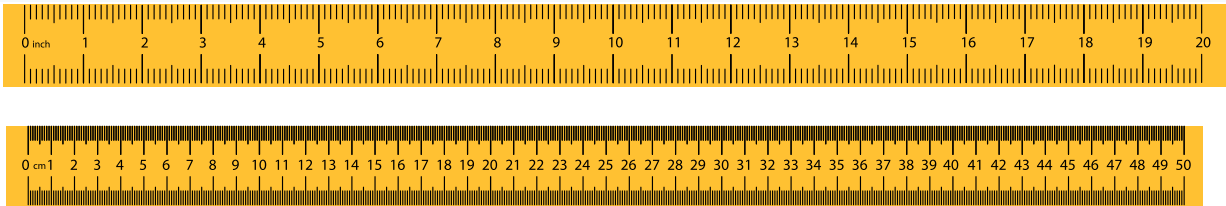
FIGURE 13.20 Top-loading balance



Length

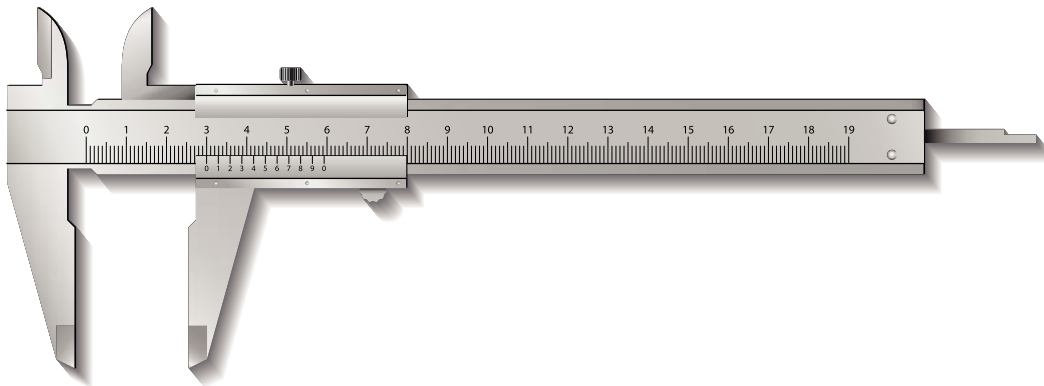
- Metre ruler (figure 13.21). Accurate; good for a range of distances; can be read to about 0.5 mm.

FIGURE 13.21 Rulers



- Laboratory jack. For fine adjustment of height.
- Vernier calliper (figure 13.22). For precision measurement of short distances; takes some time to learn how to use.

FIGURE 13.22 Vernier calliper



- Micrometer (figure 13.23). For precision measurement of thicknesses; takes some time to learn how to use and can be easily damaged.

FIGURE 13.23 Micrometer



Time

- Stopwatch. Simple to use; accurate down to your response time; not reliable for short time intervals.
- Electronic timer. Requires some instruction; very accurate; best suited for short time intervals; can be used with electrical contacts and photogates.

Temperature

- Glass thermometer. Very easy to use but often only works for set temperatures (will not work if temperature is too high or too low). Glass thermometers are not as precise due to a limited number of markings.
- Digital thermometer: Very easy to use and gives more precise measurements; however, digital thermometers can be easily affected by external air temperature if used incorrectly.

Motion

- Ticker timer (figure 13.24). Simple to use, however, limited in accuracy; best with objects moving over a short distance; results can be time consuming to analyse.
- Air track (figure 13.25). Very accurate, particularly if used with photogates; very effective in studying collisions; takes some time to set up, but data collection is very efficient once done.

FIGURE 13.24 Ticker timer



FIGURE 13.25 Air track



Source: Bhavesh Chauhan

- Ultrasonic motion detector. Quite accurate; useful with real motions; lots of data, which means data analysis in Excel can be time-consuming.

FIGURE 13.26 Ultrasonic motion detector



- Video with analysis software. Quite accurate; requires some setting up; data obtained from software; data analysis in Excel can be time consuming. Free video motion analysis software are Tracker and PhysMo. Digital cameras with high-speed video are useful for measuring short, fast events.

Electrical

- Meters: Voltmeters (figure 13.27), ammeters, galvanometers. Easy to set up, but care is needed to ensure the meter is wired into the circuit correctly, otherwise the meter can be damaged; large range of values; usually analogue displays.
- Multimeters (figure 13.28). Easy to set up; more tolerant of incorrect use, but can be damaged if incorrectly connected to a high current; large range of values; usually digital displays.

FIGURE 13.27 Voltmeter



FIGURE 13.28 Multimeter

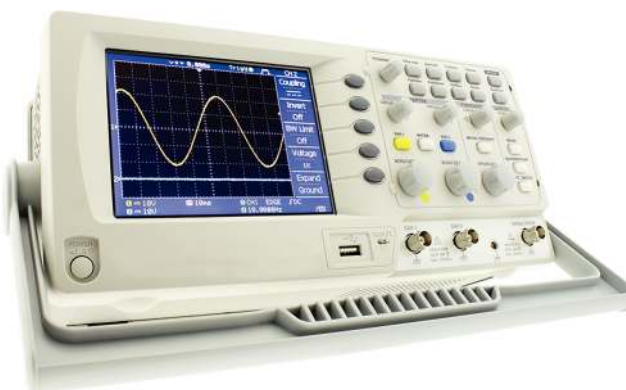


Specialist equipment

You may also have access to some specialised equipment that you could use in your practical investigation. Such equipment is unlikely to be available in a general school laboratory; however, it is important to note that the following equipment is highly accurate and precise. Discuss with your teacher if any of this equipment is available for use at your school or nearby. Alternatively, you may wish to explore these when discussing uncertainties and possible errors in the data and results you obtained.

- Cathode-ray oscilloscope (CRO). Even though the CRO is a visual voltmeter, it is a versatile instrument. It can measure both constant and varying voltages. The sweep of the trace across the screen can be used to measure time intervals of the order of millionths of a second. Many transducers, such as microphones, produce a voltage that can be displayed on the screen, either for analysis or measurement of very short time intervals. There are also computer versions of CROs that can be freely downloaded.
- Data loggers. There are sensors now available for most physical quantities, such as temperature, pressure, light intensity, motion, force, voltage, current, magnetic field and ionising radiation. The recording of data by these sensors for later analysis greatly facilitates practical investigations.
- Apps. There is an increasing number of apps that perform measurement functions. The accuracy of each needs to be confirmed before being used in a formal investigation, but it is an area worth exploring. Some sources include Physics Toolbox and Sensor Kinetics.

FIGURE 13.29 Cathode-ray oscilloscope



on Resources

 **Video eLesson** Using Vernier callipers (eles-2558)

13.5.4 Precision, accuracy, reliability and validity

For your investigation, it is important to carefully consider the data you obtain and the confidence you can have in the conclusions drawn. Understanding the precision and accuracy of your data is important to ensure your findings are both reliable and valid.

Precision

Precision refers to how close multiple measurements of the same investigation are to each other. It is often difficult to have completely precise results due to random error.

In table 13.7, student 1's data is seen to be more precise as the range of their data is smaller compared to that of student 2.

TABLE 13.7 Two investigations measuring the height a tennis ball bounces

Investigation by student 1		Investigation by student 2	
	Height of bounce (cm)		Height of bounce (cm)
Trial 1	39.3	Trial 1	39.3
Trial 2	39.4	Trial 2	42.2
Trial 3	39.3	Trial 3	31.4
Trial 4	39.2	Trial 4	35.3
Trial 5	39.0	Trial 5	45.2

FIGURE 13.30 Results vary in precision when measuring the height of a ball



Accuracy

Accuracy refers to how close an experimental measurement is to a known value. If an archer is accurate, their arrows hit close to the target. Another example is in the experimental calculation of gravity, which is known to be 9.8 m s^{-2} on Earth.

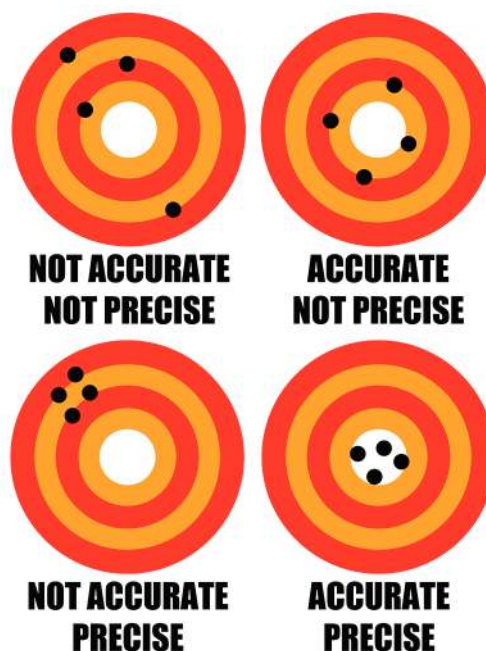
In table 13.8, student 1 is seen to clearly be more accurate, as their results have a much smaller deviation from the expected result of 9.8 m s^{-2} .

TABLE 13.8 Two investigations by different students to determine the acceleration of gravity from a pendulum.

Investigation by student 1		Investigation by student 2	
	Value of gravity		Value of gravity
Trial 1	9.85 m s^{-2}	Trial 1	12.59 m s^{-2}
Trial 2	9.75 m s^{-2}	Trial 2	12.62 m s^{-2}

While student 1 has the more accurate results, student 2 has the more precise results. In order to obtain the best experimental data, results that are both accurate and precise are required.

FIGURE 13.31 Comparing precision and accuracy



SAMPLE PROBLEM 3

Students conducted an experiment to determine the temperature of a substance as it changed from a solid to a liquid. They repeated the experiment four times and achieved the following results:

Student 1: 56.5°C, 58.0°C, 60.0°C, 55.0°C

Student 2: 60.5°C, 61.0°C, 60.5°C, 62.0°C

Student 3: 56.5°C, 58.5°C, 57.0°C, 56.0°C

Students were then provided with the exact value of the melting temperature of the substance, which was found to be 56.48°C.

- Which student had the least accurate data?
- Which student had the least precise data?
- Was the student with the most precise data also the student with the most accurate data? Explain your answer.

 **Teacher-led video:** SP3 (tlvd-0218)

THINK

- Review what accuracy means.
 - Explore the data of the three students.
 - Determine which student had the least accurate data.
- Review what precision means.
 - Explore the data of the three students.
 - Determine which student had the least precise data.
- Identify the students with the most accurate and most precise data.
 - Respond to the question and explain your answer.

WRITE

- Accuracy refers to how close a measurement is to a known value.
Student 1 had data that was 1.48°C lower and 3.52°C higher than the actual data.
Student 2 had data that was up to 5.52°C higher.
Student 3 had data that was 0.48°C lower and data that was 2.02°C higher.
Student 2 had the least accurate data, as their values were the furthest away from the actual value.
- Precision refers to how close multiple measurements of the same investigation are to one another.
Student 1 had a data range of 5.0°C.
Student 2 had a data range of 1.5°C.
Student 3 had a data range of 2.5°C.
Student 1 had the least precise data.
- Using the results from a and b, it can be seen that student 3 had the most accurate data and student 2 had the most precise data.
The student who had the most precise data was not the same student who had the most accurate data. Students may have measurements very close together (precise), but the data may not be accurate. This may be due to errors in their measuring device or their interpretation of the melting point (when the solid becomes a liquid). Data may also be accurate without being precise; you can be close to the target, but the readings are inconsistent. For reliable and valid results, data should be both accurate and precise.

PRACTICE PROBLEM 3

Students conducted an experiment to determine the temperature of a substance as it changed from a liquid to a gas. They repeated the experiment four times and achieved the following results:

Student 1: 85.4°C, 92.0°C, 82.0°C, 75.5°C

Student 2: 83.5°C, 85.0°C, 85.5°C, 86.5°C

Student 3: 85.5°C, 90.0°C, 89.50°C, 81.0°C

Students were then provided with the exact value of the boiling temperature of the substance, which was found to be 85.4°C.

- Which student had the least accurate data?
- Which student had the least precise data?
- Was the student with the most precise data also the student with the most accurate data?

Explain your answer.

Reliability

Reliability refers to whether another researcher could repeat your investigation by following your method, and obtain similar results. The more times an experiment is replicated (with similar results recorded), the more reliable the results are considered to be.

Experiments that are reliable shouldn't just be able to be carried out by the investigator, but also by a third party. The investigation should be reproducible, with the same results obtained by an individual who repeats the investigation in the same conditions using the same methodology. If a test is reliable, it usually has both accuracy and precision, as errors are reduced through repetition.

Validity

The **validity** of data refers to the credibility of the research results from experiments or from observations. Validity factors into both experimental design and implementation. Experiments that are valid usually are using the results from one manipulated variable, where other variables are controlled. It is also impacted by factors such as experimental bias.

Validity applies more to biology and psychology, where precise measurement is more difficult and there is the risk of bias on the part of the researcher. In physics and chemistry, the variables are quantifiable and physically measurable.

If your experimental method clearly relates to the purpose of the investigation and you take care to be precise in your measurements and thorough in your analysis, your results should be valid and meaningful.

Validity can be one of the following:

- Internal.** The focus is on whether the results can be believed and if they have been affected by factors that were unsuccessfully controlled: did the experiment measure the variable that was being examined in the experimental question and outlined in the hypothesis?
- External.** This does not apply much to physics, but it involves whether the results obtained in a sample are indicative of the results expected for the entire population. This can be reduced by removing bias and using a large and random sample.

Measurements that are valid must also be reliable and therefore must have accuracy and precision.

13.5.5 Distinction between uncertainty and error

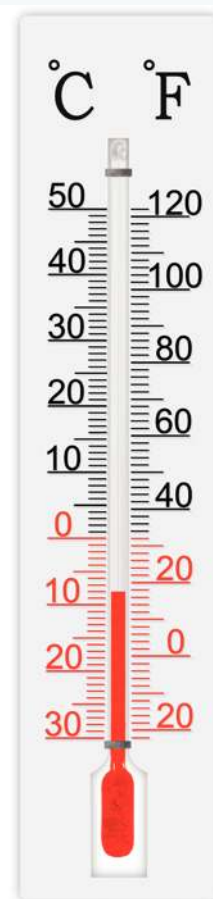
Uncertainty is the acknowledgement that, no matter how precise an instrument might be, there is a limit to that precision. The uncertainty is a range within which a measurement lies. An error bar is a way of representing that uncertainty graphically.

Every instrument has a limit to how precisely it measures. The scale or digital display imposes a constraint on how many digits you can record.

Error, on the other hand, is linked with the accuracy of an experiment. It is a measure of the difference between a measurement taken and the true value that is expected. Errors can be systematic or random, which will be investigated in section 13.7.4.

For example, there are both errors and uncertainties associated with using thermometers. Two individuals may look at a thermometer and not get the same exact result. The results may not be identical between two different thermometers. The thermometer only gives measurements to the accuracy of 1 °C and not decimal values.

FIGURE 13.32 Thermometers can have issues with precision and accuracy.



13.5 EXERCISE

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

1. Outline the differences between validity and reliability.
2. Is it essential that the results of an experiment can be replicated in order for the experiment to be considered reliable? Explain your answer.
3. Give an example of when results would not be considered reliable.
4. List three procedures that could adversely impact on the internal validity of an experiment.
5. Explain the following, with reference to an example: an experiment can be reliable but not valid, whereas an experiment that is valid must also be reliable.
6. Explain, with examples, the difference between precision and accuracy.
7. Give an example of a strength and a weakness of quantitative and qualitative data.
8. Describe why primary data is often stronger evidence than secondary data.

Fully worked solutions and sample responses are available in your digital formats.

13.6 Health and safety guidelines

KEY CONCEPT

- Identification and application health and safety guidelines.

KEY SCIENCE SKILL

- Comply with safety and ethical guidelines.

13.6.1 Health and safety guidelines

Part of the enjoyment of a practical investigation is that the topic may be unconventional or use an innovative method. Such situations, however, can present some risk, so special care needs to be taken to ensure yourself and others are safe.

General safety rules

Some general safety precautions will help to ensure that you and others are not injured in the laboratory.

- Wear protective clothing. This might include a laboratory coat, safety glasses and gloves.
- Be aware of the position of safety equipment such as the fire blanket, fire extinguisher, safety shower and eye wash.
- If you are unsure how to operate equipment or how to use an apparatus, ask your teacher to show you how to operate it.
- Read labels carefully to confirm contents and concentration of chemicals (if any are being used).
- Clean and return all equipment to the correct places.
- Check for the correct disposal of equipment and chemicals, including damaged equipment (e.g. broken glasswear).
- Read instructions carefully before starting an experiment.
- Prepare a risk assessment for required chemicals and equipment.
- Do the investigation as outlined in your approved plan. Don't vary your plan without approval from your teacher.
- Don't do experimental work unsupervised unless you have prior approval from your teacher.
- When first setting up electrical experiments, ask your teacher to check the circuit.
- Don't interfere with the equipment set up of others.

It is important to address health and safety concerns through the use of a **risk assessment**.

A risk assessment is a procedure for identifying any components of an experiment that could be a health or safety risk. This could include hazardous chemicals, or sharp objects involved in an experiment. Table 13.9 lists the usual requirements for a written risk assessment.

TABLE 13.9 Requirements for a written risk assessment

Component of risk assessment	Description of section
Outline of investigation	Title, date and location of task
Summary of method	Brief list of steps indicating how the chemicals and equipment will be used
Equipment/chemicals used	List of materials used in the experiment
Equipment/chemical risk and hazards	List of hazards associated with the equipment
Risk control measures	General precautions taken to limit risks

An example of a risk assessment is shown in figure 13.33. (Risk assessments may also be created online using various websites.)

FIGURE 13.33 Risk assessment

RISK ASSESSMENT

ACTIVITY	Energy transferred by an electric current			
SUMMARY OF EXPERIMENT				
AIM	To calculate how much energy is transformed from electrical potential energy into the internal energy of a load			
METHOD	1. Find the mass of the copper vessel in the calorimeter. 2. Add 100 mL of water to the vessel. 3. Note the initial temperature of the water. 4. Connect the circuit as shown in the diagram. 5. Set the power supply on 6 V and close the switch. Start the stopwatch. 6. Record the current passing through and the voltage drop across the calorimeter. 7. Agitate the water with the stirrer until the temperature of the water reaches a value 10 °C above its initial value. 8. Open the switch and stop the stopwatch.			
PROTECTIVE MEASURES				
GLASSES	GLOVES	DUST MASK	LAB COAT	FUME HOOD
X			X	
SAFETY INFORMATION				
CHEMICAL				
Water				
Hazards • Temperature of water will increase during this investigation, which may lead to burns.		Safety precautions • Use hot hands or metal tongs when handling hot water vessel. • Allow water to cool before packing away equipment.		
EQUIPMENT				
Wire				
Hazards • Wire may be use as a restraint. • Wire may be wrapped around neck, which may lead to strangulation.		Safety precautions • Only provide enough material for the investigation. • Ensure cotton or wire is not wrapped around students.		
EQUIPMENT				
Power supply				
Hazards • If cable or power supply is not properly maintained, it may lead to electric shock or electrocution. • Water may splash up onto power supply, leading to electric shock.		Safety precautions • Regularly inspect for damage, particularly around cords or outlets and get tagged and tested. • Ensure water is kept away from power supply.		
EQUIPMENT				
Thermometer				
Hazards • There is a risk of glass breakage, especially if there are chips or cracks present. • Some thermometers contain mercury, so if a thermometer breaks, toxic mercury is released.		Safety precautions • Wear gloves, safety glasses and a lab coat. • Try to substitute mercury thermometer with alcohol thermometer.		
CONCLUSION				
• Ensure all equipment has been maintained and checked for damage before use. • Allow equipment to cool before packing away.				

Signed: _____

Date: _____

Source: John Wiley & Sons Australia

The procedure assesses potential hazards with the equipment being used, and standard handling procedures to ensure the health and safety of individuals and the environment.

Risk assessments should also take into consideration the correct disposal of equipment and chemicals to adhere to safety and bioethical guidelines. Many chemicals are harmful to the environment, so correct disposal is paramount. While chemicals on their own are not used often in practical investigations in physics, it is still important to understand their disposal. Batteries for example, can corrode or sustain damage, and chemicals within them may leak.

13.6.2 Ethics

Ethics involves concepts concerned with acceptable and moral conduct. Ethics not only applies to scientific investigations but also to many aspects of life, in determining what is 'right' and what is 'wrong'.

Science interacts with ethics in several ways, including the following:

- The way an experiment is conducted
- Confidentiality around research
- Conflicts with religious and personal beliefs.

Ethical standards and considerations also apply to any type of research or data collection method involving people (or animals).

Due to the nature of practical investigations in physics, ethical considerations are not usually a factor. However, it is an important consideration to take into account, as situations may arise when data collection involves humans.

For example, you may be conducting surveys on issues regarding the greenhouse effect and climate science. The confidentiality of individuals who provided responses needs to be considered and permissions gained.

It is important to be mindful of individuals regarding their personal or religious beliefs. For example, many individuals are opposed to animal experimentation. This is an ethical consideration that needs to be evaluated and understood when teaching and reporting on these topics.

FIGURE 13.34 Ethics concern the idea of moral choice.



13.6 EXERCISE

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

1. Identify possible hazards and safety precautions for each of the listed pieces of equipment.
 - (a) AAA battery
 - (b) Light globe used in a circuit
 - (c) Matches
 - (d) Measuring cylinder
 - (e) Iron filings
2. Provide two examples of occasions when ethics may be important in a physics investigation.
3. List five purposes of a risk assessment.
4. What other things do you think should be added to a risk assessment?
5. Draw a plan of your laboratory and label the positions of safety equipment.

Fully worked solutions and sample responses are available in your digital formats.

13.7 Methods of organising, analysing and evaluating primary data

KEY CONCEPT

- Methods of organising, analysing and evaluating primary data to identify patterns and relationships including sources of uncertainty and error, and limitations of data and methodologies.

KEY SCIENCE SKILLS

- Conduct investigations to collect and record data.
- Analyse and evaluate data and methods.

13.7.1 Organising primary data

Scientists gather raw data or plain facts from their observations. Data must be recorded at the time in a suitable form as, for example, text entries, sketches, tables and diagrams in logbooks or in field notebooks. These may be supplemented by audio and video recordings.

Using a table

Tables should be used when you initially record data and help separate and organise your information.

All tables should:

- have a heading
- display the data clearly, with the independent variable in the first column and the dependent variable(s) in later columns
- include units in the column headings, not with every data point
- be designed to be easy to read. If a table becomes too complicated, it is better to break it down into a number of smaller tables.
- use appropriate significant figures and decimal places consistently across data sets (for example, if one data point is 2.5, the other data point cannot just be 1; it should be 1.0).

FIGURE 13.35 Using a logbook is an easy way to record data.



FIGURE 13.36 Format of a scientific table

Always include a title for your table.

Temperature of the Earth at different depths

Depth (km)	Temperature (°C)
0	15
1	44
2	73
3	102
4	130
5	158
6	187
7	215
8	242

Include the measurement units in the headings.

The column headings show clearly what has been measured.

Use a ruler to draw lines for rows, columns and borders.

Enter the data in the body of the table. Do not include units in this part of the table.

Using a graph

Presenting results as a graph makes it easier to see patterns and trends in your data, allowing more accurate result analysis.

When drawing graphs, several things must be considered:

- *Decide on the type of graph to be used.* Different types of information are better suited to different types of graphs. When one piece of data is qualitative, a pie or column graph is better; however, if both independent and dependent variables are quantitative, a line graph or scatter plot is preferred.
- *Include a title.* This should link the dependent and independent variables that are shown in the graph and provide a context for the graph.
- *The independent variable should be on the horizontal (x) axis, and the dependent variable should be on the vertical (y) axis, for most graph types (excluding pie graphs).* There may be some exceptions to this. (For example, you may draw a graph to help analyse results or show mathematical relationships, and it may not be appropriate to place the independent variable on the horizontal axis).
- *The axes should be ruled and each should be clearly labelled.* Those displaying numerical variables should have a clearly marked scale and units.
- *Make sure your scale is suitable and the numbers are evenly distributed.*
- *For continuous variables, it is often appropriate to draw a line (or curve) of best fit.* This is a smooth line or curve that passes as close as possible to most of the plotted points.
- *Include the origin, the zero value for the variables, on both axes.* (The origin may not be part of the graph, but it's location should be noted, as seen in figure 13.36b.)

The most common representations include the following:

- scatter plots
- line graphs
- bar/column graphs
- histograms

Scatterplots

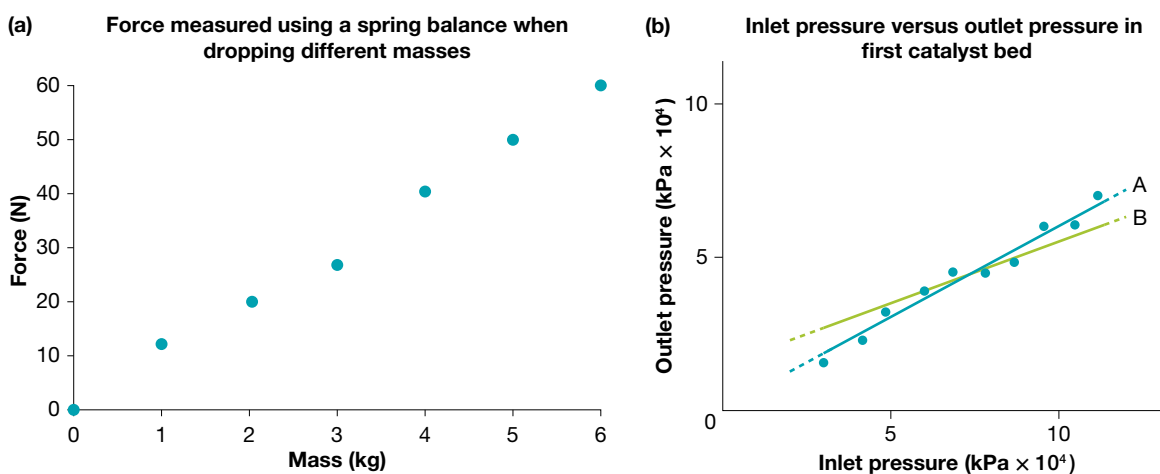
Scatterplots require both sets of data to be numerical or quantitative. Each dot represents one observation, recorded as the independent and dependent variable. A scatterplot can easily show trends between datasets, and correlations can be seen.

A **line of best fit** can be used to show the general trend of data, providing a quick summary.

The line of best fit doesn't need to pass through each data point, but should be as close as possible to them. As a general rule, try to have as many data points above your line as you have below. Don't assume your line must pass through the origin. The line of best fit may also be a curve for some data sets.

In figure 13.37b, line A is a better fit than line B although the line does not pass through any points.

FIGURE 13.37 Example of (a) scatterplot (b) scatterplot with a line of best fit

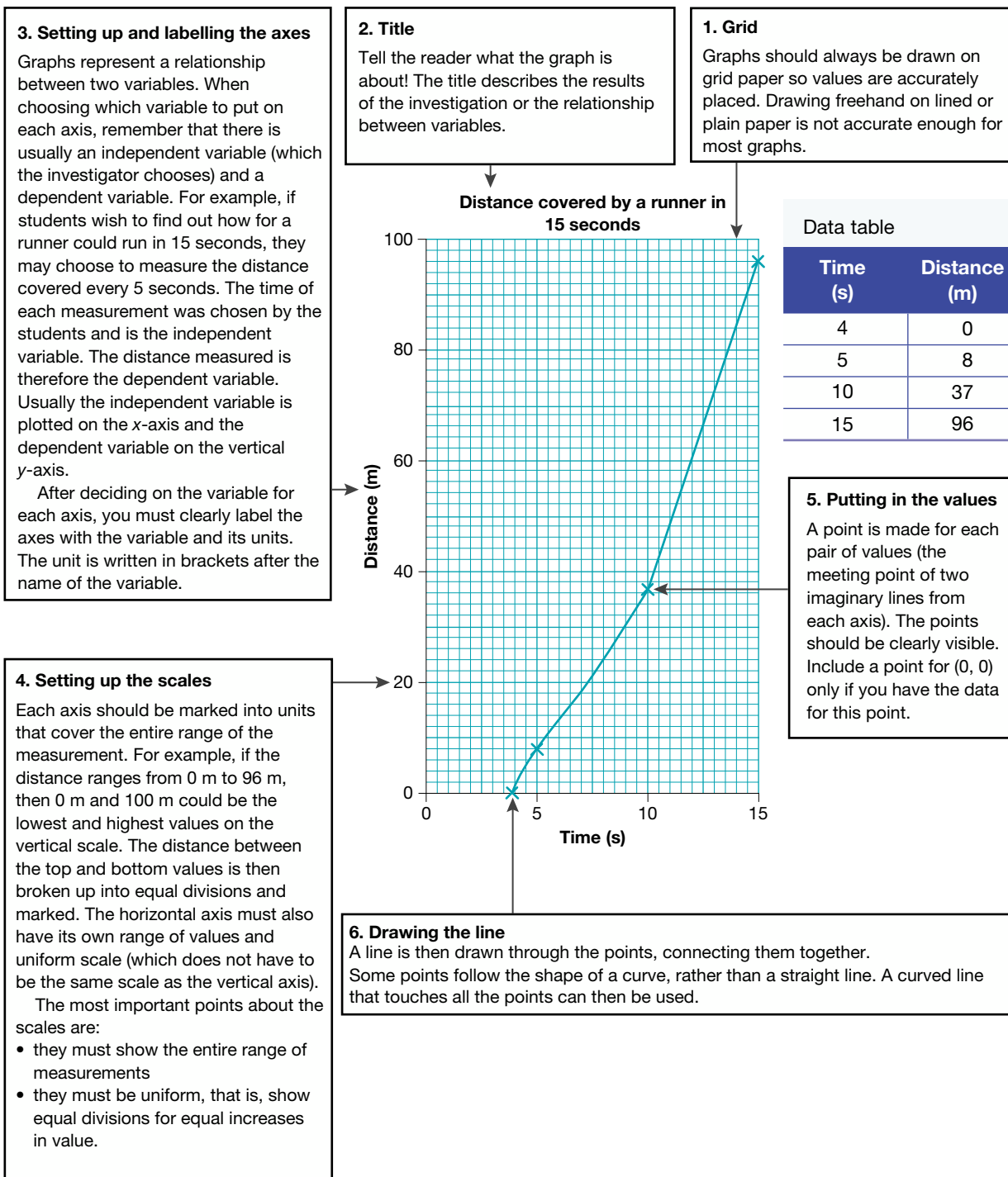


Line graphs

In a **line graph**, a series of dots represents the values of a variable, and the dots are joined using a straight line (this is different to a line of best fit, which shows a general relationship and does not have to go through each point).

Line graphs are often used to show changes over a continuous period of time, or over space. In particular, line graphs can identify patterns, trends and turning points in a dataset.

FIGURE 13.38 Setting up a line graph

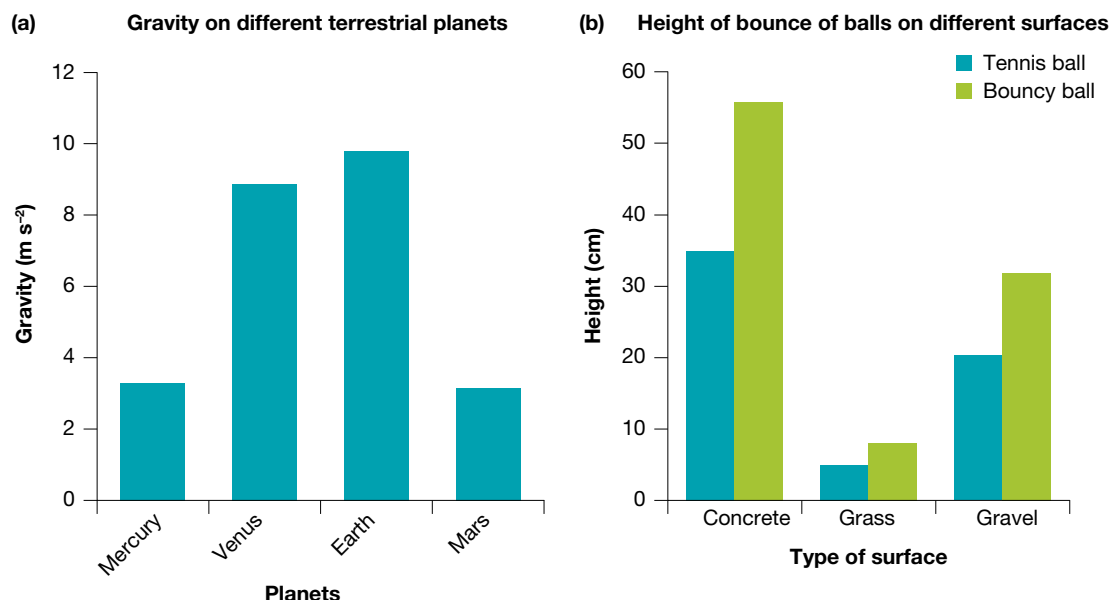


Bar/column graphs

Bar graphs are often used when one piece of data is qualitative and the other is quantitative. The bars are separated from each other. The horizontal or x -axis has no scale because it simply shows categories. The vertical or y -axis has a scale showing the units of measurements.

Bar graphs can also be used to compare two sets of data by using side-by-side bars, as shown in figure 13.39b.

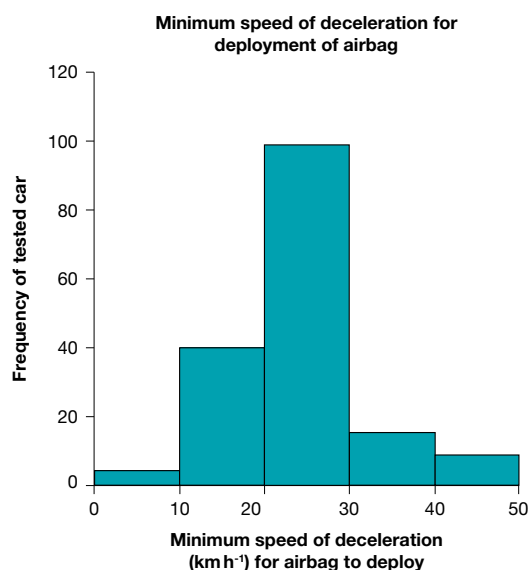
FIGURE 13.39 Example of bar graph (a) showing differences in gravity of the four terrestrial planets (b) comparing bounce of ball on different surfaces



Histograms

A **histogram** is a special kind of bar graph, showing continuous categories. The bars are not separated, unlike in a bar graph. Histograms are often used when examining frequency.

FIGURE 13.40 Histogram showing speed deceleration for airbag deployment of 166 tested cars



In figure 13.40, the exact values cannot be determined, as data is displayed in intervals. For example, it can be seen that there were 40 cars that had a speed between 10 and 20 km h^{-1} . However, the specific values are not known.

Using Microsoft Excel

The Excel spreadsheet is a very useful tool to the experimenter. It can:

- *Store your measurements.* Make sure you save your data every few minutes and do a backup every day.
- *Calculate any derived physical quantities,* such as speed and acceleration of a parachute or the percentage of energy lost by a bouncing ball. The 'Fill down' command is a timesaver.
- *Be a powerful graphing tool, but must be controlled by the user.* You will have to select the graph and choose what aspects of your graph you want showing — what scale on the axis do you want? What do you want to label your axis with? Do you want the data displayed on the graphed points?
- *Generate a line of best fit.* If you right-click on any data point, a window pops up with the option 'Add Trendline'. This is the Excel command to create a line of best fit.
- *Create error bars.* (However, all error bars are usually the same for each data point, rather than calculated separately.)

FIGURE 13.41 Excel is a useful data tool



on Resources

 **Interactivity** Selecting a graph (int-7733)

13.7.2 Analysing primary data

When analysing primary data, it is important to explore trends and patterns that can be seen.

This may include asking questions such as the following:

- Is there a clear positive or negative correlation in data? (Positive correlation is when one variable increases in response to another increasing variable.)
- Are there any **outliers** (unusual data)?
- What results would you expect for specific data that you didn't observe experimentally?
- Can you calculate the average for your data? Does this differ for the median or the mode?

Analysis of your data often depends on the type of graph selected, as it alters the way that trends and patterns can be seen.

For example, the graphs in figure 13.42 show the same data presented in three ways.

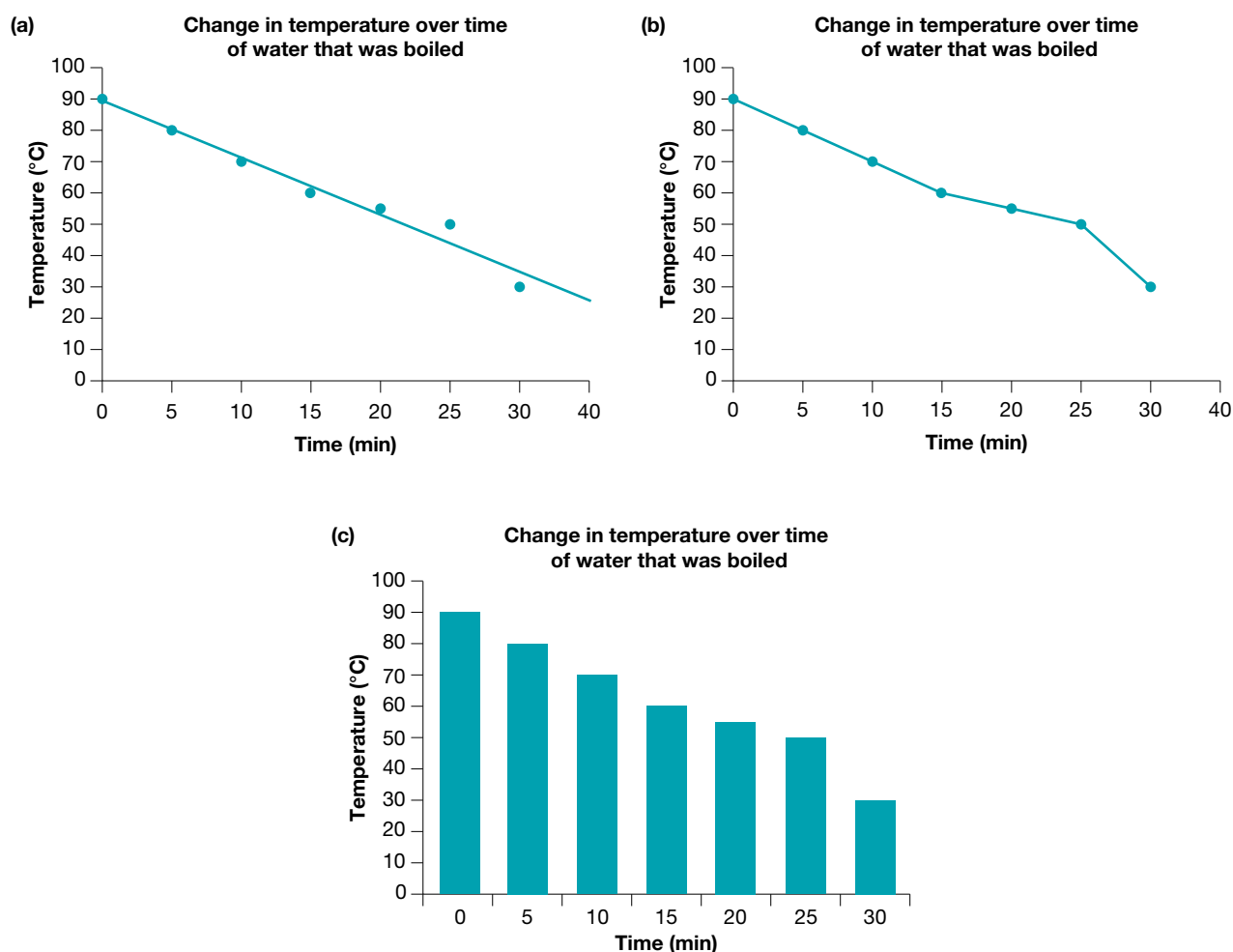
If you were analysing the data from each of the three graphs, the following trends and patterns may be observed:

Graph (a) There is a clear downward trend (or negative correlation) in the data, as temperature decreases over time. However, the temperature at 25 minutes is slightly higher than the expected pattern based on trends, and the temperature at 30 minutes is slightly lower than expected.

Graph (b) There is a clear downward trend in data, as temperature decreases over time. The rate of temperature drop slows after 15 minutes, before the rate increases again between 25 and 30 minutes.

Graph (c) There is a clear downward trend in data, as temperature decreases over time. The temperature is lowest at 30 minutes, where it is half the temperature observed at 15 minutes.

FIGURE 13.42 Various graphs showing temperature change over time: (a) scatterplot using a line of best fit; (b) line graph; (c) bar graph



Graphs (a) and (b) are more powerful representations of the given data compared to graph (c). Regardless of the graph type used, it is important that it shows any clear trends and patterns seen in the data, and that any outliers (unusual data) can be seen.

Outliers are results that are far removed from other results and seen as unusual. They should be accounted for and analysed but are not often included when averages are calculated. However, it is important to consider why outliers have occurred as part of your discussion.

Graph analysis can also be used to predict and make assumptions about data that was not gathered experimentally. This can be through interpolation (predicting data points within the dataset that were not measured) or extrapolation (predicting data points outside the dataset based on the predicted relationship).

Based on the graphs you might estimate:

- The temperature at 35 minutes
- The temperature at 13 minutes
- The time that the temperature was 45 °C.

The prediction you get may vary greatly between all the graphs, so it is important to carefully consider which one you use. Table 13.10 shows the varying predictions obtained from the different graphs in figure 13.42.

FIGURE 13.43 Outliers in data are unusual results.

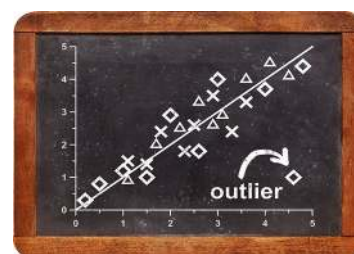


TABLE 13.10 Analysing data from different graph types

	Graph (a)	Graph (b)	Graph (c)
Temperature at 35 minutes	25	15	20
Temperature at 13 minutes	65	62	66
Time the temperature was 45 °C	24 minutes	27 minutes	26 minutes

Direct variation

When analysing data, you may find that a change in one piece of data results in a change in the other piece of data by the same proportion. Such a relationship is known as being directly proportional, and is a way to describe and analyse the data. Consider, for example, the relationship described by the equation $y \propto x$. This type of relationship is known as a direct variation. The relationship can be written as:

$$y = kx$$

where k is a constant of proportionality.

The ratio $\frac{y}{x}$ is constant. That is, if x is doubled, y doubles. If x is tripled, y triples. If x is halved, y halves.

Many relationships in physics involve direct variation or direct proportion. For example, the power, P , delivered to an electric appliance is directly proportional to the voltage, V , across it and the current, I , passing through it. In symbols:

$$P \propto VI$$

If either V or I are doubled, P changes in the same proportion — that is, it doubles. If both V and I are doubled, P changes by a factor of four.

When one quantity is directly proportional to the reciprocal of another, the relationship is defined as an inverse variation. For example, the electrical resistance, R , of a length of wire is directly proportional to the reciprocal of the cross-sectional area A of the wire. In symbols:

$$R \propto \frac{1}{A}$$

$$\Rightarrow R = \frac{k}{A} \text{ where } k \text{ is a constant of proportionality.}$$

R is said to be inversely proportional to A .

The product of R and A is constant. If A is doubled, R is halved. If A is tripled, R is divided by three. If A is halved, R doubles.

13.7.3 Evaluating primary data

When you evaluate data, it is important to link back to the initial question:

- Does the data provide an answer to the question of your investigation?
- Does the data support or refute your hypothesis?
- If there were any outliers, errors or uncertainty in your data, why might have these occurred?
- Does your data link to correctly supported models and theories?
- Are there further improvements that you could make to improve your data in future investigations that may reduce errors or limitations?

It is important when evaluating data that you can explain and justify this in relation to your question.

Two examples of students evaluating data can be shown in the following situation, based on the graphs in figure 13.42.

Student 1: It can be seen from the results that the temperature decreased.

Student 2: From table 2, it is clear that temperature decreases over time, dropping from an initial temperature of 90°C to a final recorded temperature of 30°C . While there is a clear trend in temperature decreasing over time, the rate of decrease was inconsistent, particularly between 25 and 30 minutes. This may be due to a decrease in external air temperature, causing the rate of heat loss through convection to change.

It is clear that student 2 had a better grasp on evaluating the data, being able to describe trends and a link to theory. What else should they add?

13.7.4 Sources of uncertainty and error

Several sources of error can be identified in an investigation:

- **Systematic errors** are errors that affect the accuracy of a measurement, ones that cannot be reduced or eliminated by repeating an experiment. They are usually due to equipment, or are system errors. They produce measurements that are consistently too high or too low, as, for example:
 - instrumental errors that arise because an instrument, such as a weighing balance, is uncalibrated and incorrectly set to zero
 - environmental errors that arise because of malfunctions, such as a power outage, that affect the conditions under which an experiment is being conducted.
- **Random errors** are chance variations in measurements that affect the precision of measurements and are always present in measurements of continuous data. An example of a random error is an error of judgement when reading the smallest division on the scale of a measuring instrument, such as a ruler. Unlike systematic errors, these can usually be resolved by repeating measurements.

It should be noted that so-called ‘human errors’ are not errors but are mistakes that result from carelessness. Examples include gross misreading of an instrument, and writing the wrong result in your logbook, such as 40 instead of 4.0.

Measuring errors and uncertainties

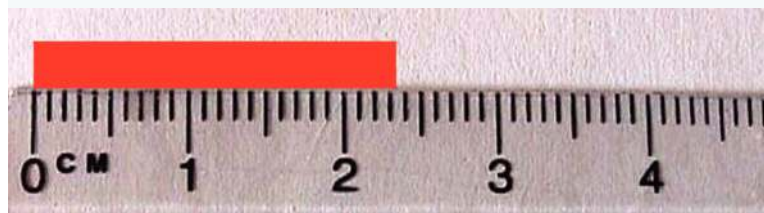
Reading rulers

A metre ruler has lines to mark each millimetre, but there is space between these lines. You could measure the length of an object to the nearest millimetre, but because of the space between the lines, if you look carefully, you can measure to a higher precision. You can measure to the nearest 0.5 mm. It is important to look carefully at the ruler you are using to see the level of precision available when you measure.

FIGURE 13.44 Reading a measuring cylinder can result in errors



FIGURE 13.45 Errors in rulers



The best estimate for the length of the red line in figure 13.45 is 2.35 cm. The actual length is closer to 2.35 cm than it is to either 2.30 cm or 2.40 cm. The measurement of 2.35 cm says the actual length is somewhere between 2.325 cm and 2.375 cm.

The way to write this is as follows:

The length of the red line = 2.35 ± 0.025 cm

The 0.025 represents the tolerance or uncertainty in the measurement (half of the precision that can be recorded). It is important that when you look at rulers, you determine the smallest value that you can accurately record. You may find you cannot determine the measurement to the nearest 0.5 mm, but only to the nearest 1 mm. Therefore your length and error would be slightly different.

Reading top-loading balances

The reading on a digital scale is 8.94 grams. The smallest measurement that can be recorded is 0.01 grams. This means the mass is not 8.93 g nor 8.95 g. The actual mass is somewhere between 8.935 and 8.945 grams. The correct way to record this is:

The mass = 8.94 ± 0.005 g.

This uncertainty is half of the smallest measurement that can be recorded.

FIGURE 13.46 Top-loading balances measure to a certain number of significant figures



SAMPLE PROBLEM 4

- Record the reading on the scale in (a), including the tolerance (uncertainty).
- Record the reading on the thermometer in (b), including the tolerance (uncertainty).



 **Teacher-led video:** SP4 (tlvd-0104)

THINK

- Determine the reading on the scale.
- Determine the range of the measurement.
- Determine the tolerance.
One way to calculate this is to determine half of the smallest unit that can be measured.
- Record the reading, including the tolerance (error).

WRITE

- 128.93 g
The measurement can be between 128.925 and 128.935.
0.01 g is the smallest measurement possible.
Therefore:
$$\frac{0.01 \text{ g}}{2} = 0.005 \text{ g}$$

$$128.93 \pm 0.005 \text{ g}$$

- b. 1. Determine the reading on the scale.
2. Determine the range of the measurement.
In this case, you can tell, due to the visible gaps, if there are 0.5°C increments on the thermometer. The range is smaller than the visible gaps.
3. Determine the tolerance.
One way to calculate this is half of the smallest unit that can be measured; as stated, the smallest unit is 0.5°C .
4. Record the reading, including the tolerance (error).

b. 47°C

The measurement can be between 46.75 and 47.25°C .

$$\frac{0.5^{\circ}\text{C}}{2} = 0.25^{\circ}\text{C}$$

$$47 \pm 0.25^{\circ}\text{C}$$

PRACTICE PROBLEM 4

Record the reading on the scale, including the tolerance (uncertainty), that shows a reading of 0.8 grams.

Repeated measurements

Measurements of independent variables are usually precise and careful, so one measurement should be enough. However, measurements of the dependent variables are often prone to some variation.

Whether the variation is caused by the human reaction time when using a stopwatch, judging the rebound height of a basketball or, in the case of a parachute, the unpredictable way the canopy will open each time, each reading may be different. So it is sensible to take several readings to obtain an average. You would expect that at least three measurements would be needed, and possibly five, but more than five is generally unnecessary.

For example, your partner drops a basketball from a height of 80.0 cm and you judge the rebound height of the ball for five trials as 68 cm, 69.5 cm, 68.5 cm, 68.5 cm and 69.5 cm. The average is 68.8 cm, which you would round to the nearest 0.5 cm because of the difficulty of judging a moving ball, giving an average of 69 cm.

This set of measurements would then be written as 69 ± 1 cm (the 1 cm is the furthest the measurement is from the average).

Graphing error bars

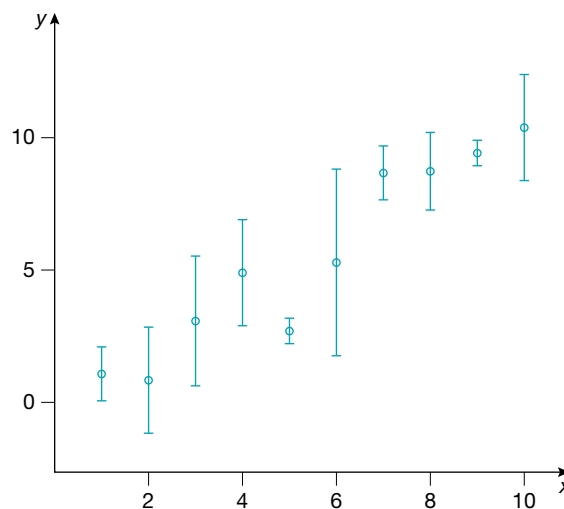
When you graph your results, the number you will plot is 69 cm. To represent the ' ± 1 cm', you can draw a line through the point, up 1 cm and down 1 cm, with a short line across the top and bottom of the line to make the ends evident. However, error bars aren't always the same for each data point, as shown in figure 13.47.

Calculating error bars

Rather than graphing rebound height against drop height, it is more revealing for the physics of the situation to calculate and graph the ratio of the rebound height to drop height against drop height. The ratio is a measure of how much of the original gravitational potential energy is restored.

In this case, the ratio would be $\frac{69}{80.0} = 0.8625$, but how many digits can be used and how big should

FIGURE 13.47 Error bars



the error bar be? The first question is reasonably straightforward. The number of digits in your answer should equal the smallest number of digits in the data you used in the calculation. In this instance, the average height has two digits, so the answer would be written as 0.86. You are not justified in including more digits because you don't know the original data accurately enough.

Working out the size of an error bar takes more effort. If the two pieces of data are 69 ± 1 cm and 80.0 ± 0.3 cm, the uncertainties can be added to get ± 1.3 cm, but that doesn't make sense when the calculated value is 0.86. Dividing the uncertainties would produce another unusual result.

The method used is to first express the uncertainty for each data value as a percentage. For example:

$$\text{Percentage error of } 69 \pm 1 \text{ cm} = \left(\frac{1}{69} \right) \times 100 = 1.4\%$$

$$\text{Percentage error of } 80.0 \pm 0.3 \text{ cm} = \left(\frac{0.3}{80} \right) \times 100 = 0.4\%$$

Now add the two percentage errors together:

$$\begin{aligned} \text{Total percentage error} &= 1.4\% + 0.4\% \\ &= 1.8\% \end{aligned}$$

Next, use this total percentage error to find the error in the calculated answer.

Error = $0.86 \times 1.8\% = 0.016$, which would be rounded to one digit as 0.02.

The full calculated answer would now be 0.86 ± 0.02 .

The percentage errors are added together regardless of whether the data values are divided, multiplied, added or subtracted. For example:

- Calculating speed using $v = \frac{\Delta x}{\Delta t}$, the percentage errors of displacement and time would be added together.
- Calculating momentum using $p = mv$, the percentage errors of mass and velocity would be added together.
- Calculating the change in momentum using $\Delta p = p_{\text{final}} - p_{\text{initial}}$, the actual uncertainties of each are added together.

on Resources

 **Video eLesson** Calculating error (eles-2560)

13.7.5 Limitations of data and methodology

The data that is gathered from the experimental results will have **limitations**. Limitations arise from several sources that can affect the quality of the data:

- Experiments create artificial situations that do not necessarily represent real-life situations.
- While every effort may be made to identify controlled variables and to keep them constant throughout the course of an experiment, it is not always possible to identify and control every one of them.
- The degree to which results obtained in the laboratory can be generalised to other situations and applied in the real world is limited.

It is important to consider limitations when analysing data and drawing conclusions from data. Limitations should be factors that are out of your control, but need to be discussed in regard to how they might impact your results. As part of your practical investigation, you need to clearly outline limitations, and suggest improvements to the method or data collection to avoid these limitations.

13.7 EXERCISE

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

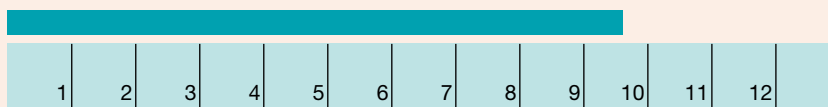
1. Describe the difference between a random and a systematic error and provide two examples of each.
2. List two ways that you can minimise uncertainty in an investigation.
3. Identify which graph type would be most appropriate for the following investigations. Justify your choice.
 - (a) Measuring the height of a jump by 6 different athletes
 - (b) Measuring the voltage in a battery every minute for 12 minutes
 - (c) Calculating the temperature of an object at different heights
 - (d) Examining the ATAR scores of all students in Victoria.
4. Using the provided data, construct an appropriate graph:

Time (mins)	Temperature ($^{\circ}\text{C}$)
5	80
0	72
10	65
15	50
20	45
25	42

Once you construct the graph, analyse and evaluate the data shown.

5. Describe how an outlier should be treated in analysing and evaluating data.
6. Determine the length of each line in the diagram below, showing the tolerance in each case.

(a)



(b)



(c)



7. The power delivered to an electrical device is directly proportional to the voltage across the device and the electric current flowing through the device. If the power delivered to the device is initially 20 W, what will it be if:
 - (a) the voltage is tripled
 - (b) the current is doubled
 - (c) the voltage and electric current are both tripled
 - (d) voltage is doubled and the current is halved?

Fully worked solutions and sample responses are available in your digital formats.

13.8 Models and theories to understand observed phenomena

KEY CONCEPT

- Models and theories, and their use in organising and understanding observed phenomena and physics concepts including their limitations.

KEY SCIENCE SKILL

- Analyse and evaluate scientific models.

As well as data limitations, limitations exist in the models and theories that are used in physics. It is important to be able to use models and theories to allow the understanding of a variety of observed phenomena, but to also understand the limitations and the idea that they may change as more observations are made and research is conducted.

13.8.1 Models

Models are representations of ideas, phenomena or scientific processes. They can be physical models, mathematical models or conceptual models. Models can provide a framework that explains observed phenomena and helps with the understanding of abstract concepts. In physics, many concepts are hard to visualise, so models help contextualise the idea on a smaller and simpler scale.

While they are very useful, models have their limitations:

- Because of the complexity of the processes, models cannot include all the details of the processes or the things that they represent.
- Models are necessarily approximations of the real world; for example, Newton's laws of motion can be used to make predictions about motion. However, this model cannot be used in certain conditions, particular at very high speeds and, therefore, its predictions would not always match what happens in real-world applications.
- Models do have some limits in their accuracy and are often simplified and stylised. For example, a ball and stick model of ozone (figure 13.48) is useful, but is a very highly simplified and stylised representation that reduces covalent bonds to sticks, and atoms to solid balls.
- Models are based on current observations and knowledge at the time. This means that they aren't definite and can change as observations allow for different ideas to come to light.

Models are constantly being refined as new information becomes available. One model that has continuously changed is that of the atom.

FIGURE 13.48 Ball and stick model of ozone, a gas that contributes to the greenhouse effect

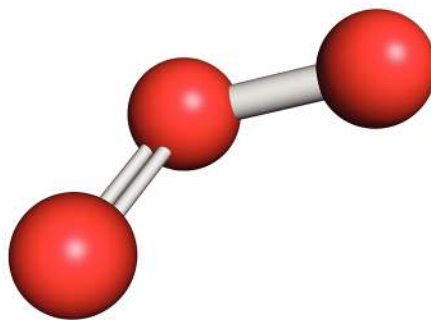


FIGURE 13.49 A model showing an electromagnetic wave

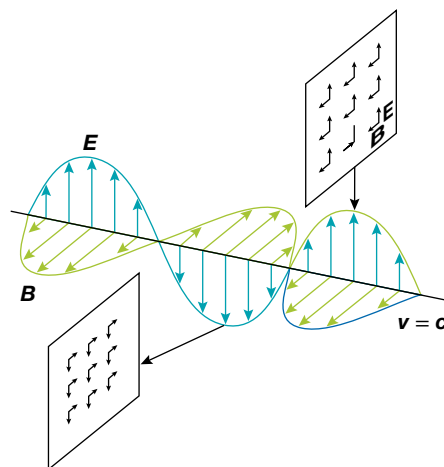
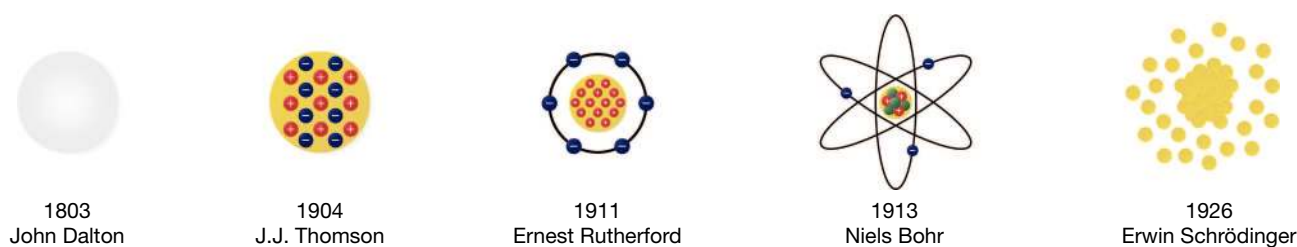


FIGURE 13.50 Various models of the atom including John Dalton's model and the Plum Pudding model by J.J. Thomson



13.8.2 Theories

A **theory** is a well-supported explanation of a phenomenon. Theories are based on the interpretation of facts that have been obtained through investigations, research and observations.

There are limitations that can exist with theories. These may include the following:

- A reliance on theories rather than observations made during practical investigations. Often, theories are treated as perfect, when in fact, they are able to be disproven as observations and evidence come to light.
- Theories often rely on a very specific set of conditions to be met. For example, Newton's laws of motion cannot be used at very small scales or very high speeds.
- Often, a phenomenon needs to be described using multiple theories. Sometimes, aspects of theories may contradict each other.

Theories can change overnight or take a very long time to change. Theories that were once popular and well accepted may be discarded when too much evidence builds up against them. They are replaced by a theory that better fits the observations.

Some examples of theories that have been superseded by other theories are:

- Miasma theory of disease — the idea that diseases were caused by bad air
- The Sun and planets orbit around the Earth (geocentrism)
- Flat Earth theory.

Another example of changing theories is seen in astrophysics, where some of Newton's theories (and Einstein's theory of relativity) are being contested. A new theory known as Modified Newtonian Dynamics (MoND) has brought forward new predictions about the universe, particularly around dark matter and astronomy.

FIGURE 13.51 The Flat Earth theory has been replaced with the idea that the Earth is spherical.



TABLE 13.11 The changing theories in astrophysics

1933	Fritz Zwicky coins the term 'dark matter' to describe unseen mass or 'gravitational glue' in galaxy clusters.
1978	Astronomers show that many galaxies are spinning too quickly to hold themselves together unless they are full of dark matter.
1983	Mordehai Milgrom publishes a modified gravity theory called MoND. It explains why galaxies don't fly apart without using dark matter, but remains at odds with Einstein's relativity.
1990s	Studies of galaxies and galaxy clusters show that their gravity bends light more strongly than is expected without dark matter. MoND researchers start devising improved theories to explain extra light bending.
1994	Jacob Bekenstein and Roger Sanders prove that any theory that resolves the light-bending issue and meshes MoND with relativity must involve at least three mathematical fields.
2000	New data on the cosmic microwave background reinforce the standard, dark matter picture of the universe.
2004	Jacob Bekenstein devises a version of MoND that is consistent with relativity.
2005	Constantinos Skordis and others show that relativistic MoND provides a good fit to the microwave background data.

How do refinements of existing theories come about?

- Carefully planned laboratory-based or field-based experiments designed to support or refute a particular hypothesis
- Critical reinterpretation of previously accepted facts, producing a new framework
- Collection and analysis of new data
- Identification and exploration of patterns or anomalies
- New technologies that allow for changes to understanding and more depth of knowledge.

13.8 EXERCISE

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

1. Describe three ways in which models can be useful.
2. Describe two limitations of models.
3. What is the difference between a model and a theory?
4. How can theories help you to understand phenomena?

Fully worked solutions and sample responses are available in your digital formats.

13.9 Nature of evidence and key findings of investigations

KEY CONCEPT

- The nature of evidence that supports or refutes a hypothesis, model or theory, and the key findings of the selected investigation and their relationship to concepts associated with waves, fields and/or motion.

KEY SCIENCE SKILLS

- Analyse and evaluate data, methods and scientific models.
- Draw evidence-based conclusions.
- Communicate and explain scientific ideas.

13.9.1 Nature of evidence — supporting or refuting a hypothesis, model or theory

Evaluating a hypothesis, model or theory uses the evidence from the results obtained in an investigation. In your investigation, it is important to understand how to best use evidence in order to correctly support or refute your hypothesis.

Evidence can be strong or weak, and it can provide different information that helps to address your hypothesis. It is vital that the evidence you choose allows the provision of strong and clear conclusions.

Strong evidence should:

- be based on facts derived from studies with high validity and minimal bias
- use data to support conclusions
- clearly link to the aim and hypothesis of an experiment
- be obtained from an investigation that has a reproducible and reliable method.

If the prediction from your hypothesis was validated by your experimental results, you should evaluate your hypothesis as ‘supported’, and if your hypothesis was not supported by results, it is evaluated as ‘rejected’, ‘not supported’ or ‘disproven’.

This is a reminder that a scientific hypothesis can be disproven, but it can never be proven true; it can only be supported. This is because the nature of evidence is that, as new technologies and information becomes available, evidence can change and be interpreted in different ways. This may then disprove a previously made hypothesis. Some examples of some very simple pieces of evidence is shown in table 13.12.

TABLE 13.12 Examples of results that can support or disprove a hypothesis

Observation	Hypothesis	Test of Hypothesis	Result	Conclusion
The light globe in a circuit is not turning on	The globe is blown	Replace the globe in the circuit	The new globe does not turn on	Hypothesis disproved
The light globe in a circuit is not turning on	The power pack is faulty	Replace with a new power pack	Light globe turns on	Hypothesis supported
The water turned to ice at 0°C	All liquids turn to a solid at 0°C	Place different liquids at 0°C	Alcohol does not freeze at 0°C	Hypothesis disproved

13.9.2 The key findings of investigations

In your investigation, you would have written a question and a hypothesis, created a clear reproducible methodology, conducted an experiment and collected and analysed data.

From this point, it is then important to determine the key findings of your investigation.

Your key findings should include:

- information about the data obtained in the practical investigation and any patterns and trends
- the relationship of your findings to physics concepts including waves, fields or motion
- an answer to the question of your investigation.

Example:

How does the length of a pendulum affect the number of oscillations?

Key findings

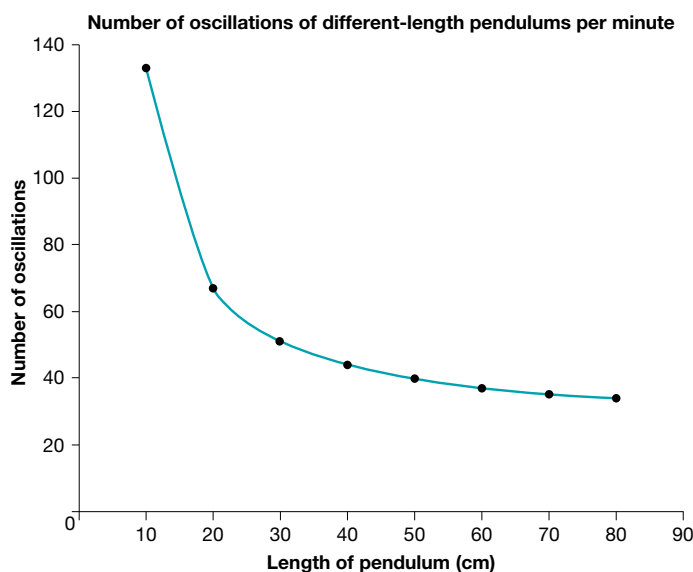
It is expected that, based on the formula $T = 2\pi\sqrt{\frac{L}{g}}$ (assuming no loss of energy and the same gravitational field of 9.8 m s^{-2}), as the length increases, the time for an oscillation would also increase, as observed in figure 13.52.

The number of oscillations over a one-minute period would be inversely proportional to the time of an oscillation, in which n (number of oscillations) reduces as the time of an oscillation increases, as calculated

$$\text{by } n = \frac{60}{T}.$$

From the investigation, it can be seen that the length of the pendulum does have an impact on the number of oscillations as observed in the graph shown, however, this relationship is not linear. This supports the hypothesis of this investigation.

FIGURE 13.52 Exploring oscillations of pendulums of different lengths



13.9 EXERCISE

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

1. Why would you say that you 'support' a hypothesis rather than saying you 'prove' it?
2. Provide three examples of strong evidence.
3. Describe what key findings you should communicate in a discussion.
4. Why is it important to show the relationship of your results to concepts such as waves, fields and motion?

Fully worked solutions and sample responses are available in your digital formats.

13.10 Conventions of scientific report writing and scientific poster presentation

KEY CONCEPT

- The conventions of scientific report writing and scientific poster presentation, including physics terminology and representations, symbols, equations and formulas, units of measurement, significant figures, standard abbreviations and acknowledgement of references.

KEY SCIENCE SKILL

- Communicate and explain scientific ideas.

13.10.1 Conventions of report writing

It is vital in scientific report writing to follow the set structure. This will also be the same structure of headings that you use when presenting your scientific poster. An example of a set structure that may be useful to follow is outlined in table 13.13.

Remember, your teacher will also mark both your scientific poster and the work in your logbook, so make sure that all required work is there. You may have some of the information that only appears in your logbook, some that appears in both and some that only appears on your poster. Your logbook and poster are components of your practical investigation skills.

TABLE 13.13 Aspects of a written report

Section	Description
Title	A precise and complete description of what you investigated
Abstract	An optional section, which summarises the scope of the investigation
Introduction	A paragraph explaining the relevant physics and background concepts and relationships and how they apply to this investigation. It should explore any prior investigations conducted on this topic. This should also include a clear aim and hypothesis.
Methodology	A detailed section that describes your selection of equipment and measuring instruments, and your step-by-step method. This may include diagrams and photos. Refer to how you controlled variables; achieved the desired accuracy; and overcame, avoided or anticipated difficulties. It should be clear enough for someone else (at your level) to repeat your experiment. Do not forget to highlight how the relevant ethical and safety concerns have been addressed. This section is often detailed in your logbook and summarised in your final report.
Results	A clear representation of your results includes your data and graphs. If there is too much data, then refer to your logbook for the full set. Make sure you present your results in an organised and clear manner, following accepted conventions (such as numbering items sequentially). Make sure you include the appropriate units and use the correct number of significant figures. Try to organise this in such a way that any patterns or relationships start to become obvious, thus making it easier to analyse in the discussion. Show sample calculations if required.
Discussion	A detailed analysis and evaluation of your results. How does your data support your initial intentions and link to relevant physics concepts? What trends and relationships are apparent as a result of your investigation? How much is your analysis limited by uncertainties? Were there any outliers in your investigation and how were they treated? What limitations and sources of error were present in your investigations and how would you improve this in future repetitions? What would be your next steps in the investigation if you had more time?
Conclusion	This should relate to the aim and must be based entirely on the evidence obtained in the experiment. It should state whether the hypothesis is supported, summarising the meaning of your results in response to your question. No new information should be included.
References and acknowledgements	You should quote the sources of any content that you include that is not your own original work. Unaltered tables, diagrams and graphs are examples that fit this description, as are direct quotes. In your introduction, you may have mentioned previous work that your investigation is based on. This also needs to be acknowledged, along with any sources that inform your discussion of concepts and theory in a more general sense. This section is not counted in your final word count.

Some other things that are important to a scientific report (and your poster):

- Try to avoid subjective language; where possible, use third-person language and write in the past tense.
- Don't just record the data you believe supports your hypothesis; you should also include errors, uncertainties and outliers.
- If you used any calculations, show your workings.
- Use subheadings throughout your report as shown earlier. Make your report clear to read.
- Provide headings for all graphs, tables and figures and label them sequentially. (Graph 1, Graph 2, etc.)

13.10.2 Terminology and representations

It is important throughout your report to use clear and concise terminology relevant to the related physics concept. The use of key terms was covered previously in section 13.4.2.

As well as this, physics representations are required to be accurate and use common conventions. These representations were discussed in section 13.4.3. There may be other representations used that are appropriate to your specific investigation. These should be used consistently in both your logbook and your poster.

13.10.3 Symbols

Table 13.14 contains some commonly used symbols in physics. Many of these are taken from the Greek alphabet.

TABLE 13.14 Some common symbols used in physics — many of these come from the Greek alphabet

Symbol	Name	Representation
λ	Lambda	Wavelength (nm)
θ	Theta	Angle (degrees)
ω	Omega (lowercase)	Angular frequency
Ω	Omega (uppercase)	Electrical resistance (ohm)
μ	Mu	Coefficient of friction
γ	Gamma	Lorentz factor
ϕ	Phi	Work function of metal (joule)
ϕ_B		Magnetic flux
ϵ	Epsilon	EMF (electromagnetic field)
Σ	Sigma	Summation
Δ	Delta	Change in variable
$\perp$		Perpendicular to

Due to the sheer quantity of variables that has to be represented, it is important to note that uppercase and lowercase versions of a given letter usually represent different things (for example v represents velocity, but V represents voltage). There are also differences depending on whether the variable is in a roman, bold or italicised typeface. As well, sometimes the same symbol is used to represent different variables.

The symbol μ , for example, is used to represent:

- the mean in statistics
- micro in measurement
- the coefficient of friction.

The style of the symbol is also important: is it a vector that needs to be bold, a variable that needs to be italicised, or a unit that needs to be in roman text?

It is important to carefully use the correct symbol in your report to minimise confusion.

There are many other variables used in physics, and it is vital that you can apply these in different formulas available from the formula sheet.

13.10.4 Equations and formulas

During your exam, you will be provided with a formula sheet for your reference.

When using formulae in your scientific investigation, it is important to:

- define all variables
- provide any figures for constants (for example Planck's constant).

Some key formulas in physics are:

Motion and energy transformation

- Newton's Second Law of Motion: $\Sigma \mathbf{F} = m\mathbf{a}$
- Newton's Law of Universal Gravitation: $\mathbf{F} = G \frac{M_1 M_2}{r^2}$
- Hooke's Law: $\mathbf{F} = -k\Delta \mathbf{x}$
- Lorentz factor: $\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}$

Fields

- Coulomb's Law: $\mathbf{F} = k \frac{q_1 q_2}{r^2}$

Electricity

- Electromagnetic induction (EMF): $\varepsilon = -N \frac{\Delta \phi_B}{\Delta t}$

Waves

- Wave equation: $v = f\lambda$
- Snell's Law: $n_1 \sin \theta_1 = n_2 \sin \theta_2$

Light and matter

- De Broglie wavelength: $\lambda = \frac{h}{p}$
- Photoelectric effect: $E_{k \max} = hf - \phi$

Refer to appendix 3 for additional useful formulae.

13.10.5 Units of measurement

In physics, it is vital to use the correct unit of measurement for accurate and clear scientific communication.

Prefixes

TABLE 13.15 Prefixes for units of measurement

pico (p)	nano (n)	micro (μ)	milli (m)	centi (c)	deci (d)	kilo (k)	mega (M)	giga (G)
10^{-12}	10^{-9}	10^{-6}	10^{-3}	10^{-2}	10^{-1}	10^3	10^6	10^9

These prefixes shift the value from the base unit. Base units don't have a prefix (for example, metres, seconds, grams). These have the value of 10^0 or 1. All other prefixes are compared to this base unit.

Understanding different prefixes allows the correct units to be used in practical investigations, and also allows for easy conversion between different units.

The following formula can be used when converting between units:

$$\frac{\text{initial unit } (10^n)}{\text{changed unit } (10^m)} \times \text{value}$$

SAMPLE PROBLEM 5

Convert:

- 12.412 millilitres to microlitres
- 26 153 milligrams to decigrams
- 8.7 metres to nanometres

 **Teacher-led video:** SP5 (tlvd-0105)

THINK

1. Determine the conversion between the

units: $\frac{\text{millilitre}}{\text{microlitre}}$

2. Multiply this by the value to be converted.
3. Add the new unit.

1. Determine the conversion between the

units: $\frac{\text{milligram}}{\text{decigram}}$

2. Multiply this by the value to be converted.
3. Add the new unit.

1. Determine the conversion between the

units: $\frac{\text{metre}}{\text{nanometre}}$

10^0 is used for metres as it is the standard unit, so it is equal to 1.

2. Multiply this by the value to be converted.
3. Add the new unit (round if required).

WRITE

- $\frac{10^{-3}}{10^{-6}} = 10^3$

$$10^3 \times 12.412 \text{ mL} = 12\,412$$

$$12\,412 \mu\text{L}$$

- $\frac{10^{-3}}{10^{-1}} = 10^{-2}$

$$10^{-2} \times 26\,153 \text{ mg} = 261.53$$

$$261.53 \text{ dg}$$

- $\frac{10^0}{10^{-9}} = 10^9$

$$10^9 \times 8.7 \text{ m} = 8\,700\,000\,000$$

$$8\,700\,000\,000 \text{ nm}$$

PRACTICE PROBLEM 5

Convert the following:

- 45 215 decimetres into kilometres
- 213 microseconds into nanoseconds

SI units of measurement

SI units or *Système International d'unités*, meaning internationally standardised, is the metric system of measurements. The system is shown in table 13.16.

For units that are named after an individual, such as André-Marie Ampère, Lord Kelvin and Sir Isaac Newton, the symbol (or first letter of the symbol) is capitalised. However, when the full word is written out, it is not capitalised. For example, 60 A would be written out as 60 amperes. However, there is one exception: degrees Celsius (the unit 'degrees' is lowercase, but Celsius is capitalised).

TABLE 13.16 Common SI units used in physics

Quantity	Unit	Symbol
Length	metre	m
Mass	kilogram	kg
Time	second	s
Temperature	kelvin	K
Electric current	ampere	A
Energy	electron volt	eV

Derived units

Derived units are units of measurements derived from the SI units. Table 13.17 shows some commonly used derived SI units.

TABLE 13.17 Common derived units used in physics

Quantity	Unit	Symbol	Unit in terms of other units
Force	newton	N	kg m s^{-2}
Energy and work	joule	J	N m
Pressure	pascal	Pa	N m^{-2}
Power	watt	W	J s^{-1}
Electric charge	coulomb	C	A s
Voltage	volt	V	J C^{-1}
Resistance	ohm	Ω	V A^{-1}
Radiation dose	sievert	Sv	J kg^{-1}
Temperature	degrees Celsius	$^{\circ}\text{C}$	$\text{K} + 273$

Speed is another example of a quantity that is measured in derived SI units. The SI derived unit of speed is the metre per second, written as m/s or m s^{-1} .

Derived units are often expressed with negative indices. The relationship is shown here:

$$\begin{aligned}1 \text{ m/s} &= 1 \text{ m} \times \frac{1}{\text{s}} \\&= 1 \text{ m} \times 1 \text{ s}^{-1} \\&= 1 \text{ m s}^{-1}\end{aligned}$$

13.10.6 Significant figures

A degree of uncertainty exists in any physical measurement. The uncertainty can be due to human error or to the limitations of the measuring instrument.

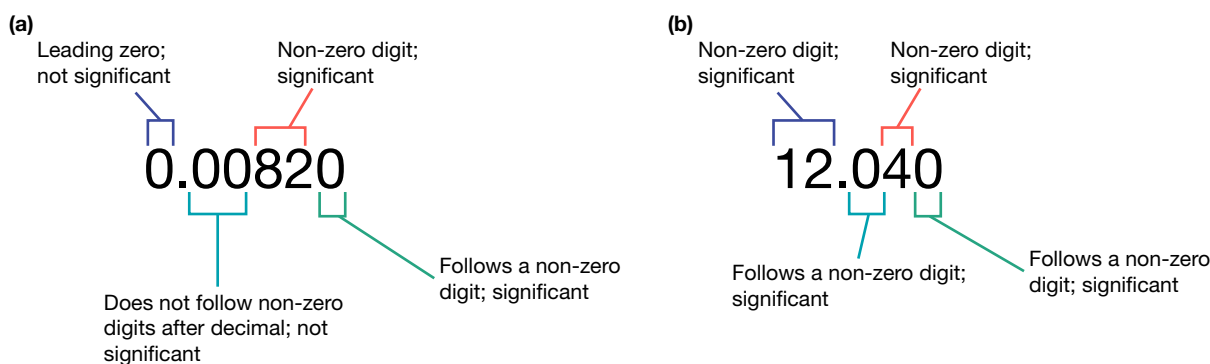
In most physical measurements, the last significant figure shows a small degree of uncertainty. For example, the length of an Olympic competition swimming pool is correctly expressed as 50.00 m. The last zero has a small degree of uncertainty.

Complicated by zeros

Two simple rules can be used to help you decide if zeros are significant:

- Zeros before the decimal point are significant if they are between non-zero digits. For example, all the zeros in the numbers 4506, 27 034 and 602 007 are significant. The numbers therefore have four, five and six significant figures respectively. The zero in the number 0.56 is not significant.
- Zeros after the decimal point are significant if they follow a non-zero digit. For example, in the number 28.00, the zeros are significant. The number has four significant figures. However, in the number 0.0028, the zeros are not significant. They do not follow a non-zero digit and are present only to indicate the position of the decimal point. This number therefore has only two significant figures. The number 0.002 80 has three significant figures (the last zero is significant as it follows a non-zero digit).

FIGURE 13.53 Examples of significant figures (a) Three significant figures (b) Five significant figures



Working with significant figures

When multiplying or dividing, the answer is written to the least number of significant figures in the initial values provided.

When adding or subtracting, the answer is written to the least number of decimal places in the initial values provided.

For example, if you travelled a distance of 432 m in a car for 25 s, your average speed would be given by:

$$\begin{aligned}\text{average speed} &= \frac{\text{distance travelled}}{\text{time taken}} \\ &= \frac{432 \text{ m}}{25 \text{ s}} \\ &= 17 \text{ m s}^{-1}\end{aligned}$$

The result should be rounded off to two significant figures (from 17.28 m s^{-1}) as this is the least number of significant figures that were provided.

When quantities are added or subtracted, the result should be expressed to the minimum number of decimal places used in the data. For example, if you travelled three consecutive distances of 63.5 m, 12.2517 m and 32.78 m, the total distance travelled would be given by:

$$\begin{array}{r} 63.5 \text{ m} \\ + 12.2517 \text{ m} \\ + 32.78 \text{ m} \\ \hline 108.5317 \text{ m} \\ = 108.5 \text{ m} \end{array}$$

The result should be rounded off to one decimal place as the minimum number of decimal places used in the data is one (in the distance of 63.5 m).



Resources



Video eLesson Determining significant figures (eles-2559)

SAMPLE PROBLEM 6

In determining the density of a particular liquid, a student measured the volume of a sample as 8.3 mL. She then weighed the same sample and obtained a mass of 7.2136 g. Calculate the density to the correct level of significant figures.



Teacher-led video: SP6 (tlvd-0106)

THINK

1. Determine the number of significant figures you have been provided.
2. Determine the least number of significant figures — this is the number of significant figures for your answer.
3. Calculate the density: $\text{density} = \frac{\text{mass}}{\text{volume}}$
4. Round down to the appropriate number of significant figures.

WRITE

7.2136 = 5 significant figures

8.3 = 2 significant figures

2 significant figures

$$\text{Density: } \frac{7.2136}{8.3} = 0.8691$$

Round 0.8691 down to 2 significant figures: 0.87 g mL^{-1}

PRACTICE PROBLEM 6

In determining the density of a particular liquid, a student measured the volume of a sample as 21.1 mL. She then weighed the same sample and obtained a mass of 9.762 g. Calculate the density to the correct level of precision.

13.10.7 Standard abbreviations

Often, it is appropriate to abbreviate terms rather than writing the terms out in full at each occurrence, which can make a report bulky and hard to follow.

Some common abbreviations used in Physics are as follows:

- AC — alternating current
- DC — direct current
- EMF — electromagnetic field
- LDR — light-dependent resistors
- LED — light-emitting diodes
- RCD — residual current devices
- RMS — root mean square

For other terms that can be abbreviated, the full term needs to be shown at the first occurrence, or the meaning of the abbreviation needs to be acknowledged. If you are unsure, write the term out in full. In subsequent occurrences, the abbreviation alone may be used.

An example of this, is as follows.

In direct current (DC), the current is only applied to flow in one direction. Portable electronic sources, such as laptops and mobile phones, use DC.

13.10.8 Acknowledgement of references

In-depth scientific reporting requires a depth of research for concepts relating to an investigation. This depth of research may include the following:

- Using other sources for definitions and background material
- Finding examples of similar investigations
- Research on the obtained results to link to scientific understanding.

If you use any material that is the work of another person, you *must* acknowledge its source. Do not claim it as your own work. Acknowledgements come in two formats: a short version when it occurs in the body of your poster, and a longer version when it occurs in the *Reference and Acknowledgements* section at the end of your poster or scientific investigation.

There are many ways to make such acknowledgements, and various institutions and publications use different systems. Details of these systems can be found online and can be quite complicated. You should check with your teacher as to how this is to be done. There are many guides online that can help you with referencing a variety of resources.

Acknowledging sources within your report: In-text referencing

An in-text reference is an abbreviated form of a reference and should be used in the body of your report in the location in which the sourced information is referred to. This type of referencing should be used for direct quotes as well as for tables, images and any text that has been paraphrased.

There are numerous ways to do this and it depends on what style you are using, so, again, check with your teacher.

Author-date system

This style of in-text referencing is more commonly used, particularly in the APA (American Psychological Association) and Harvard styles of referencing. As well as the shortened in-text referencing, a full reference is included in the reference list:

- The in-text reference is positioned at the end of the sourced information. This may be in the middle of a sentence, as seen here:

... over the past 10 years, the number of eligible children has increased (Kringler, 2008) and a need has therefore developed for sleighs to travel faster to meet the required delivery schedule. More efficient fuels are required for this purpose.

- Tables, diagrams, graphs etc. that are being inserted without being substantially altered can often be acknowledged by stating the details directly underneath them. Table 13.18 shows an example.

TABLE 13.18 Energy content of commonly available sleigh fuels

Fuel	Energy content (kJ L ⁻¹)
Rudolphene	45
Polar plus	29
Super sleigh	53

(Claus, 2016, p. 45)

Notes

- If an online article is undated, put (n. d.) in place of the date.
- If there is no author listed, use the title in place of the author's name or company's name.
- If there are up to three authors, list all their names.
- If there are more than three authors, only use the name of the first author and follow it by the phrase 'et al.' (meaning 'and others').
- If you quote directly from an author or cite a specific idea or piece of information from the source, you need to include the page number of the quote in your in-text reference.

Footnotes system

This style of in-text referencing is usually used in the Chicago and Vancouver style of referencing.

In this style, the citation involves using a superscript number showing the point in which a reference have been used. Here is an example:

... over the past 10 years, the number of eligible children has increased⁵ and a need has therefore developed for sleighs to travel faster to meet the required delivery schedule. More efficient fuels are required for this purpose.

In the footnotes section of the page (depending on the format of the report), the work is referenced with the corresponding superscript number, which is also included again in the reference list. Here is an example:

⁵ Kringle, K. (2008). *Journal of Polar Transport*, vol. **34**, p. 356.

Acknowledging sources at the end of your report: Reference list

At the end of a scientific report or poster, a reference list is included.

In your reference list, references should be listed alphabetically. If the footnotes version of in-text referencing was used, references should be listed in order of footnote numbers.

The following provides examples of the use of Harvard style in creating references:

Book

Author surname(s), initial(s), (Year published). *Title*, Edition (if applicable), Place of publication: publisher.

Example:

Langley, P & Jones, M (2013). *The search for Richard III: The king's grave*, London, John Murray.

Do not use et al. in your reference list. This is only appropriate in your in-text referencing.

Journal

Author surname(s), initial(s) (Year published). 'Title of article'. *Title of Journal*. Volume number. Page numbers.

Example:

Boiero, D & Bagaini, C (2018). 'S-wave splitting intensity analysis and inversion', *Geographical Prospecting*, vol. 67, no. 2, pp. 362–378

If available, you may also include the DOI (digital object identifier) after the page numbers. A DOI is a permanent identifier for a journal article and is often used in place of a URL.

TV programs

Title of program (date) (TV program) Channel identification.

Example:

Gene editing made simple (2016), (TV program), ABC Sydney.

Websites

Example:

Author surname(s), initial(s) (Year published). 'Title of page'. Name of website, date and website of retrieval

Fein, B (2011), 'The Patriot Act is at war with the constitution', The American view: God, family, republic, viewed 8 November 2011, <http://archive.theamericanview.com/index.php?id=1770>.

13.10.9 Presenting a scientific poster

Your logbook will also be read in depth by your teacher. A poster has a different intent and a different audience. The structure of your investigation should be apparent and give the viewer a good sense of the investigation within several minutes' perusal.

The poster should have an obvious and logical structure. One format is shown in the following example:

FIGURE 13.54 Format of a scientific poster

SCHOOL LOGO/ OTHER IMAGE	TITLE The question under investigation with a clear link to the independent and dependent variables	NAME
INTRODUCTION • Aim • Hypothesis • Purpose of the investigation • Background information	RESULTS • Presentation of collected data/evidence in an appropriate form to illustrate trends, patterns and/or relationships • This may include graphs, images and tables with clear headings	CONCLUSION • Conclusion that provides a response to the question referring to the aim and hypothesis
METHODOLOGY • Summary of the materials and method used that can be authenticated by logbook entries • Information about the choice of equipment and how variables were controlled • Identification and management of relevant risks, including health, safety and ethics	DISCUSSION • Analysis and evaluation of primary data- does it support your initial intentions and relevant theory • Identification of outliers and their subsequent treatment • Discussion of sources of error • Identification of limitations in data and methods and suggested improvements • Linking of results to relevant physics concepts • What would the next steps in the investigation be?	REFERENCES/ ACKNOWLEDGEMENTS • Referencing and acknowledgement of all quotations and sourced content from your poster

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13.10.10 Practical investigation checklist

- ☐ Your name, the title and the aim/hypothesis are listed.
- ☐ An introduction describes the purpose and outlines the investigation in a logical and concise manner. Key terms are defined and variables are stated clearly. Relevant theory is addressed.
- ☐ The method is outlined clearly in step form including a consideration of ethics, health and safety. A risk assessment is provided.
- ☐ Your logbook contains dates, headings and complete records.
- ☐ Any abbreviations are explained.

- ☐ Results are presented in an organised way, in a table if possible. All relevant measurements are recorded with appropriate accuracy and units.
- ☐ Observations are clear and concise, as are all diagrams, graphs and tables used.
- ☐ Any calculations are shown.
- ☐ There is a concise summary and interpretation of key findings, including trends and any unexpected results with connection to theory.
- ☐ The experimental design is evaluated, and possible improvements are included.
- ☐ There are suggestions for future investigations.
- ☐ The conclusion concisely summarises how your results support or contradict your original hypothesis.
- ☐ All sources are acknowledged and references correctly cited.
- ☐ The layout of your poster is clear and logical.
- ☐ The use of key terms, symbols and equations is appropriate.

A poster should address the sections outlined in table 13.2 without going into too much detail. For example, you would display only a subset of the data to convey your findings and accuracy. Similarly, not all your graphs need to appear, only those that best show the trends and patterns in your data.

Your poster may be a hardcopy or a digital poster. Speak to your teacher about what you are required to submit.

In your poster you should:

- restrict the text to 800–1000 words
- avoid large blocks of text and long sentences
- avoid plagiarising; if you must quote, then acknowledge your sources
- use serif fonts, such as Times New Roman or Palatino, and use italics for emphasis, rather than underlining or bold
- check spelling and grammar as well as whether the correct word has been chosen, for example: affect or effect; it's or its.

13.10 EXERCISE

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

1. Convert the following units to the SI base unit shown:
 - (a) 1500 mA (to A)
 - (b) 0.52 km (to m)
 - (c) 150 μ s (to s)
2. Convert the following to the unit shown:
 - (a) 0.652 km (to cm)
 - (b) 8 673 628 μ g (to mg)
3. Describe the following aspects of a scientific report:
 - (a) Introduction
 - (b) Discussion
 - (c) Conclusion
4. Write a reference in Harvard style for this textbook. Show both in-text referencing and the full reference for the reference list.
5. How many significant figures are in the following?
 - (a) 643.1
 - (b) 0.002 34
 - (c) 0.0301
 - (d) 503.40
6. Calculate the following and express in the appropriate number of significant figures:
 - (a) The total length of three pieces of wire of 5.2 m, 6.53 m and 4.11 m
 - (b) The area of a rectangular building that is 64.2 m by 12 m

Fully worked solutions and sample responses are available in your digital formats.

13.11 Review

13.11.1 Summary

- It is important to choose a topic that allows for the development of a question and for observations to be made.
- An aim is a brief outline of the purpose of the investigation, linking the dependent and independent variables.
- A hypothesis is a tentative, testable and falsifiable statement for an observed phenomenon and acts as a prediction for the investigation.
- Part of the scientific method or process is in designing an experiment, conducting the experiment and analysing the results.
- Variables are factors that an investigator can control, change or measure.
- An independent variable is manipulated by the investigator — for example, the type of ball used.
- A dependent variable is measured by the investigator and is influenced by the independent variable — for example, the height that a ball bounces.
- A controlled variable is one that is kept the same in an investigation. There are usually numerous controlled variables in an experiment — for example, the surface the ball bounces on, the size of ball and the height that the ball is initially dropped from.
- It is important to control variables in order to examine one independent variable at a time, to better understand the relationship to the dependent variable.
- Key terms can be defined as part of a scientific report or in a glossary.
- Key terms that are selected should be those that are vital to understand the investigation.
- There are various representations used in physics, including symbols, models, equations and formulas.
- Understanding various representations helps make communication easier and clearer.
- Primary sources of data are direct or firsthand evidence, often gained through practical investigations.
- Data can be quantitative (numerical) or qualitative (categorical).
- It is vital to carefully choose the best techniques and equipment for an investigation. These should be precise, accurate and easy to conduct within a school environment.
- In an investigation, it is vital to consider the accuracy, precision, reliability and validity.
- Accuracy is how close a measurement is to a known value (like hitting the target on a bullseye).
- Precision is how close multiple measures are to each other (like hitting a '6' on a target three times in a row).
- Reliability shows that if an experiment is replicated (by oneself or another researcher), the results should be similar.
- Validity is how much credibility can be given to the results — do the results measure what they intended to and back up their claims?
- The best designed experiments are accurate, precise, reliable and valid, while minimising errors and uncertainties.
- Both errors and uncertainty can affect the results gained. Errors are a measurement of the difference between a measured value and the true value (the accuracy) whereas uncertainty defines the limits to precision and the range of values that can be measured.
- In an investigation, care must be taken to follow ethical, health and safety guidelines.
- Ethics ensures moral conduct, particularly when humans and animals are involved as test subjects. This does not tend to be an issue in physics, compared to biology and psychology.
- Health and safety is often evaluated using a risk assessment, where different hazards are analysed and safety requirements are made.
- Data can be organised in a variety of ways, including through the use of tables and graphs.
- Scatterplots and line graphs are used when both variables are quantitative.
- Bar graphs are used when one piece of data is qualitative and the other is quantitative.
- Histograms are used when intervals and frequency are being explored.

- It is important to choose an appropriate type of organising data in order to analyse trends, patterns and relationships.
- Graphs can be used to predict data outside of the investigated set.
- When evaluating data, it is important to link this to scientific concepts, models and theories, and to link these back to your aim and hypothesis, to describe trends and patterns, and identify any outliers or limitations.
- Models represent ideas, phenomena or scientific processes. They can be physical models, mathematical models or conceptual models.
- Limitations of models include an oversimplification of concepts, an inability to be completely accurate and being specific to a set of conditions, which may or may not reflect the real world.
- Theories are well-supported explanations of phenomena.
- Similar to models, theories are often oversimplifications of concepts, specific to a set of conditions and subject to change as new information becomes available.
- Evidence can be used to support or reject a hypothesis. A hypothesis is not stated to be confirmed or proven true as new evidence may come to light that later leads to its rejection.
- When reporting key findings, it is important to provide information about the data obtained in the practical investigation and any patterns and trends, to show the relationship of your findings to physics concepts including waves, fields or motion and to provide an answer to the question of your investigation.
- Both your logbook and scientific poster are forms of scientific reporting and combine for your mark for Unit 4 AOS 3.
- Components required in a scientific report include a title, date, name, introduction, aim, hypothesis, methodology (method and materials), results, discussion, conclusions and references.
- A variety of key symbols, formulas, equations, terminology, representations and abbreviations are used in physics and are required for effective communication.
- All sourced information must be correctly and clearly referenced using a style such as Harvard or APA.
- Your poster will not have every piece of information that your logbook will, but will show the important and key points that will allow for a clear understanding of your investigation.

13.11.2 Key terms

The **accuracy** of an experimental measurement indicates how close the measurement is to a known value. An **aim** is a statement outlining the purpose of an investigation, linking the dependent and independent variables. A **bar graph** is a graph in which data is represented by a series of bars. Such a graph is usually used when one variable is quantitative and the other is qualitative.

Categorical data, also known as qualitative data, contains labels or names rather than a range of numerical quantities.

A **conclusion** is a section at the end of a report that relates back to the question, summarises the key findings and states whether the hypothesis was supported or rejected.

A **control group** is a group that is not affected by the independent variables and is used as a baseline for comparison.

A **controlled variable** is a variable that is kept constant across different experimental groups.

The **dependent variable** is the variable that is influenced by the independent variable. It is the variable that is measured.

A **discussion** is a detailed area of a report in which results are discussed, analysed and evaluated, relationships to concepts are made, errors, limitations and uncertainties are assessed and suggestions for future improvements are made.

An **error** is the difference between a measurement taken and the true value that is expected. Errors lead to a reduction in the accuracy of the investigation.

Ethics constitute the acceptable and moral conduct determining what is 'right' and what is 'wrong'.

An **experimental group** is a test group that is exposed to the independent variable.

Falsifiable means there has to be a way to prove the hypothesis is wrong.

A **histogram** is a graph in which data is sorted in intervals (usually in columns), and frequency is examined. Such graphs are used when the data for both independent and dependent variables is quantitative. In a histogram, the columns are presented side by side (i.e. attached to one another).

A **hypothesis** is a tentative, testable and falsifiable statement for an observed phenomenon and acts as a prediction for the investigation.

The **independent variable** is the variable that is changed or manipulated by an investigator.

A **limitation** is a factor that has impacted the interpretation and/or collection of findings in a practical investigation.

A **line graph** is a graph in which points of data are joined by a connecting line. These are used when both pieces of data are quantitative (numerical).

A **line of best fit** is a trend line that is added to a scatterplot to best express the data shown. These are straight lines, and they are not required to pass through all the data points.

A **model** is a representation of an idea, phenomenon or scientific process. A model can be a physical model, a mathematical model or a conceptual model.

Numerical data, also known as quantitative data, is data that involves numbers that can be measured or counted.

An **outlier** is a result that is far removed from other results and seen as unusual.

Precision is a measure of how close multiple measurements from the same investigation are to one another.

A **primary source** provides direct or firsthand evidence about a phenomenon.

Qualitative data is categorical data that examines the quality of something (e.g. colour or gender) rather than numerical values.

Quantitative data is numerical data that examines the quantity of something (e.g. length or time).

A **random error** is a chance variation in measurements.

Reliability is a measure of whether another researcher, by following your method, could repeat your investigation and obtain similar results.

The **results** is a section in a report in which all the data obtained is recorded. This section is usually in the form of tables and graphs.

A **risk assessment** examines the different hazards in an investigation and recommends safety precautions. It is written up as a formal document.

A **scatterplot** is a graph in which two quantitative variables are plotted as a series of dots.

The **scientific method**, sometimes referred to as scientific process, is the procedure that must be followed in scientific investigations. It consists of questioning, researching, predicting, observing, experimenting and analysing.

Scientific research methodology consists of the principles of research based on the scientific method.

A **secondary source** comments on, summarises and interprets primary data.

A **systematic error** is an error that affects the accuracy of a measurement, and one that cannot be eliminated by repeating an experiment. Such an error usually results from equipment or system errors.

A **testable** hypothesis is a hypothesis that can be easily tested by observations and/or investigations.

A **theory** is a well-supported explanation of a phenomenon, based on facts that have been obtained through investigations, research and observations.

Uncertainty limits the precision of equipment. It is a range within which a measurement lies.

Validity is a statement about the credibility of the research results obtained from an experiment or from observations. Validity is achieved if the research results are highly credible — that is, if the results reflect what an experiment was designed to measure.



Resources

Digital document Key terms glossary (doc-32299)

13.11 Exercises

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

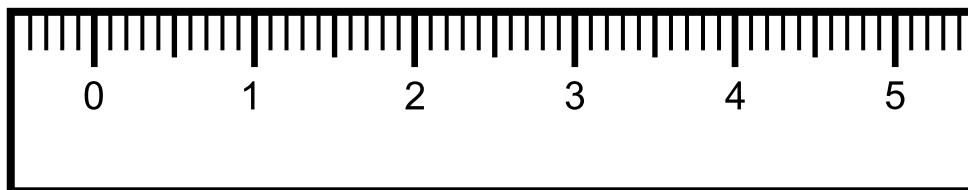
13.11 Exercise 1: Multiple choice questions

- Rani conducted an experiment to test the effect of different types of surfaces on friction. In this experiment, which of the following best defines the types of surfaces?
 - A dependent variable
 - An independent variable
 - A controlled variable
 - A control group
- Students were conducting an experiment to explore the effect of pH on a substance. Each measurement was taken four times using a universal indicator and recorded by the student. A digital pH monitor was also used.

Student	Recorded pH by student using universal indicator				Digital pH reader
	Measurement 1	Measurement 2	Measurement 3	Measurement 4	
Sam	10.0	8.0	6.5	7.5	10.0
Claude	8.5	8.5	8.4	8.6	9.8
Mel	9.1	9.5	8.8	9.3	9.1
Josette	8.0	9.0	8.5	7.5	9.2

Which one of the following statements is correct?

- Sam had the most accurate measurements.
 - Claude had the most precise measurements.
 - Mel had the least accurate measurements.
 - Josette had the least precise measurements.
- In physics, which one of the following does the symbol ϵ represent?
 - Electromagnetic field
 - Energy
 - Mass
 - Magnetic flux
 - A ruler is shown in the following diagram:



Which one of the following is the measure of tolerance/error in the ruler?

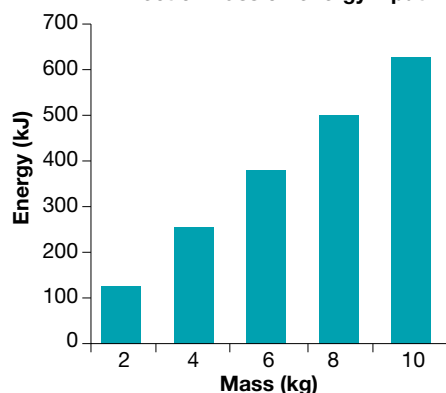
- 0.5 cm
- 0.1 cm
- 0.05 cm
- 0.025 cm

5. Gordon was investigating the effect of the mass of water on the amount of heat required as he increased the temperature from 55 to 70 °C. The results of his investigation are shown in the following table:

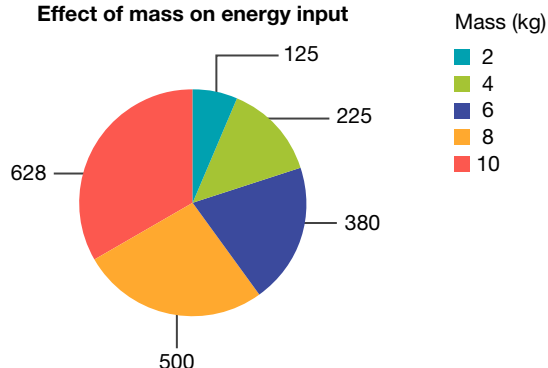
Mass	Heat released (kJ)
2	125
4	255
6	380
8	500
10	628

Which one of the following graphs is the most appropriate to show and analyse trends in this data?

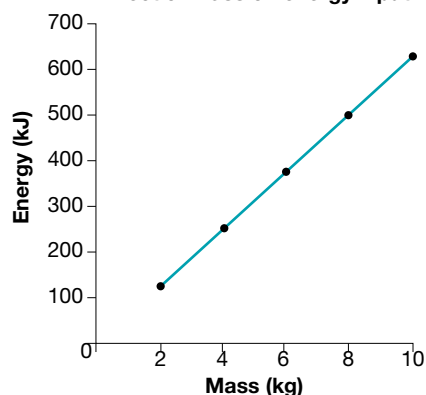
A. Effect of mass on energy input



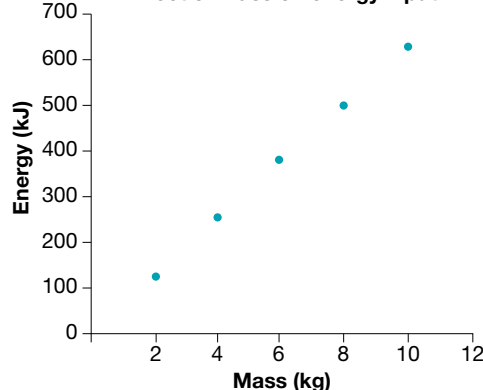
B. Effect of mass on energy input



C. Effect of mass on energy input



D. Effect of mass on energy input



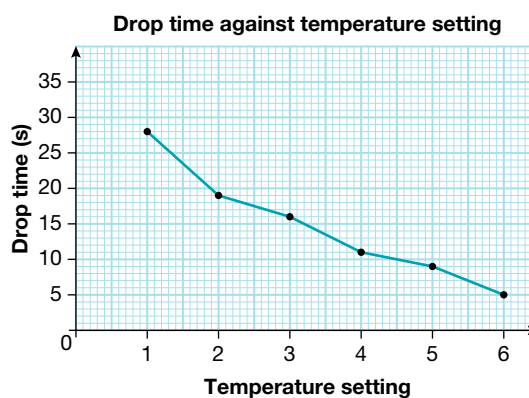
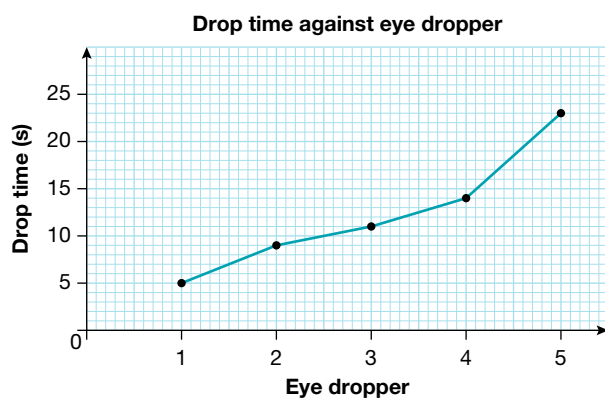
6. Which one of the following is true regarding random errors?
- They can affect the precision of a reading.
 - They are caused by faulty equipment.
 - They cannot be improved by repeating an experiment.
 - They are caused by the deliberate changing of results due to bias.
7. Which one of the following statements best describes the difference between an aim and a hypothesis?
- The aim of an experiment is a statement, but the hypothesis is a question.
 - The aim includes the dependent and independent variables, but a hypothesis doesn't.
 - The aim explains the expected data, but the hypothesis explains how you will get the data.
 - The aim outlines the purpose of the investigation, but the hypothesis is a testable prediction.
8. Olivia completed an investigation to record how long it takes for a ball to reach the ground from her apartment. She found that it took 608 milliseconds. Which of the following statements is correct about her result?
- It is equal to 60 800 microseconds.
 - It contains 2 significant figures.
 - It can be written as 6.08×10^2 milliseconds
 - It can be shortened to 608 Ms.

9. Which of the following is **not** an example of a limitation to a model?
 - A. It helps to make abstract concepts tangible.
 - B. It cannot show all the details of what it represents.
 - C. It is not always reflective of the situation in the real world.
 - D. It is forced to simplify concepts to make key ideas clear.
10. Which of the following is **not** a required component of a risk assessment?
 - A. The list of hazards of equipment being used
 - B. The ethics involved in the experiment
 - C. General safety equipment used
 - D. An outline of the experiment, including the date

13.11 Exercise 2: Short answer questions

1. An investigation was conducted to explore colour dispersion through a prism.
 - a. Identify two pieces of quantitative data that you could record and measure.
 - b. What instruments, if any, would you need to make these observations?
 - c. Identify two pieces of qualitative data that you could observe.
 - d. What instruments, if any, would you need to make these observations?
2. Identify a key difference between the members of the following pairs:
 - a. independent and dependent variables
 - b. qualitative and quantitative data
 - c. control group and experimental group
 - d. primary and secondary sources of data
 - e. uncertainty and error
3. In an investigation conducted in class, Clancy recorded a voltage of 0.062 40 V.
 - a. How many significant figures does this recorded voltage have?
 - b. Write this voltage in scientific notation.
4. Chris observes that when a droplet of water falls on a hot plate, it fizzes and shoots around the plate for some time. The droplet slowly gets smaller and finally disappears to nothing. Chris decides to investigate how long the droplet lasts, and how that might be affected by the temperature of the hot plate and the size of the droplet.

The equipment used was a hot plate, several droppers and a stopwatch. The length of time was measured three times for each eye dropper at six different temperature settings. The middle reading of each set of three readings was plotted. The following graphs were drawn from the recorded data:



- In one sentence, describe the aim of the investigation.
 - List the variables in Chris's investigation. For each variable, indicate whether it is an independent or dependent variable, and for each independent variable, indicate whether it is a continuous variable or a discrete variable. Give a reason for each answer.
 - Write a conclusion for this investigation.
 - A number of limitations may be identified in this investigation. Discuss these limitations and suggest some suitable improvements. Your discussion could address the following: selection of variables, experimental design, scientific method, data analysis, interpretation of results.
 - Suggest another independent variable.
 - Suggest a method for estimating the size of a water droplet.
5. Ammie conducted an experiment to explore the effect of different angled inclines on the speed of an object. Her data is shown in the following table:

Angle of incline (°)	Time to reach bottom of ramp (s)
10	7.2
20	5.0
30	4.1
40	3.4
50	2.6
60	1.9

- Sketch a graph of the data, including correct scale and labels.
- Describe the trends and patterns in this graph.
- What conclusions would you make from this investigation?

13.11 Exercise 3: Exam practice questions

Question 1 (8 marks)

Vicki decided to investigate an experiment found in the Amateur Scientist section of a very old edition of *Scientific American*. The following is a description of the experiment:

A large watch glass was placed on the cone of an upright loudspeaker. A small amount of water was added to the watch glass to a depth of a few millimetres. A signal generator was connected to the speaker, turned on and set at a high frequency. The water began to vibrate like a standing wave pattern. An eye dropper was then used to drop a water droplet onto the water surface. The droplet did not disappear into the water; instead, it moved around on the surface for some time before being absorbed.

Vicki decided to explore this further, investigating how long it took for the water droplet to absorb as the frequency increased.

- Identify the dependent variable in this investigation. **1 mark**
- List two variables that need to be controlled in this investigation. **1 mark**
- Describe what measuring equipment should be used in this investigation and identify **one** factor that could affect the accuracy of this piece of equipment. **2 marks**
- Write a clear experimental method for Vicki that shows how she can conduct this investigation. You may need to add to her method to make sure that more data is being collected and to ensure it is reproducible. **4 marks**

Question 2 (10 marks)

An investigation is being conducted to determine how mass affects the period of a pendulum.

- a. Write a suitable aim for this investigation. **1 mark**
- b. Identify the hypothesis for this investigation. **1 mark**
- c. Describe **one** piece of qualitative data and **one** piece of quantitative data that may be collected in this investigation. **2 marks**
- d. Explain **two** factors that may lead to differences in results between different students. **2 marks**
- e. Write a clear methodology for this investigation, with an explanation of how you will collect results and how you will control variables. **4 marks**

Question 3 (8 marks)

An investigation was being conducted to examine how the distance from a point charge affects the electric field.

The results from the investigation are shown in the following table:

Distance (mm)	Electric field (μT)
20	50 ± 4
30	31 ± 3
40	24 ± 2.5
50	19 ± 2
60	15 ± 1
70	12 ± 0.5

The student also calculated the uncertainty in electric field for each measurement.

- a. On graph paper, do the following:
 - i. Plot the graph showing the data provided, ensuring that the electric field is shown on the vertical axis. **1 mark**
 - ii. Label the graph and axes as appropriate. **1 mark**
 - iii. Draw a line of best fit. **1 mark**
 - iv. Show error bars for the electric field. **1 mark**
- b. Describe the trends seen in your data. **2 marks**
- c. Explain why error bars are important to include when examining data. **2 marks**

Question 4 (8 marks)

Two students, Brian and Michael, are exploring a spring that they were told obeys Hooke's Law. They examine this by determining whether the spring constant is the same when different masses of toy cars are tested. The spring is compressed by 0.10 m for each test.

Their results for their calculated spring constant are shown in the following table:

Mass of toy car (kg)	Calculated spring constant (N m^{-1})	
	Brian	Michael
0.10	40.1	50.4
0.20	42.1	56.1
0.30	39.8	47.2
0.40	43.3	48.5
0.50	39.0	52.4

- a. Describe **one** error that may have occurred that reduced the accuracy of the data for both Brian and Michael, and identify how this error might have been avoided. **2 marks**
- b. For the 0.10 kg car for both Brian and Michael, determine the strain potential energy using the following formula:

$$\text{Strain potential energy} = \frac{1}{2}k(\Delta x)^2$$

where k = the spring constant and Δx = the compression of the spring.

Be sure to use appropriate significant figures based on the data provided. **3 marks**

- c. Describe, with reference to Hooke's Law, why the results obtained by Brian are more accurate than those obtained by Michael. **2 marks**
- d. The spring constant is often calculated in N m^{-1} . Convert the spring constant that Brian found for the 0.40 kg car into N cm^{-1} . **1 mark**

Question 5 (12 marks)

A student conducted an investigation to explore different metallic surfaces using a photocell. The voltage required to stop the most energetic electrons emitted from the photocell was recorded.

A sample of the student's report is shown:

Introduction:

In this experiment, light with a wavelength of 425 nm is used to strike a clean piece of metal. Four different metals were examined — caesium, rubidium, potassium and sodium. The frequency of the incident light was increased through the experiment.

Aim:

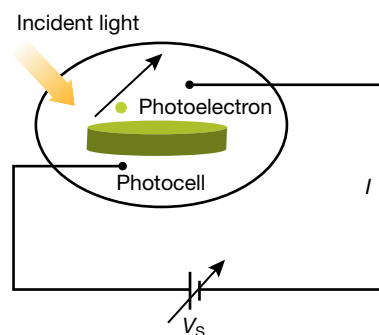
To determine the differences in the stopping voltage when different metals are used.

Hypothesis:

If caesium, rubidium, potassium and sodium are used in a photocell, then caesium will have the highest stopping frequency, as the emitted photoelectrons will have a greater kinetic energy.

Method:

1. Set up a simple photoelectric cell as shown in the following diagram. The photocell should contain the metal being tested, a collector electrode and a glass case.
2. For the incident light, set up a set of filters allowing 425 nm light to pass through and allow the frequency to be adjusted to the settings listed in the results table.
3. Add a voltmeter, variable power supply and ammeter into the circuit. The voltmeter should be in parallel and the ammeter in series.
4. Adjust the power supply until the ammeter is at 0.
5. Note the stopping voltage by looking at the value on the voltmeter at this point.



Results:

Different stopping voltages for each metal at different frequencies				
Frequency (Hz)	Caesium (V)	Rubidium (V)	Potassium (V)	Sodium (V)
4.0×10^{14}	2.0	1.7	1.4	1.1
5.0×10^{14}	2.4	2.1	1.8	1.5
6.0×10^{14}	2.8	2.5	2.2	1.9
7.0×10^{14}	3.2	2.9	2.6	2.3
8.0×10^{14}	3.6	3.3	3.0	2.7

- a. Describe an issue with the hypothesis written by the student. How would you adjust this to make it testable? **2 marks**
- b. A microammeter is recommended for this investigation, but the student used an ammeter. Explain why this may lead to errors in the data obtained. **2 marks**
- c. The voltmeter used could only record measurements to the nearest 0.1 V. Identify the tolerance or uncertainty of this device and describe how this will affect the data. **2 marks**
- d. Outline **two** limitations in the experimental method or data collection process that would affect the conclusions drawn. **2 marks**
- e. Describe the most appropriate graph that the student should use to represent their data. Justify your choice. **2 marks**
- f. Based on the student's results, write a conclusion for this investigation, linking back to the hypothesis. **2 marks**

APPENDIX 1

Periodic table

	Group 1								
Period 1	1 Hydrogen H 1.0								
	Group 2								
Period 2	3 Lithium Li 6.9	4 Beryllium Be 9.0							
Period 3	11 Sodium Na 23.0	12 Magnesium Mg 24.3							
			Group 3	Group 4	Group 5	Group 6	Group 7	Group 8	Group 9
Period 4	19 Potassium K 39.1	20 Calcium Ca 40.1	21 Scandium Sc 45.0	22 Titanium Ti 47.9	23 Vanadium V 50.9	24 Chromium Cr 52.0	25 Manganese Mn 54.9	26 Iron Fe 55.8	27 Cobalt Co 58.9
Period 5	37 Rubidium Rb 85.5	38 Strontium Sr 87.6	39 Yttrium Y 88.9	40 Zirconium Zr 91.2	41 Niobium Nb 92.9	42 Molybdenum Mo 96.0	43 Technetium Tc (98)	44 Ruthenium Ru 101.1	45 Rhodium Rh 102.9
Period 6	55 Caesium Cs 132.9	56 Barium Ba 137.3	57–71 Lanthanoids	72 Hafnium Hf 178.5	73 Tantalum Ta 180.9	74 Tungsten W 183.8	75 Rhenium Re 186.2	76 Osmium Os 190.2	77 Iridium Ir 192.2
Period 7	87 Francium Fr (223)	88 Radium Ra (226)	89–103 Actinoids	104 Rutherfordium Rf (261)	105 Dubnium Db (262)	106 Seaborgium Sg (266)	107 Bohrium Bh (264)	108 Hassium Hs (267)	109 Meitnerium Mt (268)

1
Hydrogen
H
1.0

2
Helium
He
4.0

← Atomic number

← Name

← Symbol

← Relative atomic mass

1	2	Key
Hydrogen	Helium	← Atomic number
H	He	← Name
1.0	4.0	← Symbol
		← Relative atomic mass

- Alkali metal
- Alkaline earth metal
- Transition metal
- Lanthanoids
- Actinoids
- Unknown chemical properties
- Post-transition metal
- Metalloid
- Reactive non-metal
- Halide
- Noble gas

Lanthanoids

57 Lanthanum La 138.9	58 Cerium Ce 140.1	59 Praseodymium Pr 140.9	60 Neodymium Nd 144.2	61 Promethium Pm (145)	62 Samarium Sm 150.4	63 Europium Eu 152.0

Actinoids

89 Actinium Ac (227)	90 Thorium Th 232.0	91 Protactinium Pa 231.0	92 Uranium U 238.0	93 Neptunium Np (237)	94 Plutonium Pu (244)	95 Americium Am (243)

									Group 18
			Group 13	Group 14	Group 15	Group 16	Group 17	2 Helium He 4.0	
			5 Boron B 10.8	6 Carbon C 12.0	7 Nitrogen N 14.0	8 Oxygen O 16.0	9 Fluorine F 19.0	10 Neon Ne 20.2	
Group 10	Group 11	Group 12	13 Aluminium Al 27.0	14 Silicon Si 28.1	15 Phosphorus P 31.0	16 Sulfur S 32.1	17 Chlorine Cl 35.5	18 Argon Ar 39.9	
28 Nickel Ni 58.7	29 Copper Cu 63.5	30 Zinc Zn 65.4	31 Gallium Ga 69.7	32 Germanium Ge 72.6	33 Arsenic As 74.9	34 Selenium Se 79.0	35 Bromine Br 79.9	36 Krypton Kr 83.8	
46 Palladium Pd 106.4	47 Silver Ag 107.9	48 Cadmium Cd 112.4	49 Indium In 114.8	50 Tin Sn 118.7	51 Antimony Sb 121.8	52 Tellurium Te 127.6	53 Iodine I 126.9	54 Xenon Xe 131.3	
78 Platinum Pt 195.1	79 Gold Au 197.0	80 Mercury Hg 200.6	81 Thallium Tl 204.4	82 Lead Pb 207.2	83 Bismuth Bi 209.0	84 Polonium Po (210)	85 Astatine At (210)	86 Radon Rn (222)	
110 Darmstadtium Ds (271)	111 Roentgenium Rg (272)	112 Copernicium Cn (285)	113 Nihonium Nh (280)	114 Flerovium Fl (289)	115 Moscovium Mc (289)	116 Livermorium Lv (292)	117 Tennessine Ts (294)	118 Oganesson Og (294)	

64 Gadolinium Gd 157.3	65 Terbium Tb 158.9	66 Dysprosium Dy 162.5	67 Holmium Ho 164.9	68 Erbium Er 167.3	69 Thulium Tm 168.9	70 Ytterbium Yb 173.1	71 Lutetium Lu 175.0

96 Curium Cm (247)	97 Berkelium Bk (247)	98 Californium Cf (251)	99 Einsteinium Es (252)	100 Fermium Fm (257)	101 Mendelevium Md (258)	102 Nobelium No (259)	103 Lawrencium Lr (262)

APPENDIX 2

Astronomical data

	Mean radius of orbit		Orbital period		Equatorial radius (m)	Mass (kg)
	(AU)	(m)	(years)	(seconds)		
Sun					6.96×10^8	1.99×10^{30}
Mercury	0.387	5.79×10^{10}	0.241	7.60×10^6	2.44×10^6	3.30×10^{23}
Venus	0.723	1.08×10^{11}	0.615	1.94×10^7	6.05×10^6	4.87×10^{24}
Earth	1.00	1.50×10^{11}	1.00	3.16×10^7	6.37×10^6	5.98×10^{24}
Moon	2.57×10^{-3}	3.84×10^8	27.3 days*	2.36×10^6 *	1.74×10^6	7.35×10^{22}
Mars	1.52	2.28×10^{11}	1.88	5.94×10^7	3.39×10^6	6.42×10^{23}
Jupiter	5.20	7.78×10^{11}	11.9	3.74×10^8	6.99×10^7	1.90×10^{27}
Saturn	9.58	1.43×10^{12}	29.5	9.30×10^8	5.82×10^7	5.68×10^{26}
Titan	8.20×10^{-3}	1.22×10^9	15.9 days*	1.37×10^6 *	2.57×10^6	1.35×10^{23}
Uranus	19.2	2.87×10^{12}	84.0	2.65×10^9	2.54×10^7	8.68×10^{25}
Neptune	30.1	4.50×10^{12}	165	5.21×10^9	2.46×10^7	1.02×10^{26}
Pluto	39.48	5.91×10^{12}	248	7.82×10^9	1.15×10^6	1.31×10^{22}

* The orbital period for the Moon and Titan is the time it takes to complete one orbit around Earth and Saturn respectively. All other listed measurements for the orbital period shows the time to orbit the Sun.

The Milky Way	1.50×10^5 light-years across
Alpha Centauri	4.37 light-years away
Andromeda	2.25×10^6 light-years away
Edge of observable universe	4.65×10^{10} light-years away

Source: Data derived from <https://solarsystem.nasa.gov>.

APPENDIX 3

Formulae and data

Velocity; acceleration	$\mathbf{v} = \frac{\Delta \mathbf{x}}{\Delta t}; \mathbf{a} = \frac{\Delta \mathbf{v}}{\Delta t}$

Equations for constant acceleration	$\mathbf{v} = \mathbf{u} + \mathbf{a}t$ $\mathbf{s} = \mathbf{u}t + \frac{1}{2}\mathbf{a}t^2$ $\mathbf{v}^2 = \mathbf{u}^2 + 2\mathbf{a}\mathbf{s}$ $\mathbf{s} = \frac{1}{2}(\mathbf{v} + \mathbf{u})t$

Newton's Second Law of Motion	$\Sigma \mathbf{F} = m\mathbf{a}$

Circular motion	$a = \frac{v^2}{r} = \frac{4\pi^2 r}{T^2}$

Hooke's Law	$\mathbf{F} = -k\Delta x$

Elastic potential energy	$E_e = \frac{1}{2}k(\Delta x)^2$

Kinetic energy	$E_k = \frac{1}{2}mv^2$

Newton's Law of Universal Gravitation	$\mathbf{F} = G \frac{M_1 M_2}{r^2}$

Gravitational field strength	$\mathbf{g} = G \frac{M}{r^2}$

Gravitational potential energy near the Earth's surface	$E_g = mgh$

Impulse	$\mathbf{J} = \mathbf{F}\Delta t \text{ or } \Delta \mathbf{p}$

Momentum	$\mathbf{p} = m\mathbf{v}$

Lorentz factor	$\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}$

Time dilation	$t = t_0 \gamma$

Length contraction	$l = \frac{L_0}{\gamma}$

Relativistic mass	$m = m_0 \gamma$

(continued)

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Relativistic total energy	$E_{\text{total}} = \gamma mc^2$
Rest energy	$E_{\text{rest}} = mc^2$
Relativistic kinetic energy	$E_k = (\gamma - 1)mc^2$
Magnetic force on a current-carrying conductor	$F = nI l B$
Magnetic force on a moving charge	$F = qvB$
Radius of a charged particle in a magnetic field	$r = \frac{mv}{qB}$
Energy transformation for electrons in an electron gun ($< 100 \text{ keV}$)	$\frac{1}{2}m_e v^2 = eV$
Radius of electron path in a magnetic field	$r = \frac{m_e v}{eB}$
Magnetic force on a moving electron	$F = evB$
Electric field between charged plates	$E = \frac{V}{d}$
Energy transformation of charges in an electric field	$\frac{1}{2}mv^2 = qV$
Field of a point charge	$E = \frac{kq}{r^2}$
Force on an electric charge	$F = qE$
Coulomb's Law	$F = \frac{kq_1 q_2}{r^2}$
Voltage; power	$V = RI; P = VI = I^2 R$
Resistors in series	$R_T = R_1 + R_2$
Resistors in parallel	$\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2}$
Transformer action	$\frac{V_1}{V_2} = \frac{N_1}{N_2}$
AC voltage and current	$V_{\text{RMS}} = \frac{1}{\sqrt{2}} V_{\text{peak}}; I_{\text{RMS}} = \frac{1}{\sqrt{2}} I_{\text{peak}}$
Electromagnetic induction	EMF: $\varepsilon = \frac{-N\Delta\Phi}{\Delta t};$ flux: $\Phi = B_{\perp} A$

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Transmission losses

$$V_{\text{drop}} = I_{\text{line}} R_{\text{line}};$$

$$P_{\text{loss}} = I_{\text{line}}^2 R_{\text{line}}$$

Photoelectric effect

$$E_{\text{kmax}} = hf - W$$

Photon energy

$$E = hf = \frac{hc}{\lambda}$$

Photon momentum

$$p = \frac{h}{\lambda}$$

De Broglie wavelength

$$\lambda = \frac{h}{p}$$

Wave equation

$$v = f\lambda$$

Constructive interference

$$\text{path difference} = n\lambda$$

Destructive interference

$$\text{path difference} = \left(n - \frac{1}{2}\right)\lambda$$

Fringe spacing

$$\Delta x = \frac{\lambda L}{d}$$

Snell's law

$$n_1 \sin \theta_1 = n_2 \sin \theta_2$$

Data and constants

Universal Gravitational constant

$$G = 6.67 \times 10^{-11} \text{ N m}^2 \text{ kg}^{-2}$$

Mass of Earth

$$M_{\text{E}} = 5.98 \times 10^{24} \text{ kg}$$

Radius of Earth

$$R_{\text{E}} = 6.37 \times 10^6 \text{ m}$$

Acceleration due to gravity at the Earth's surface

$$g = -9.8 \text{ m s}^{-2}$$

Mass of an electron

$$m_{\text{e}} = 9.1 \times 10^{-31} \text{ kg}$$

Charge of an electron

$$e = -1.6 \times 10^{-19} \text{ C}$$

Planck's constant

$$h = 6.63 \times 10^{-34} \text{ J s}$$
$$= 4.14 \times 10^{-15} \text{ eV s}$$

Speed of light

$$c = 3.0 \times 10^8 \text{ m s}^{-1}$$

Coulomb constant

$$k = 8.99 \times 10^9 \text{ N m}^2 \text{ C}^{-2}$$

Source: VCAA

GLOSSARY

The **absolute refractive index** of a substance is the relative refractive index for light travelling from a vacuum into the substance. It is commonly referred to as the refractive index.

An **absorption spectrum** is a spectrum produced when light passes through a cool gas. It includes a series of dark lines that correspond to the frequencies of light absorbed by the gas.

Acceleration is the rate of change of velocity. It is a vector quantity.

The **accuracy** of an experimental measurement indicates how close the measurement is to a known value.

An **aim** is a statement outlining the purpose of an investigation, linking the dependent and independent variables.

Air resistance is the force applied to an object opposite to its direction of motion, by the air through which it is moving.

An **alternating current** is an electric current that reverses direction at short, regular intervals.

An **alternator** is a device in which the ends of the coil are connected to slip rings, causing the voltage to alternate in direction, inducing an alternating current (AC).

The **amplitude** of a periodic disturbance is the maximum variation from zero.

The **amplitude** of a wave is the size of the maximum disturbance of the medium from its normal state.

The **angle of incidence** is the angle between an incident ray and the normal.

The **angle of reflection** is the angle between a reflected ray and the normal.

The **angle of refraction** is the angle between a refracted ray and the normal.

An **antinodal line** is a line where constructive interference occurs on a surface.

An **antinode** is a point at which constructive interference takes place.

An **armature** is a frame around which a coil of wire is wound, which rotates in a motor's magnetic field.

A **back emf** is an electromagnetic force that opposes the main current flow in a circuit. When the coil of a motor rotates, a back emf is induced in the coil due to its motion in the external magnetic field.

A **bar graph** is a graph in which data is represented by a series of bars. Such a graph is usually used when one variable is quantitative and the other is qualitative.

A **black body** is an ideal absorber of energy. It absorbs all electromagnetic radiation that falls on it and does not reflect any.

Brushes are conductors that make electrical contact with the moving split ring commutator in a DC motor.

Categorical data, also known as qualitative data, contains labels or names rather than a range of numerical quantities.

The **centre of mass** is the point at which all of the mass of an object can be considered to be positioned when modelling the external forces acting on the object.

Centripetal acceleration is the acceleration towards the centre of a circle experienced by an object moving in a circular motion.

Centripetal acceleration is the centre-directed acceleration of an object moving in a circle.

Coherent emitted light is light in which all photons are emitted in phase, leading to intense light.

Two waves are **coherent** if there is a constant relative phase between them.

A **compression** is a region of increased pressure in a medium during the transmission of a sound wave.

A **conclusion** is a section at the end of a report that relates back to the question, summarises the key findings and states whether the hypothesis was supported or rejected.

A **conductor** is a material that allows electrical currents to flow.

Constructive interference describes the addition of two wave disturbances to give an amplitude that is greater than either of the two waves.

A **continuous spectrum** is a spectrum that has no gaps. There are no frequencies or wavelengths missing from the spectrum.

A **control group** is a group that is not affected by the independent variables and is used as a baseline for comparison.

A **controlled variable** is a variable that is kept constant across different experimental groups.

The **critical angle** is the angle of incidence for which the angle of refraction is 90° . The critical angle exists only when light passes from one substance into a second substance with a lower refractive index.

The **de Broglie wavelength** is the wavelength associated with a particle or discrete piece of matter.

The **dependent variable** is the variable that is influenced by the independent variable. It is the variable that is measured.

The **design speed** is the speed at which the force due to friction becomes zero, as seen on a banked track.

Destructive interference is the addition of two wave disturbances to give an amplitude that is less than either of the two waves.

Diffraction is the spreading out, or bending of, waves as they pass through a small opening or move past the edge of an object.

Diffuse reflection is reflection from a rough or irregular surface.

A **dipole field** is the electric field surrounding a positive charge and a negative charge that are separated by a short distance.

A **direct current** is an electric current that flows in one direction only.

A **discussion** is a detailed area of a report in which results are discussed, analysed and evaluated, relationships to concepts are made, errors, limitations and uncertainties are assessed and suggestions for future improvements are made.

Dispersion is the separation of light into different colours as a result of refraction.

Displacement is a measure of the change in position of an object. It is a vector quantity.

Distance is a measure of the length of the path taken when an object changes position. It is a scalar quantity.

An **eddy current** is an electric current induced in the iron core of a transformer by changing magnetic fields.

An **elastic collision** is a collision in which the total kinetic energy is conserved.

An **electric dipole** is the separation of a pair of oppositely charged or magnetised poles.

An **electric field** is a vector field describing the property of the space around a charge that causes a second charge in that space to experience a force due only to the presence of the first charge.

An **electrical force** is the force experienced by a charged particle if it is placed within the electric field of a second charged particle.

An **electromagnet** is a temporary magnet produced in the presence of a current-carrying wire.

Electromagnetic induction is the generation of an electric current in a coil as a result of a changing magnetic field or as a result of the movement of the coil within a constant magnetic field.

An **electron gun** is a device to provide free electrons for a linear accelerator. It usually consists of a hot wire filament with a current supplied by a low-voltage source.

An **electron volt** is the quantity of energy acquired by an elementary charge ($q_e = 1.6 \times 10^{-19} \text{ C}$) passing through a potential difference of 1 V. Thus, $1.6 \times 10^{-19} \text{ J} = 1 \text{ eV}$.

An **emf** is a source of voltage that can cause an electric current to flow.

Emission spectra are produced when light is emitted from an excited gas and passed through a spectrometer. A spectrum includes a series of bright lines on a dark background. The bright lines correspond to the frequencies of light emitted by the gas.

An **error** is the difference between a measurement taken and the true value that is expected. Errors lead to a reduction in the accuracy of the investigation.

Ethics constitute the acceptable and moral conduct determining what is 'right' and what is 'wrong'.

An **excited state** is a state in which an electron has more energy than its ground state.

An **experimental group** is a test group that is exposed to the independent variable.

Falsifiable means there has to be a way to prove the hypothesis is wrong.

The **frequency** is the number of revolutions that an object completes each second.

The **frequency**, f , of a periodic wave is the number of times that the wave repeats itself every second.

A **galvanometer** is an instrument used to detect small electric currents, as well as being able to detect the direction of current (such as in AC).

A **generator** is a device in which a rotating coil in a magnetic field is used to induce a voltage.

A satellite in **geostationary** orbit is stationary relative to a point directly below it on the Earth's surface.

A geostationary orbit has the same period as the rotation of Earth.

A **gravitational field** is a vector field describing the property of space around an object with mass that causes a second object with mass to experience a gravitational force towards the object.

Gravitational potential energy is the energy stored in an object as a result of its position relative to another object to which it is attracted by the force of gravity.

The **ground state** is the state of an electron in which it has the least possible amount of energy.

A **histrogram** is a graph in which data is sorted in intervals (usually in columns), and frequency is examined. Such graphs are used when the data for both independent and dependent variables is quantitative. In a histogram, the columns are presented side by side (i.e. attached to one another).

A **hypothesis** is a tentative, testable and falsifiable statement for an observed phenomenon and acts as a prediction for the investigation.

An **ideal transformer** is a transformer that is 100% efficient. Its input power is equal to its output power.

Impulse is the product of a force and the time interval over which it acts. Impulse is a vector quantity with SI units of N s.

Incandescent objects are luminous objects that produce light because they are hot. The higher the temperature, the brighter the light, and the colour also changes.

The **independent variable** is the variable that is changed or manipulated by an investigator.

An **induced voltage** is a voltage that is caused by the separation of charge due to the presence of a magnetic field.

An **inelastic collision** is a collision in which the total kinetic energy is not conserved.

An **inertial reference frame** is a reference frame that is not accelerating.

Instantaneous speed is the speed at a particular instant of time.

Instantaneous velocity is the velocity at a particular instant of time.

An **insulator** is a material that does not allow electrical current to flow.

An **invariant** quantity is a quantity that has the same value in all reference frames.

The **inverse square law** describes a relationship in which one variable is proportional to the reciprocal of the square of another variable.

Ionisation energy is the amount of energy required to be transferred to an electron to enable it to escape from a material.

An **isolated system** is one on which no external forces act. The only forces acting on objects in the system are those applied by other objects in the system.

Kinetic energy is the energy associated with the movement of an object. Like all forms of energy, it is a scalar quantity.

The **left-hand rule** and **right-hand-slap rule** are used to determine the direction of the magnetic force of a magnetic field on a current or moving positive charge.

A **light ray** can be considered as an infinitely narrow beam of light and can be represented as a straight line.

A **light-emitting diode (LED)** is a small semiconductor diode that emits light when a current passes through it.

The term **like charges** indicates charges with the same polarity.

A **limitation** is a factor that has impacted the interpretation and/or collection of findings in a practical investigation.

A **line emission spectrum** shows the discrete frequencies or wavelengths produced by an excited material.

A **line graph** is a graph in which points of data are joined by a connecting line. These are used when both pieces of data are quantitative (numerical).

A **line of best fit** is a trend line that is added to a scatterplot to best express the data shown. These are straight lines, and they are not required to pass through all the data points.

A **linear particle accelerator** is a type of particle accelerator based on the work done by the field in moving a charge from one plate to the other.

A **longitudinal wave** is a wave for which the disturbance is parallel to the direction of propagation.

Luminous objects are objects that are seen because they give off their own light.

A **magnetic field** is a vector field describing the property of the space around a magnet that causes an object in that space to experience a force due only to the presence of the magnet.

Magnetic flux density, B , is the strength of a magnetic field, which is measured in tesla (T) or weber per square metre (Wb m^{-2}).

Magnetic flux is a measure of the amount of magnetic field passing through an area. It is measured in webers (Wb).

The **magnetic induction** process is the creation of magnetic properties in an object as the result of the presence of a second, nearby object with magnetic properties.

As mass and energy are equivalent, they can be described as a single concept, **mass–energy**. The mass–energy of an object is given by $E = mc^2$.

A **model** is a representation of an idea, phenomenon or scientific process. A model can be a physical model, a mathematical model or a conceptual model.

Momentum is the product of the mass of an object and its velocity. Momentum is a vector quantity.

Monochromatic describes light of a single frequency and, hence, very clearly defined colour.

A **nanocrystal** is a very small crystal with only a few hundred to a thousand atoms.

Net force is the vector sum of all the forces acting on an object.

A **nodal line** is a line where destructive interference occurs on a surface, resulting in no displacement of the surface.

A **node** is a point at which destructive interference takes place.

The **normal** is a line that is perpendicular to a surface or a boundary between two surfaces.

Numerical data, also known as quantitative data, is data that involves numbers that can be measured or counted.

An **optical fibre** is a thin tube of transparent material that allows light to pass through without being refracted into the air or another external medium.

The **orbital period**, or sidereal period, is the time it takes for a satellite to complete one orbit around a central object.

An **outlier** is a result that is far removed from other results and seen as unusual.

Path difference is the difference between the lengths of the paths from each of two sources of waves to a point.

The **peak current**, I_{peak} , is the amplitude of an alternating current.

The **peak voltage**, V_{peak} , is the amplitude of an alternating voltage.

The **peak-to-peak voltage**, $V_{\text{p-p}}$, is the difference between the maximum and minimum voltages of a DC voltage.

The **period** is the time taken for an object, moving in a circular path and at a constant speed, to complete one revolution.

The **period**, T , of a periodic wave is the time it takes a source to produce a complete wave. This is the same as the time taken for a complete wave to pass a given point.

A **periodic wave** is a disturbance that repeats itself at regular intervals.

The **photoelectric effect** is the release of electrons from a metal surface as a result of exposure to electromagnetic radiation.

A **photon** is a discrete bundle of electromagnetic radiation. Photons can be thought of as discrete packets of light energy with zero mass and zero electric charge.

Polarisation is the blocking of transverse waves except for those travelling in a single plane.

The **power rating**, or wattage, of an electrical appliance indicates the rate at which it uses electrical energy.

Precision is a measure of how close multiple measurements from the same investigation are to one another.

A **primary source** provides direct or firsthand evidence about a phenomenon.

The **proper length** of an object is the length measured in the rest frame of the object.

The **proper time** between two events is the time measured in a frame of reference where the events occur at the same point in space. The proper time of a clock is the time the clock measures in its own reference frame.

Qualitative data is categorical data that examines the quality of something (e.g. colour or gender) rather than numerical values.

Quantised describes quantities that cannot be divided or broken up into smaller parts.

Quantitative data is numerical data that examines the quantity of something (e.g. length or time).

A **quantum** is a small quantity of a fixed amount.

A **random error** is a chance variation in measurements.

A **rarefaction** is a region of reduced pressure in a medium during the transmission of a sound wave.

Refraction is the bending of light as it passes from one medium into another.

Regular reflection (also referred to as specular reflection) is reflection from a smooth surface.

Relative refractive index is a measure of how much light bends when it travels from any one substance into any other substance.

A quantity is **relative** when it has different values for different observers.

Reliability is a measure of whether another researcher, by following your method, could repeat your investigation and obtain similar results.

Resonance is the condition where a medium responds to a periodic external force by vibrating with the same frequency as the force.

The **rest mass** is the mass of an object measured at rest.

The **restoring force** applied by a spring is the force it applies to resist compression or extension.

The **results** is a section in a report in which all the data obtained is recorded. This section is usually in the form of tables and graphs.

A **risk assessment** examines the different hazards in an investigation and recommends safety precautions. It is written up as a formal document.

The **RMS** (root mean square) **voltage**, V_{RMS} , is the value of the constant DC voltage that would produce the same power as AC voltage across the same resistance.

Road friction is the force applied by the road surface to the wheels of a vehicle in a direction opposite to the direction of motion of the vehicle.

A **satellite** is an object that is orbiting a larger central mass. Satellites can be natural (such as the Moon) or man-made (such as the International Space Station).

A **scalar quantity** has magnitude (size) but not direction.

A **scatterplot** is a graph in which two quantitative variables are plotted as a series of dots.

The **scientific method**, sometimes referred to as scientific process, is the procedure that must be followed in scientific investigations. It consists of questioning, researching, predicting, observing, experimenting and analysing.

Scientific research methodology consists of the principles of research based on the scientific method.

A **secondary source** comments on, summarises and interprets primary data.

A **semiconductor** is a material that has a resistivity between that of conductors and insulators.

A **solenoid** is a coil of wire wound into a cylindrical shape.

A **spectrometer** is a device used to disperse light into its spectrum.

Speed is a measure of the time rate at which an object moves over a distance.

A **split ring commutator** is a device that reverses the direction of the current flowing through an electric circuit.

A **standing wave** is the superposition of two wave trains at the same frequency and amplitude travelling in opposite directions. Standing waves are also known as stationary waves because they do not appear to move through the medium. The nodes and antinodes remain in a fixed position.

A **step-down transformer** produces an output (secondary) voltage that is less than the input (primary) voltage.

A **step-up transformer** produces an output (secondary) voltage that is greater than the input (primary) voltage.

Strain potential energy is the energy stored in an object as a result of a reversible change in shape.

Superposition is the adding together of amplitudes of two or more waves passing through the same point.

A **systematic error** is an error that affects the accuracy of a measurement, and one that cannot be eliminated by repeating an experiment. Such an error usually results from equipment or system errors.

A falling object reaches its **terminal velocity** when the upward air resistance becomes equal to the downward force of gravity.

A **testable** hypothesis is a hypothesis that can be easily tested by observations and/or investigations.

A **theory** is a well-supported explanation of a phenomenon, based on facts that have been obtained through investigations, research and observations.

A **thermal spectrum** is the spectrum produced by a body due to its temperature.

A **thought experiment** (also known as a gedanken experiment) is an imaginary scenario designed to explore what the laws of physics predict would happen.

The term **time dilation** describes the slowing of time by clocks moving relative to the observer.

The **torque** is the turning effect of the forces on the coil in an electric motor.

Total internal reflection is the total reflection of light from a boundary between two substances. It occurs when the angle of incidence is greater than the critical angle.

A **transformer** is a device in which two multi-turn coils may be wound around an iron core. One coil acts as an input while the other acts as an output. The purpose of the transformer is to produce an output AC voltage that is different from the input AC voltage.

A **transverse wave** is a wave for which the disturbance is at right angles to the direction of propagation.

Uncertainty limits the precision of equipment. It is a range within which a measurement lies.

A **uniform electric field** is an electrical field in which the strength and direction are constant at every point.

The term **unlike charges** indicates charges with opposite polarity.

Validity is a statement about the credibility of the research results obtained from an experiment or from observations. Validity is achieved if the research results are highly credible — that is, if the results reflect what an experiment was designed to measure.

A **vector quantity** has direction as well as magnitude (size).

Velocity is a measure of the time rate of displacement, or the time rate of changing position. It is a vector quantity.

A **wave** is a transfer of energy through a medium without any net movement of matter.

Wave-particle duality describes light as having characteristics of both waves and particles. This duality means that neither the wave model nor the particle model adequately explains the properties of light on its own.

The **wavelength** is the distance between successive corresponding parts of a periodic wave.

A **Wien filter** (or **velocity selector**) is a device that can be used as a velocity filter using a magnetic field to deflect the beam of charged particles in one direction, and an electric field to deflect the beam in the opposite direction.

The **work function** is the minimum energy required to release an electron from the surface of a material.

Work is the energy transferred to or from another object by the action of a force. Work is a scalar quantity.

Answers

1 Gravitational, electric and magnetic fields

1.2 Gravitational forces and fields

Sample problem 1

- 688 N towards the centre of the Earth.
- 688 N towards the person.

Practice problem 1

$$F_{\text{on Moon by the Earth}} = 1.98 \times 10^{20} \text{ N towards Earth}$$

$$F_{\text{on Earth by the Moon}} = 1.98 \times 10^{20} \text{ N towards Moon}$$

Sample problem 2

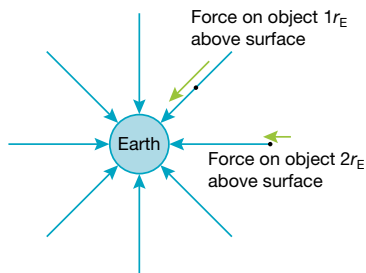
$$1.62 \text{ N kg}^{-1}$$

Practice problem 2

$$5.93 \times 10^{-3} \text{ N kg}^{-1}$$

1.2 Exercise

1. a.



b. The ratio of the forces experienced is

$$\frac{F_{2r_E}}{F_{3r_E}} = \frac{(3r_E)^2}{(2r_E)^2} = \frac{9}{4} = 2.25$$

c. Non-uniform as seen in the spacing between the field lines which increase as the distance from the Earth increases.

- 9.83 N kg^{-1}
 - 688 N
- 3.73 N kg^{-1}
 - 261 N
- 8.87 N kg^{-1}
 - 621 N
- 0.661 N kg^{-1}
 - 46.3 N

3. Gravitational field lines point inwards because masses are only attracted to other masses.

- 3.99 N kg^{-1}
 - 0.997 N kg^{-1}
 - 0.443 N kg^{-1}

b and c. (i) : (ii) = $1 : \frac{1}{4}$

(i) : (iii) = $1 : \frac{1}{9}$

(ii) : (iii) = $\frac{1}{4} : \frac{1}{9}$

Comparing ratios demonstrates the inverse square relationship for the field.

- $3.53 \times 10^{22} \text{ N}$
- The force due to gravity would be a quarter of the initial force.
- $g_{\text{Sun}} = 0.00590 \text{ N kg}^{-1}$
 $g_{\text{Earth}} = 0.00270 \text{ N kg}^{-1}$

8. (a)

Red dot:
 $0.0058991 \text{ N m}^{-1}$ towards the Sun

Orange dot:
 $0.0058960 \text{ N m}^{-1}$ towards the Sun

(b)

Red dot:
 $0.0059656 \text{ N m}^{-1}$ towards the Sun

Orange dot:
 $0.0059352 \text{ N m}^{-1}$ towards the Sun

9. 2.5

1.3 Electric forces and fields

Sample problem 3

$$3.6 \times 10^{-6} \text{ N}$$

This force is repulsive.

Practice problem 3

$$8.1 \times 10^{-8} \text{ N}$$

This force is attractive.

Sample problem 4

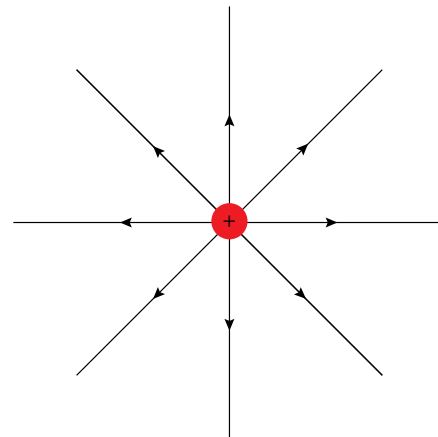
$$7.2 \times 10^3 \text{ N C}^{-1}$$

Practice problem 4

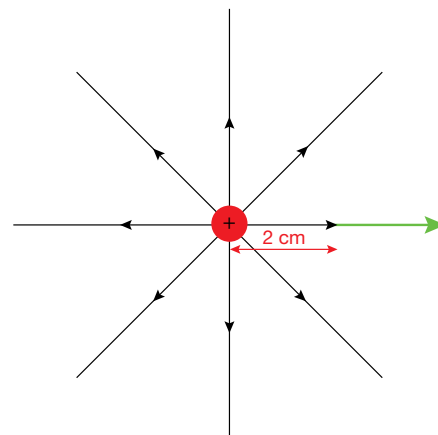
$$-3.00 \times 10^5 \text{ N C}^{-1}$$

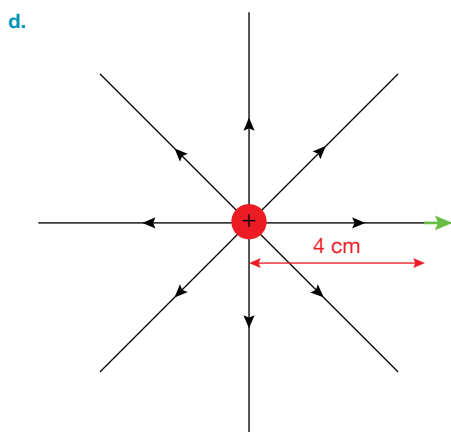
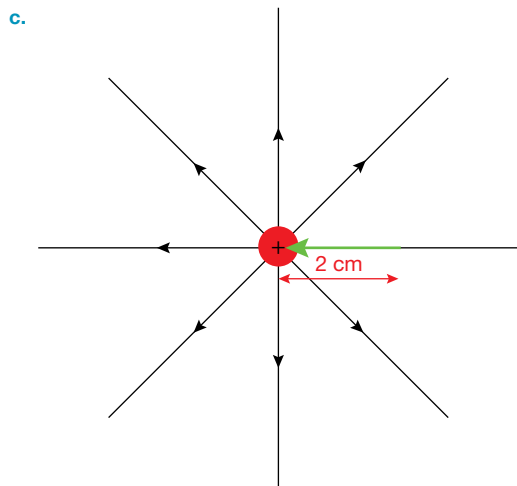
Sample problem 5

a.

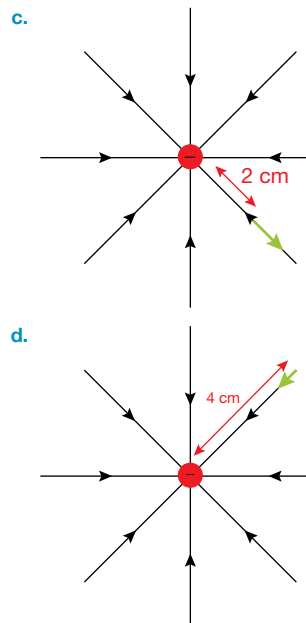
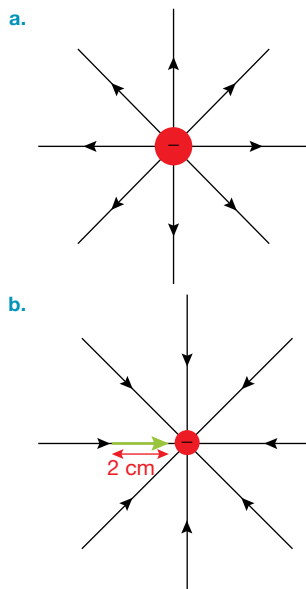


b.

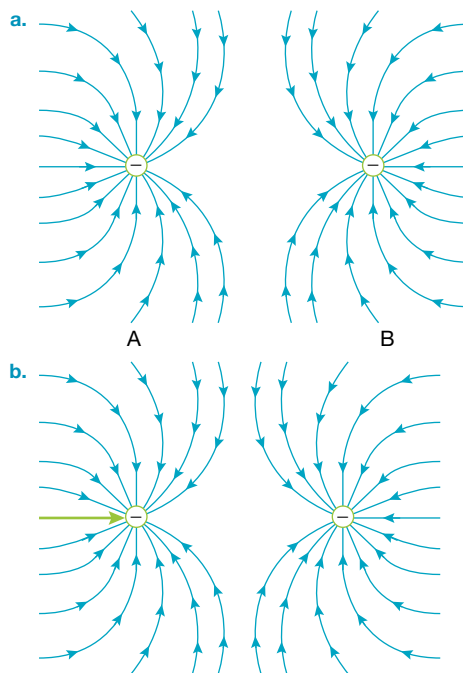




Practice problem 5

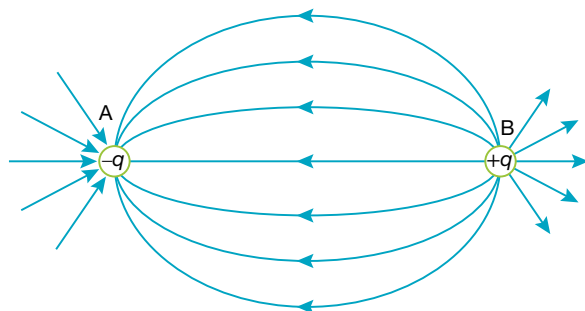


Sample problem 6



- c. When the 1 nC charge moves past particle A to the right-hand side, it experiences an attractive force to the left from particle A and also an attractive force to the right from particle B. Because the charge is closer to particle A than particle B, the force acting to the left is stronger than the force to the right, so the net (or overall) force on the 1 nC charge at this point is to the left (but it is smaller in magnitude than the force it experienced in part b). As the charge is moved closer to particle B, the magnitude of the leftwards net force decreases to zero at the point halfway between the two particles. When the charge moves closer to particle B than particle A, the net force acts to the right and becomes stronger as the charge moves closer to particle B.

Practice problem 6



- A positive charge to the left of A would be attracted to the right towards the negatively charged particle (particle A). A positive charge to the right of A would be both attracted to A by particle A and repelled towards A by particle B, so the force experienced by the charge would be larger, but to the left.
- As a positive charge moves along an imaginary line separating particles A and B, the direction of the force would always be to the left; however, it would be a minimum at the halfway point.

Sample problem 7

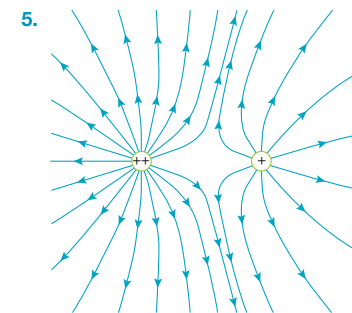
- $1.6 \times 10^{-18} \text{ N}$
- The electron experiences a force in the opposite direction to the electric field.
- $1.9 \times 10^5 \text{ m s}^{-1}$

Practice problem 7

- $3.2 \times 10^{-18} \text{ N}$
- Towards the negative plate
- $6.2 \times 10^3 \text{ m s}^{-1}$

1.3 Exercise

- The direction of the field is westerly.
- $1.2 \times 10^7 \text{ N C}^{-1}$
 - 120 N parallel to the electric field
- $5.0 \times 10^5 \text{ N C}^{-1}$ up
- $1.25 \times 10^{-4} \text{ N}$
 - $1.5 \times 10^{-3} \text{ N}$
 - $1.0 \times 10^{-3} \text{ N}$
 - $4.0 \times 10^{-3} \text{ N}$



- Right
 - Right
- 0.08 m from the smaller charge
- $4.0 \times 10^{-3} \text{ N}$
- $1.8 \times 10^{17} \text{ m s}^{-2}$
 - $1.7 \times 10^{-10} \text{ s}$
 - 2.5 mm
- $s = \frac{Eq t^2}{2mv^2}$
 - $8.0 \times 10^{-13} \text{ C}$

1.4 Magnetic forces and fields

Sample problem 8

- At X, the north point of the compass would point towards the right.
At Y, the north point of the compass would point towards the left.
At Z, the north point of the compass would point to the right at an angle of approximately 45° upwards.
- Y, Z, X.

Practice problem 8

- Left
- Right
- Between the poles of the horseshoe magnet

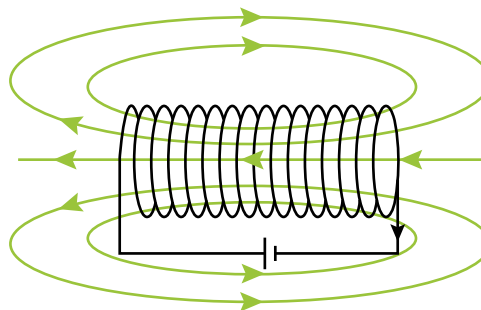
Sample problem 9

- Into the page
- Out of the page

Practice problem 9

- Out of the page
- Vertically upwards

Sample problem 10



Practice problem 10

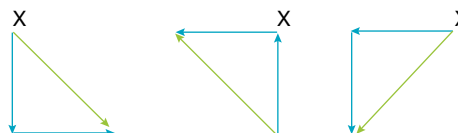
The field lines would be the same as in the sample problem, just with the directions reversed.

Sample problem 11

- North-East
- $35 \mu\text{T}$

Practice problem 11

- 0.014 T
- The direction of the resultant field depends on the orientation of the two magnets and will be at 45° to the initial magnetic fields (as shown by the green arrows in the following diagrams).

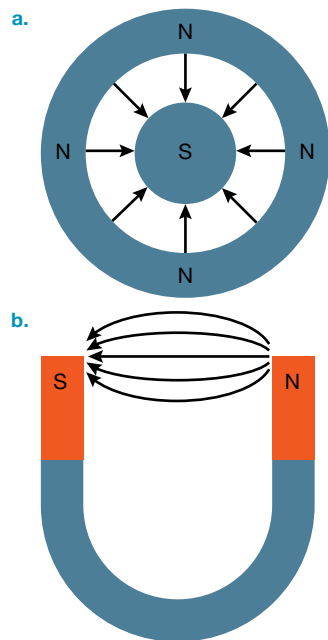


1.4 Exercise

1. If a permanent magnet attracts a piece of metal, that metal must be a magnetic material.
2. As pieces of ferromagnetic material cool, the magnetic domains within the material are aligned by the Earth's magnetic field, thus forming natural permanent magnets.
3. A permanent magnet has two poles, both of which are able to induce ferromagnetic materials, such as iron nails, to behave like magnets.

4. North

5. a.



6. a. out of the page
b. out of the page
c. to the right
7. a. up the page
b. to the left
c. diagonally down to the right
d. into the page
e. out of the page
8. a. At W, the magnetic field is coming out of the page. At X, Y and Z, the magnetic field is going into the page.
b. At W and X, the magnetic field is going from left to right. At Y and Z, the magnetic field is going to the left.
9. Since the iron rods are inside the solenoid, they are induced to become temporary magnets (when the solenoid has a current running through it), both with equivalent orientations of their magnetic poles. Thus, they repel each other because like poles repel.
10. a. The compass needle direction remains the same.
b. The compass needle points in the opposite direction.

1.5 Comparing gravitational, magnetic and electric fields

Sample problem 12

Similarities:

1. The gravitational field generated from a point mass and the electric field generated from a positive charge both obey an inverse square law.

2. The gravitational field and electric field are both non-uniform and static.
3. The point mass and positive charge can both be described as monopoles.

Differences:

1. The direction of the gravitational field is inwards towards the point mass, whereas the electric field generated from a positive charge is outwards, away from the point charge.
2. The gravitational field is attractive for all other masses, whereas the electric field generated from a positive charge repels other positive charges and attracts negative charges.

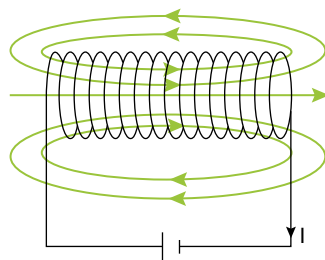
Practice problem 12

The electric field from an electric dipole and the magnetic field from a bar magnet or solenoid have very similar overall shapes. The key differences are as follows:

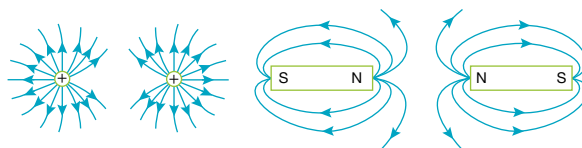
1. For a bar magnet, there are no field lines inside the magnet between the poles.
2. All the magnetic field lines must form closed loops so that all field lines must eventually loop back to pass through the solenoid from the other side.
3. In the electric dipole, the direction of the field lines change sign as they pass through the poles. This is not the case for magnetic field lines, and it is not possible to isolate points in space as 'the north pole' or 'the south pole'.

1.5 Exercise

1. Repulsion and attraction were both observed.
2. Similarities: the inverse square law exists, proportional to the product of a property of the objects (a consequence of Newton's third law).
Difference: mass cannot be positive or negative, whereas charge can.
3. A uniform magnetic field is found inside a solenoid whereas the field outside the solenoid is non-uniform, as illustrated below.



4. The overall field shapes are similar; however, the magnetic field lines all form closed loops, and, unlike the positive charges, the north poles cannot be isolated to single points.



5. $F_g = 3.61 \times 10^{-47} \text{ N}$
 $F_e = 8.1 \times 10^{-8} \text{ N}$

The electric force is thirty-nine orders of magnitude greater than the gravitational force.

6. $1.0 \times 10^{-7} \text{ N C}^{-1}$

7. The unit for gravitational fields is newtons per kilogram. Newtons per kilogram is simply $\text{kg m s}^{-2} \text{ kg}^{-1} = \text{m s}^{-2}$, which is the unit for acceleration. In electric fields, the unit is newtons per coulomb of charge, $\text{kg m s}^{-2} \text{ C}^{-1}$. This cannot be cancelled out as it relies on an object's charge. Therefore, the unit for electric fields is fundamentally different to the unit for acceleration.
8. $6.1 \times 10^{10} \text{ N m}^{-1}$
9. $5.7 \times 10^{13} \text{ C}$
You don't need to know the separation because it cancels, as both forces follow inverse square laws.
10. 5.0 A

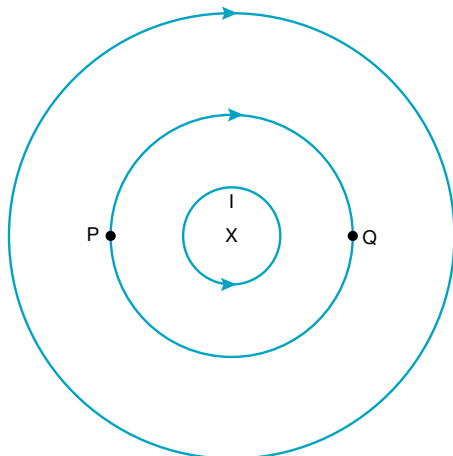
1.6 Review

1.6 Exercise 1: Multiple choice questions

1. D
2. A
3. D
4. C
5. A and C
6. A
7. A
8. A
9. A and B
10. C

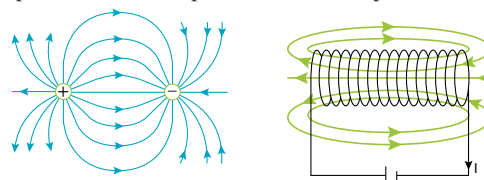
1.6 Exercise 2: Short answer questions

1. $g_{\text{Mercury}} = 3.699 \text{ N kg}^{-1}$
 $\frac{g_{\text{Mercury}}}{g_{\text{Earth}}} = 0.38$
2. $1.4 \times 10^{-3} \text{ N C}^{-1}$
3. 7.9 N
4. Separation would need to increase by a factor of 2.8.
5. The strength of the magnetic field is $2.0 \times 10^6 \text{ N C}^{-1}$ and the direction of the field is up.
6. a.

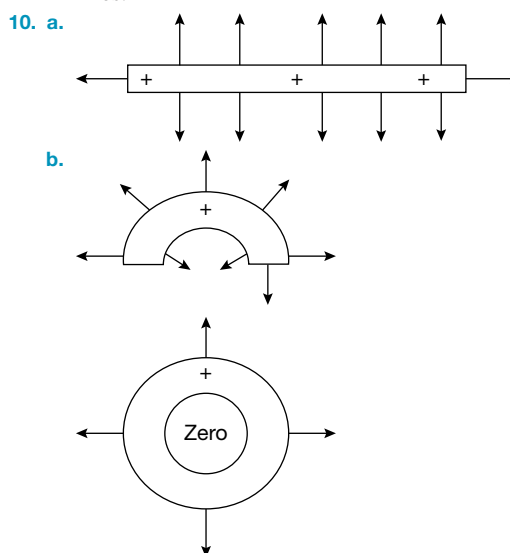


- b. At P the total magnetic field strength is $30 \mu\text{T}$ pointing up the page. At Q the total magnetic field strength is $10 \mu\text{T}$ pointing down the page.
7. The field from an electric dipole and the magnetic field from a solenoid have a very similar overall shape. The key differences are (i) all the magnetic field lines must form closed loops so that all field lines must eventually loop back to pass through the solenoid from the other side. (ii) In the

electric dipole, the direction of the field lines change sign as they pass through the poles. This is not the case for magnetic field lines, and it is not possible to isolate a point in space as 'the north pole' or 'the south pole'.

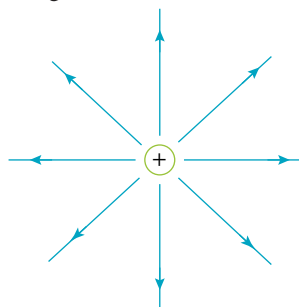


8. $9.8 \times 10^5 \text{ N C}^{-1}$
9. a. The direction of an electric field at any point can only point in one direction.
b. If the particle is stationary or already moving along the field line, it will move along the field line, but if the particle is crossing the field line, the direction of its initial velocity will change and it will not follow the field lines.



1.6 Exercise 3: Exam practice questions

1. 2.4 N kg^{-1}
2. a.



- b. $3.4 \times 10^{-3} \text{ N}$
- c. Yes. Consider the following diagram:

$$+15 \quad -10$$

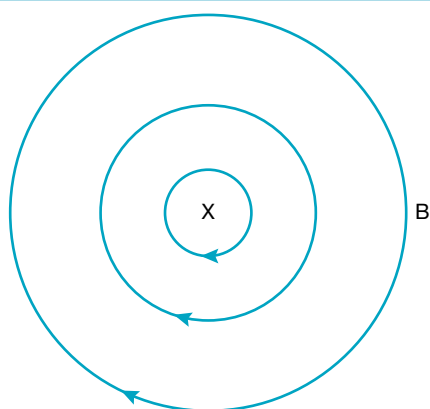
Directly to the right of the -10 nC charge, the field lines will point to the left, back towards the charge. At some point to the far right of the -10 nC charge, the field lines will be pointing to the right, as the total charge in the dipole is positive. Therefore, somewhere in between these two points, there must be a point at which the electric field due to the 2 charges is zero.

3. a. S_2 is 1.5 times further away than S_1 , so the gravitational field decreases by $(1.5)^2 = 2.25$.
b. $4.2 R_E = 2.7 \times 10^7 \text{ m}$

4.

Data Set	Gravitational	Electric	Magnetic
Field A	Surface of Earth	Between +ve and -ve charged conducting plate	Inside large solenoid
Field B	Earth	-ve point charge	Not possible
Field C	Not possible	-ve and +ve charge, electric dipole	Not possible (similar to electric dipole, but not identical)

5. a.



- b. Total magnitude of the field at P of 0.10 T. The direction of the magnetic field is diagonally up and to the left, towards the top left wire.

2 Gravitational fields (effects and applications)

2.2 Motion in a gravitational field

Sample problem 1

20 m.

Practice problem 1

20 m s^{-1}

Sample problem 2

a. 1020 m s^{-1} b. 0.00272 m s^{-2} c. $6.02 \times 10^{24} \text{ kg}$

Practice problem 2

a. $2.14 \times 10^3 \text{ m s}^{-1}$ b. 0.486 m s^{-2} c. $6.41 \times 10^{23} \text{ kg}$

Sample problem 3

Mercury: 3.36×10^{18}
Venus: 3.35×10^{18}
Mars: 3.36×10^{18}

The values of $\frac{r^3}{T^2}$ for the three planets are approximately the same, confirming Kepler's Third Law.

Practice problem 3

Saturn: 3.38×10^{18}
Uranus: 3.37×10^{18}
Neptune: 3.36×10^{18}

Sample problem 4

$6.73 \times 10^5 \text{ m}$

Practice problem 4

$2.67 \times 10^7 \text{ m}$

Sample problem 5

$3.59 \times 10^7 \text{ m}$

Practice problem 5

$1.70 \times 10^7 \text{ m}$

Sample problem 6

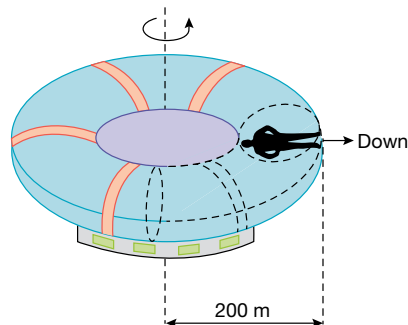
0 N

Practice problem 6

The scales continue to read zero.

2.2 Exercise

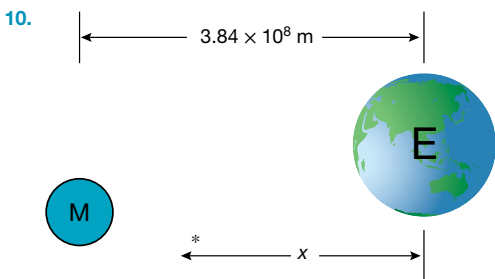
- a. 9.8 N kg^{-1} b. 14.7 N
- a. 97 N downwards b. 97 N
c. $6.41 \times 10^6 \text{ m}$
- $1.02 \times 10^3 \text{ m s}^{-1}$
- a. $7.65 \times 10^3 \text{ m s}^{-1}$
b. 8.72 m s^{-2}
c. 8.80 N kg^{-1}
d. (i) The two answers should be the same.
(ii) Discrepancies between the numbers are due to the rounding off of data.
e. $1.06 \times 10^7 \text{ N}$
f. 0 N
- One possible answer:



Period of rotation 28 s

- $6.26 \times 10^{16} \text{ kg}$
- 13
- $0.35 = \frac{1}{2.83}$

9. $4.2 \times 10^7 \text{ m}$



$x = 3.45 \times 10^8 \text{ m}$

2.3 Energy changes in gravitational fields

Sample problem 7

$4.22 \times 10^8 \text{ J}$

Practice problem 7

a. $1.17 \times 10^{14} \text{ J}$

b. $3.47 \times 10^{14} \text{ J}$

The ratio of the two results $\left(\frac{b}{a}\right)$ is 2.96.

Sample problem 8

$2.55 \times 10^8 \text{ J}$

Practice problem 8

$2.04 \times 10^8 \text{ J}$

Sample problem 9

a. 44 100 J

b. $44\,100 \text{ J} = 4.4 \times 10^4 \text{ J}$

Practice problem 9

19.6 J

2.3 Exercise

1. $6.43 \times 10^9 \text{ J}$

2. $6.0 \times 10^{10} \text{ J}$

3. The unit of the area under a force–distance graph is $\text{N m} = \text{J}$, which is a unit of energy. The area under a gravitational field strength vs. distance graph has the unit $\text{N kg}^{-1} \text{ m} = \text{J kg}^{-1}$, which is a unit of energy per mass.

4. As the space probe gets closer to Planet Q, the gravitational potential energy of the probe decreases, increasing its kinetic energy. As the space probe moves further away from Planet Q, towards Y, kinetic energy is converted into gravitational potential energy. The total energy of the space probe (Planet Q system) is constant.

5. $4.0 \times 10^7 \text{ J}$

6. a. $1.4 \times 10^9 \text{ J}$

b. $5.8 \times 10^3 \text{ s}$

c. As $\frac{r^3}{T^2}$ is constant for any satellite around Earth, the period of the 8000 kg satellite could be found using the known radius of the space shuttle and the satellite's orbits and the known period of the space shuttle's orbit.

d. If the new satellite's mass was halved, the work needed to deploy it from the shuttle would halve as $W = Fs$ and the force is proportional to the mass. The period of the new satellite would remain unchanged.

7. a. $1.4 \times 10^4 \text{ N}$ b. $1.7 \times 10^{10} \text{ J}$ c. $7.9 \times 10^3 \text{ m s}^{-1}$

8. 2.5 J

9. 103 m s^{-1}

2.4 Review

2.4 Exercise 1: Multiple choice questions

1. D

2. D

3. C

4. B

5. C

6. D

7. B

8. B

9. A

10. D

2.4 Exercise 2: Short answer questions

1. a. $1.733 \times 10^4 \text{ m s}^{-1}$

b. 0.7126 m s^{-2}

c. 7.154 days

d. $1.90 \times 10^{27} \text{ kg}$

2. 0.0337 m s^{-2}

In Victoria, the radius of the circular path would be smaller. If r decreases, acceleration also decreases. Therefore, in Victoria, you would experience less centripetal acceleration due to the Earth's motion than people on the equator.

3. $2.98 \times 10^3 \text{ m}$

4. $5.9 \times 10^{23} \text{ kg}$

5. The period would be increased by a factor of $2\sqrt{2}$.

6. According to Newton's first law, an object will move in a straight line, with constant speed, unless an unbalanced force is acting on it. As gravity acts at right angles to the satellite's velocity, it does not change the speed of the satellite; rather, it changes its direction. This causes the satellite to move around the Earth. Because the force of gravity and the speed of the satellite remain constant, so

must its radius as $r = \frac{mv^2}{F}$; therefore, it cannot move closer to the Earth.

7. a. 8.81 N kg^{-1}

b. 0 N

c. 617 N

8. There is no normal force by the chair acting on the astronaut.

9. $1.95 \times 10^8 \text{ J}$

10. a. $2.2 \times 10^4 \text{ J}$

b. $2.1 \times 10^4 \text{ J}$

11. 405 J

2.4 Exercise 3: Exam practice questions

1. a. 447 N

b. $1.59r_{S1} = r_{S2}$

2. a. 8.97 N kg^{-1}

b. $1.21 \times 10^5 \text{ s}$

3. 6.0×10^4

4. $7.2 \times 10^5 \text{ J}$

5. a. $3.56 \times 10^4 \text{ m s}^{-1}$

b. $1.90 \times 10^{27} \text{ kg}$

c. The net force experienced by the astronaut is mg , which is causing the astronaut to orbit Jupiter.

As the net force is equal to the force due to gravity, there is no normal force by the chair on the astronaut.

3 Electric and magnetic fields (effects and applications)

3.2 Motion of a charged particle in a uniform electric field

Sample problem 1

2000 V m^{-1}

Practice problem 1

$20\,000 \text{ V m}^{-1}$

Sample problem 2

a. $1.6 \times 10^{-17} \text{ J}$ b. $5.9 \times 10^6 \text{ m s}^{-1}$

Practice problem 2

a. $1.6 \times 10^{-16} \text{ J}$ b. $1.9 \times 10^7 \text{ m s}^{-1}$

3.2 Exercise

- 6.7 m
- a. $4.0 \times 10^{-3} \text{ N}$ b. $5.3 \times 10^{-3} \text{ N}$ c. 180 V
- $6.0 \times 10^{-10} \text{ N m}$
- $3.0 \times 10^{-8} \text{ J}$
- $1.5 \times 10^4 \text{ V}$
- a. i. $1.6 \times 10^{-16} \text{ J}$ ii. $8.0 \times 10^{-17} \text{ J}$ iii. 0 V
b. i. 500 eV ii. 1000 eV
- $9.0 \times 10^4 \text{ V m}^{-1}$
- a. The 100 V battery
b. $1.6 \times 10^{-17} \text{ J}$
c. Unchanged
d. No difference
e. The electron would not leave the left plate.
f. Doubled
g. The stronger force acts over a shorter distance, achieving the same gain in kinetic energy.
- a. $5.0 \times 10^9 \text{ m s}^{-2}$
b. 0.028 N C^{-1}
The electric field is pointing vertically downwards.
c. $1.4 \times 10^{-4} \text{ V}$
d. Upper plate

3.3 Motion of a charged particle in a magnetic field

Sample problem 3

a. $1.4 \times 10^{-15} \text{ N}$ b. Up the page

Practice problem 3

- $1.9 \times 10^{-13} \text{ N}$
- Into the page.
- The positron is moving parallel to $\mathbf{B}$, so there is no force on the positron.

Sample problem 4

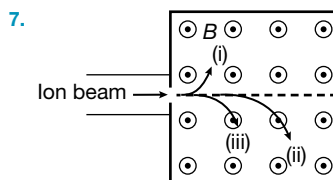
$5.6 \times 10^{-3} \text{ m}$

Practice problem 4

$5.3 \times 10^5 \text{ m s}^{-1}$

3.3 Exercise

- $1.9 \times 10^{-16} \text{ N}$
- a. 0 N
b. The particle would pass through the magnetic field undeflected.
- a. $4.6 \times 10^{-14} \text{ N}$, perpendicular to the direction of travel.
b. Deflected in the perpendicular direction. As long as the electron remains in the magnetic field, it would experience a force in the perpendicular direction and would undergo uniform circular motion.
c. $5.1 \times 10^{16} \text{ m s}^{-2}$
- a. The force on a positive particle is upwards, which means that the charge on the tauon must be negative, reversing the direction of the force.
b. Continues with the same velocity, in a straight line downwards.
- a. Down the page
b. Out of the page
c. Down the page and right
- By being injected parallel to the direction of the magnetic field.



- a. 0.043 mm b. 78 mm c. 157 mm
- Magnetic fields control the movement of particles by separating ions based on their charge and their mass. As different ions (or isotopes) have different mass to charge ratios, they have different path radii as they move. This allows a mass spectrometer to separate ions in a sample with the aid of a magnetic field.
- The overall trajectory of the positron will be an anti-clockwise helix, with the circular motion perpendicular to the page.

3.4 Forces on current-carrying wires in a magnetic field

Sample problem 5

a. $6.0 \times 10^{-3} \text{ N}$ b. 0 N

Practice problem 5

a. 1.25 N b. 2.3 T

Sample problem 6

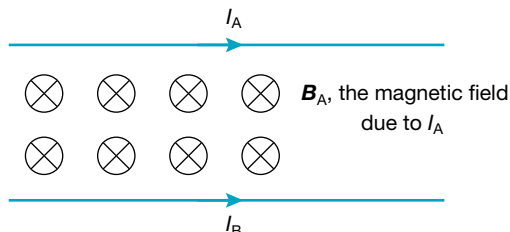
- i. $1.5 \times 10^4 \text{ N}$, down ii. 0 N
iii. $1.5 \times 10^4 \text{ N}$, up
- Torque is a maximum when the axis of rotation and the line of action of the force are perpendicular to each other, and the distance between them is at a maximum. This occurs when the coil is parallel to the field.
- The loop would just oscillate around the vertical position. The commutator enables the direction of current through the loop to be reversed every time the loop passes through the vertical position.

Practice problem 6

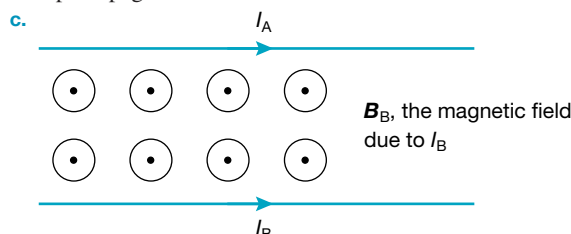
- a. i. 1.5×10^4 N, up ii. 0 N
 iii. 1.5×10^4 N, down
- b. The only difference is that the coil rotates in the opposite direction from the coil in the sample question.

3.4 Exercise

1. 0.07 N
2. 0 N
3. 1.4 N
4. a. Into page b. Into page c. South
 d. Out of page e. North f. East
 g. South-east h. South
5. a.



- b. Up the page



$F_{\text{on B by A}}$ would be down the page according to the right-hand-slap rule

- d. Yes, because according to Newton's Third Law of Motion, $F_{\text{on B by A}}$ is equal in magnitude but opposite in direction to $F_{\text{on A by B}}$.
6. a. Provides a magnetic field.
 b. Enable current to flow from stationary conductors.
 c. Enables the circuit to switch the direction of the current within the course of one rotation.
 d. The more turns there are, the larger the force and the faster the rotation.
7. a. If the coil is perpendicular to the magnetic field, the forces on the sides of the coil are co-linear, resulting in no turning force (or torque) on the coil and hence it would not rotate. This can be overcome by having a second coil at right angles to the first coil, each coil having its own section of the split ring commutator.
 b. Yes. This can be achieved either by connecting the motor to an AC power supply or by replacing the split ring commutator with a slip ring commutator.
 c. Yes. This can be achieved by either increasing the voltage of the DC power supply and thereby increasing the current and turning force on the coil.
8. No. The motor would just run backwards and forwards.
9. The two sides of the loop form a parallel circuit supplied by the battery. The current flowing through the loop interacts with the field of the button magnet to create a torque on the loop. As the loop rotates, the direction of the torque is the same, so the loop rotates continuously.

10. a. The field coils (electromagnet) and the armature coils (rotating) may be connected in series to each other or in parallel to each other.
 b. The series-wound motor produces a large starting torque (turning force), making it ideal as motors for trains and trams. The parallel-wound motor can regulate its speed over a range of loads, making it ideal for power tools.

3.5 Combining electric and magnetic fields

Sample problem 7

$1.67 \times 10^5 \text{ m s}^{-1}$ through the Wien filter

Practice problem 7

$1 \times 10^5 \text{ N C}^{-1}$

3.5 Exercise

1. $3.3 \times 10^4 \text{ m s}^{-1}$
2. 0.63 mT
3. Deflected upwards
4. $1.3 \times 10^6 \text{ m s}^{-1}$
5. The electric force on the particles needs to be out of the page, (the positive plate is behind the negative plate). If the charged particles are negative, the magnetic force on the particles will be out of the page and the electric force on the particles will be into the page, so they will still be balanced for particles with $v = \frac{E}{B}$.
6. a. $5.93 \times 10^6 \text{ m s}^{-1}$ b. $3.56 \times 10^4 \text{ V m}^{-1}$
 c. $1.78 \times 10^3 \text{ V}$
7. The positron will spiral outwards in a clockwise fashion, with the circles perpendicular to the page. As the velocity increases, the radius of curvature of the spiral will increase.

3.6 Review

3.6 Exercise 1: Multiple choice questions

1. B
2. D
3. A
4. D
5. A
6. C
7. C
8. D
9. D
10. C

3.6 Exercise 2: Short answer questions

1. a. $6.7 \times 10^4 \text{ V m}^{-1}$ from the left plate towards the right plate
 b. $5.1 \times 10^{-18} \text{ s}$
 c. $3.2 \times 10^{-16} \text{ J}$
 d. $3.2 \times 10^{-16} \text{ J}$
 e. $1.6 \times 10^{-16} \text{ J}$
 f. The negative plate will become the positive plate and the electron will not leave it.
2. The energy of the emitted particles will not change.
3. a. $2.0 \times 10^{-13} \text{ N}$ b. $2.2 \times 10^{17} \text{ m s}^{-2}$
 c. $1.2 \times 10^{14} \text{ m s}^{-2}$

4. Out of the page.
5. 6.3 mT perpendicular to the momentum of the electrons
6. 0.18 N
7. a. Deflected to the right.
b. Deflected towards the wire, using the right-hand-slap rule.
8. Out of the page.
9. In a DC motor, as current flows through a coil inside a magnetic field, one side that is perpendicular to the magnetic field experiences an upward force, while the opposite side experiences a downward force of equal magnitude, due to the current flowing in opposite directions. The combination of forces on the coil causes it to rotate. The direction of the current needs to be reversed so that the coil continues rotating in the same direction, and this is achieved by a split ring commutator, which changes the direction of current flow twice every rotation.
10. Yes.

3.6 Exercise 3: Exam practice questions

1. a. Upwards arrow
b. 10 V
c. 1.2×10^{-18} J
2. a. 3.3×10^5 m s⁻¹
b. 5.3×10^{-14} N
c. 0.025 m
3. a. At P, the magnetic field from Q is out of the page, which is indicated by a dot.
b. At Q, the force on the right-hand wire is to the right.
c. Forces are in opposite directions, so the wires repel each other.
4. a. 0.68 N
b. Vertically upwards.
c. Current initially flows in the opposite direction through the loop, so the direction of rotation of the loop is reversed.
d. The split in the ring of the commutator needs to be perpendicular to the direction of the magnetic field. If the change in current direction does not occur, then as the loop moves past the vertical, the direction of the torque on the loop changes so that the loop is slowed, and it starts to rotate in the opposite direction. This will be the case if the commutator is attached with the split in the ring significantly altered from being perpendicular to the vertical.
5. a. 6.4×10^{-16} N
b. 8.0×10^{-4} T
c. Since the velocity is higher, the electric and magnetic forces on the proton will not be balanced, so the proton will be deflected.

4 Generation of electricity

4.2 Generating voltage and current with a magnetic field

Sample problem 1

5.0 mV

Practice problem 1

80 m s⁻¹

4.2 Exercise

1. 14 mV
2. 0.823 m s^{-1}
3. 0.83 m
4. 0 V
5. 0.92 V
6. The energy came from the loss of gravitational potential energy as the metal rod was falling.
7. If the rod falls faster, the force due to the magnetic field increases, thereby allowing more electrons to overcome the electrostatic repulsion and gather at the left, thus creating a higher voltage difference with the right end.
8. Since the upward retarding force of the magnetic fields is proportional to the velocity of the falling magnet, there exists a terminal velocity where the downward force on the magnet is equal to the upward retarding force.

4.3 Magnetic flux

Sample problem 2

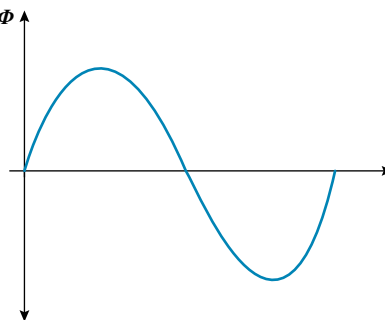
- a. 0.015 Wb b. 0.004 Wb c. 0 Wb

Practice problem 2

0.000 54 Wb

4.3 Exercise

1. Magnetic flux is the amount of magnetic field across an area, and is the product of the magnetic field strength and the perpendicular cross-sectional area.
2. a. 0.15 Wb
b. 1.8×10^{-4} Wb
c. 7.1×10^{-3} Wb
3. a. 0 Wb
b. 0.000 075 Wb
c. Φ



4.4 Generating emf from a changing magnetic flux

Sample problem 3

- a. 0.025 V
- b. The induced current must flow in an anticlockwise direction around the loop.
- c. 0.05 A

Practice problem 3

- a. 0.0184 V
- b. The current must be travelling in the anticlockwise direction.
- c. 0.46 A

4.4 Exercise

- Increasing the number of turns increases the magnetic flux through the coils by increasing the cross-sectional area.
- Clockwise
- The initial flux through the top coil is zero. A clockwise current in the bottom coil would produce a final flux into the page as seen from above. Hence, the direction of the change in flux is into the page. The flux from the induced current would be out of the page and would be anticlockwise around the top loop.
 - No, the effect would not be different, because the flux directions in part a are also applicable if the coils are swapped.
 - Yes, the effect would be different: the opposite direction, clockwise, would result.
- An anticlockwise current is produced.
 - Yes, the effect is different: a clockwise current is produced.
- Yes
 - Yes
 - No
 - No
- 0.0157 V
 - 17 V
 - 38 V
- 0.004 88 A
 - 0.5408 A
 - 0.2 A

8. a. $\varepsilon = -N \frac{\Delta \Phi_B}{\Delta t}$

$$\Rightarrow \Delta \Phi_B = \frac{-\varepsilon \Delta t}{N}$$

The unit for voltage is volts and the unit for change in time is seconds. The number of coils has no units.

So, the unit for change in flux is volt seconds.

Flux has the same unit as the change in flux.

$$\Phi_B = BA$$

$$\Rightarrow B = \frac{\Phi_B}{A}$$

So, the unit for magnetic field strength (tesla) is volt seconds per metre squared, volt $\times$ second $\times$ metre⁻².

- b. Combining $B = \frac{\varepsilon \Delta t}{A}$, $V = IR$ (Ohm's Law), and

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

$$B = \frac{QR}{A} \Rightarrow \text{tesla} = \frac{\text{ohm} \times \text{coulomb}}{\text{metre}^2}$$

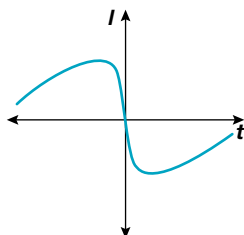
- c. Combining $B = \frac{QR}{A}$ and $\Phi = BA$:

$$\Phi = QR \Rightarrow \text{weber} = \text{ohm} \times \text{coulomb}$$

9. a. 6000 m b. $3 \times 10^7 \text{ m}^2$ c. 3000 V

10. a. i. Anticlockwise
ii. There is no current
iii. Clockwise

b.



- The electrical energy comes from the loss of gravitational potential energy as the magnet drops.
- The overall change in magnetic flux through the loop is zero; therefore, the two areas under the graph — one above the x-axis and the other below the x-axis — would cancel each other out.

11. 0.024 C

12. The passing magnet would induce an emf in both loops; that is, the electrons inside the metal loop as well as the plastic loop would experience a magnetic force from the passing magnet. However, since plastic is an insulator, no current would flow in the plastic loop, in contrast to the metal loop.

13. As the north end of the magnet approaches the loop of conducting wire, it would induce a current in the loop. If Lenz's Law is reversed, the induced current would have a magnetic field that attracts the north end of the magnet. The magnet would accelerate and gain kinetic energy from nothing, hence violating the principle of the conservation of energy.

14. 0.002 V

4.5 Generators and alternators

Sample problem 4

18 V

Practice problem 4

$$I_{\text{RMS}} \approx 7.826$$

$$I_{\text{peak}} \approx 11.07$$

4.5 Exercise

- 2000 V
 - Zero
- A motor can operate as a DC generator by having a load connected to its terminals and then having its shaft rotated. The rotating coils of the motor experience changing magnetic flux from the permanent magnets, thus generating an emf.
- As the speed of the motor increases, the rotating coil cuts the magnetic field faster, therefore increasing the back emf.
 - At low speeds, the back emf is small, so the current in the rotating coil is higher than when the motor rotates at higher speeds.
 - The high currents at low speeds due to the lower back emf, combined with the low resistance of the conducting coils, increase the risk of burning out the motor.
- 8.9 V
- 30 ms
 - 33.3 Hz
 - 50 mV
 - 100 mV
 - 35 mV
- 6.4 V

4.6 Review

4.6 Exercise 1: Multiple choice questions

- D
- C
- C
- B
- A
- C
- C

8. C
9. A
10. C

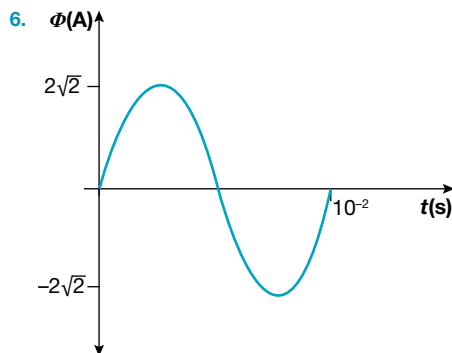
4.6 Exercise 2: Short answer questions

1. The current that is induced by the change in flux as the magnet approaches the tube will create a field to oppose this change. Therefore, the tube will have a south pole at the end near A and a north pole at the end near B.
 - a. At Point A there will be a repulsive force.
 - b. At Point B there will be an attractive force.

2. 10.24 V
3. 2×10^{-6} Wb

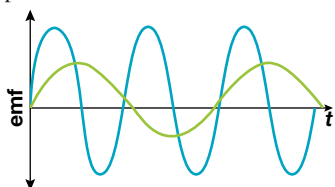
4. $\frac{20B}{3t}$ V

5. 1.5×10^{-3} V

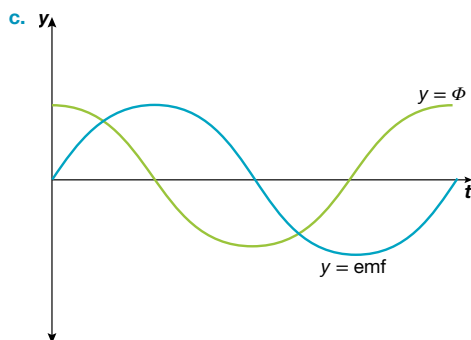


4.6 Exercise 3: Exam practice questions

1. a. 3.6×10^{-2} Wb
 b. 0.12 V
 c. The period should be reduced to half the original and the amplitude should be extended to twice the original:



2. a. 5.625×10^{-6} Wb
 b. Ninety degrees about the horizontal axis will render the coil parallel to the magnetic field and thus there will be zero flux threading the coil.
 c. 1.125×10^{-5} V
3. a. 5.71×10^{-3} m²
 b. 0.16 V

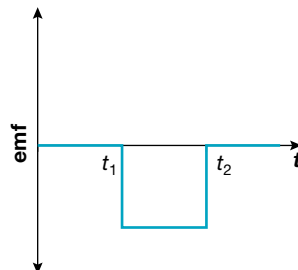


- d.
 - increase the rate of rotation.
 - increase the number of coils that create the loop.
 - increase the magnetic field strength.
 - increase the size of the coil.

4. a. 0.25 Wb

b. 1.6 V

c.



5. a. The induced voltage can be thought of as the negative rate of change of flux. Given the flux is being reduced by a constant amount until it reaches zero, it is expected that the voltage will be constant and positive as is seen in the graph in the question.
 b. 3.53×10^{-3} m²

5 Transmission of power

5.2 Transformers

Sample problem 1

- a. 0.435 A
- b. 529 Ω
- c. i. 529 Ω ii. 230 V
- d. i. 2730 Ω ii. 44.6 V
- e. The globe would not light up.

Practice problem 1

- a. 3.48 A
- b. 66.1 Ω
- c. i. 66.1 Ω ii. 230 V
- d. i. 766 Ω ii. 19.8 V
- e. The toaster would not operate properly.

Sample problem 2

10 turns

Practice problem 2

1:20, making this transformer a step-up transformer.

5.2 Exercise

1. 4600 V
2. a. 4.6 V b. 450 V
3. a. 960 turns b. 8 A c. 0.4 A
4. A transformer requires a changing magnetic flux in order to work; thus, a transformer will not work with a DC input voltage, which produces a constant magnetic flux.
5. This allows the magnetic field to change direction quickly as the current changes direction.
6. a. Step-down transformer b. 46 turns
7. a. 135 V b. 41 W c. 0.68 A

5.3 Power distribution and transmission line losses

Sample problem 3

- a. i. 50.0 A ii. 250 V iii. 62.5% iv. 150 V
b. i. 2.50 A ii. 12.5 V iii. 0.156% iv. 400 V

Practice problem 3

- a. i. 200 A ii. 40.0 V iii. 16.0% iv. 210 V
b. i. 20.0 A ii. 4.00 V iii. 0.160% iv. 250 V

5.3 Exercise

- a. 200 A
b. 12 kW
c. 60 V
d. 190 V
e. i. 30 W ii. 3.0 V iii. 250 V
- a. 5.8 Ω
b. 6.0 Ω
c. 222 V
d. i. 2.01 Ω ii. 205 V
e. Within 1% of 230 V for the appliances to work properly.
f. When the workshop is turned off, it does not draw any current on the transmission line, resulting in a lower transmission line current and therefore a lower voltage drop across the transmission line. This increases the voltage at the primary side of the step-down transformer.
- a. 667 A
b. 180 kW
c. 270 V
d. Voltage = 330 kV
Power = 220 MW
- a. 25%
b. The power loss in transmission would decrease from 25% to 0.25%.

5.4 Review

5.4 Exercise 1: Multiple choice questions

- C
- C
- C
- C
- D
- C
- C
- A
- A
- B

5.4 Exercise 2: Short answer questions

- a. 1.5 Ω b. 8.5 V
- a. 400 b. 0.17 A
- 4200 V
- $\frac{N_2}{N_1} = \frac{5}{1}$
- a. 400 turns
b. 1.4 W
c. i. The power at the input to the primary coil is the same as the power at the globe: 6.0 W.
ii. 7.4 W
d. The globe would not glow.

- 0.15 A
- a. 2000 turns b. 50 A
c. 1.0×10^4 W d. 8.2×10^3 V

5.4 Exercise 3: Exam practice questions

- 1.20×10^4 W
- 2400 W
- 480 V
- The step-up transformer will increase the voltage from 600 V to 6000 V
- 240 turns
- 24 W
- 12 V

6 Newton's laws of motion

6.2 Motion review

Sample problem 1

- a. 3.3 m s^{-1} north b. 10 m s^{-2} N37°E
c. 2.8 m s^{-2} south-east

Practice problem 1

- a. 3 m s^{-2} b. 7.1 m s^{-2} south-west
c. 7.1 m s^{-2} east 39° south

Sample problem 2

- a. 10 m south b. 3.0 m s^{-2} south
c. 6.1 m s^{-1} south

Practice problem 2

- a. 3 m s^{-2} south b. 5 m s^{-2} north c. 8.3 m s^{-1} south

Sample problem 3

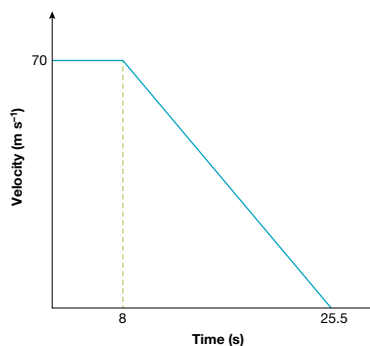
- a. 3.8 m s^{-2} b. 3.2 s c. 4.7 m d. 1.6 s

Practice problem 3

- a. 30 m s^{-1}
b. 0.63 m s^{-2}
c. 25 m s^{-1}
d. i. 21 m s^{-1} ii. 25 m s^{-1}

6.2 Exercise

- 3.5 m s^{-1}
- a. $25 \text{ km h}^{-1} \text{ s}^{-1}$ S 37°E b. 6.9 m s^{-2} S 37°E
- a. 25.5 s
b.



- c. 1172.5 metres
4. 632 kg m s^{-1}

6.3 Newton's laws of motion and their application

Sample problem 4

- a. 3.0 m s^{-2} east
b. i. 2.3 m s^{-2} east ii. 1120 N

Practice problem 4

- a. i. 500 N ii. 100 N
b. i. 1200 N ii. 1300 N iii. 4500 N

Sample problem 5

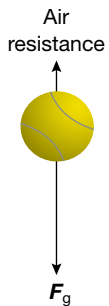
- a. 660 N b. 180 N

Practice problem 5

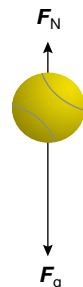
- a. i. 248 N ii. 852 N
b. 1.98 m s^{-2}

6.3 Exercise

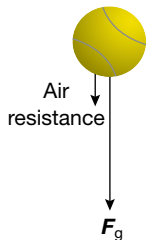
1. a.



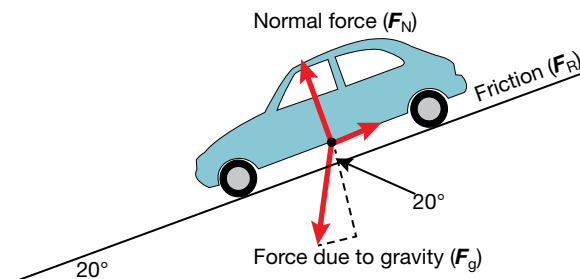
b.



c.



2. a. F b. C c. X
3. a. 39.2 N b. 10 N c. 33.2 N
4. a. -35 m s^{-2} b. -7000 N
5. a.



- b. $13\,800 \text{ N}$
c. 0 N
d. 5000 N
6. a. As the skier is moving at a constant speed there is no net force.
b. 294 N

7. a. 380 N north b. 1680 N north
8. 980 N
9. 8.7°

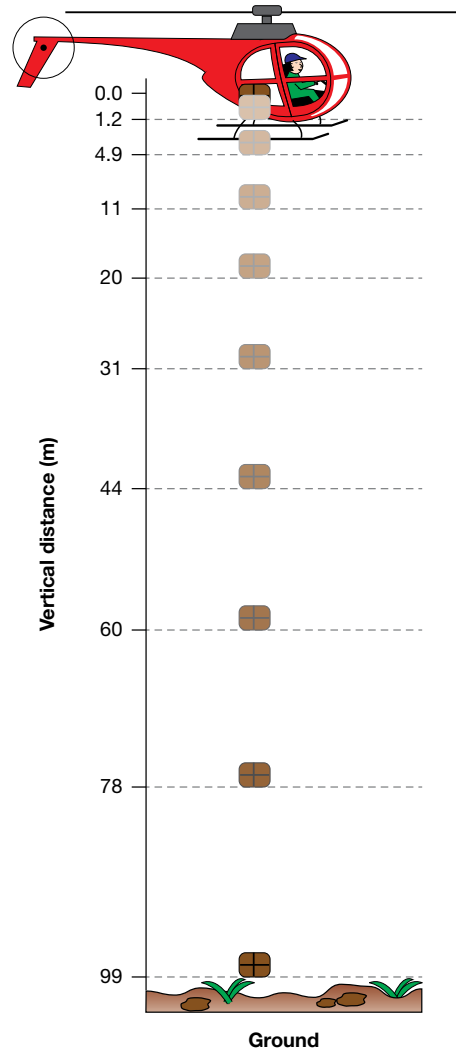
6.4 Projectile motion

Sample problem 6

a. 4.5 s

b.

Time (s)	Vertical distance (m)
0.5	1.2
1.0	4.9
1.5	11
2.0	20
2.5	31
3.0	44
3.5	60
4.0	78
4.5	99



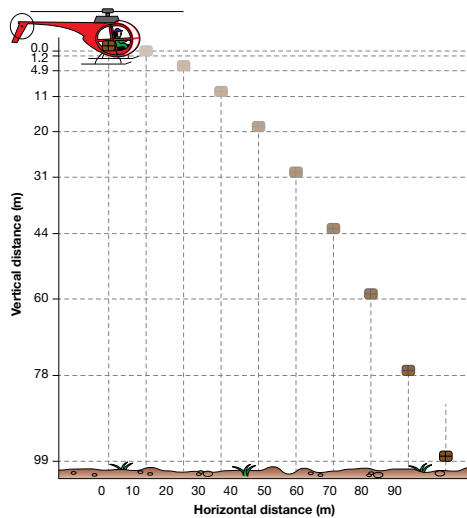
Practice problem 6

- a. 44 m b. 29.4 m s^{-1}

Sample problem 7

- a. 4.5 s
b. 90 m
c.

Time (s)	Vertical distance (m)	Horizontal distance (m)
0.50	1.2	10
1.0	4.9	20
1.5	11	30
2.0	20	40
2.5	31	50
3.0	44	60
3.5	60	70
4.0	78	80
4.5	99	90



Practice problem 7

- a. 76.4 m b. 160 m c. -39.2 m s^{-1} d. 44.4°

Sample problem 8

- a. 0.41 s
b. 0.82 m
c. 9.8 m s^{-2} downwards
d. 4.0 m s^{-1} downwards

Practice problem 8

- a. 3.13 m s^{-1} down b. 0.64 s

Sample problem 9

$s = 48 \text{ m}$

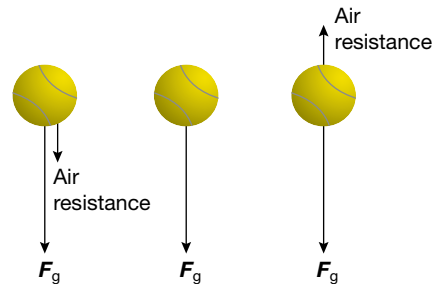
Therefore, the unlucky stunt driver will fall short of the second ramp and will land in the river.

Practice problem 9

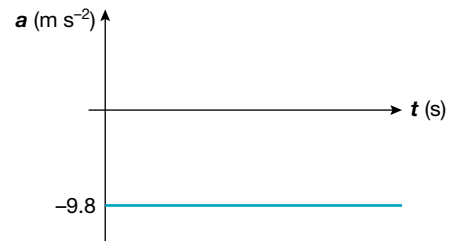
- a. $u_{\text{vertical}} = 13.5 \text{ km h}^{-1}$
 $u_{\text{horizontal}} = 29 \text{ km h}^{-1}$
b. 0.767 s
c. 6.18 m

6.4 Exercise

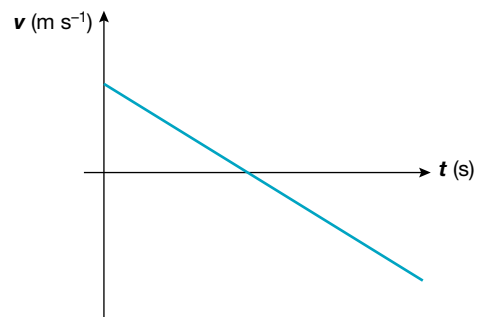
1. Going up At the top Going down



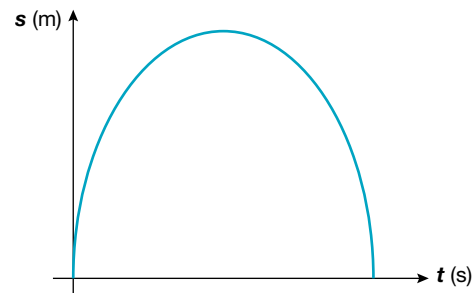
2. The acceleration of a projectile when in motion is due to gravity, which is a constant near the earth's surface (9.8 m s^{-2} downwards). This is displayed by the following acceleration–time graph:



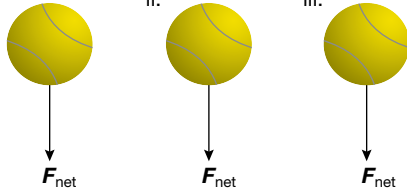
Acceleration is the change in velocity (or the gradient), so the velocity of a projectile is a straight line of gradient -9.8 as shown in the following diagram:



Velocity is the change in position (or the gradient), so the position of a projectile is a negative parabola. This is displayed on the following position–time graph:



3. a. $v_v = 15 \text{ m s}^{-1}$ $v_h = 13 \text{ m s}^{-1}$
 b. $v_v = 10 \text{ m s}^{-1}$ $v_h = 4.3 \text{ m s}^{-1}$
 c. $v_v = 5 \text{ m s}^{-1}$ $v_h = 0 \text{ m s}^{-1}$
 d. $v_v = 0 \text{ km h}^{-1}$ $v_h = 10 \text{ km h}^{-1}$
 e. $v_v = 16.5 \text{ m s}^{-1}$ $v_h = 29 \text{ m s}^{-1}$
4. a. 3.67 s
 b. 16.5 m
 c. i.



5. You should not lie down as the 11th person, as your friend will not make the jump!
6. a. 4.76 m s^{-1}
 b. 18°
 c. 0.12 m
7. a. 0.71 s
 b. Vertical component: 2.45 m
 Horizontal component: 4.92 m
 c. 0.30 s
 d. The ball will just be out of the reach of the goalkeeper and so will go into the net.
8. a. 0.81 s
 b. Vertical component: 3.2 m
 Horizontal component: 9.2 m
 c. 0.90 s
 d. 19.5 m
9. a. 19.6 m
 b. 15.0 m s^{-1} in the direction of 37° below the horizontal.
10. 5.4 m s^{-1}
11. 18.5°

6.5 Uniform circular motion

Sample problem 10

- a. 5 m s^{-1} b. 0 m s^{-1} c. 5 m s^{-1} north

Practice problem 10

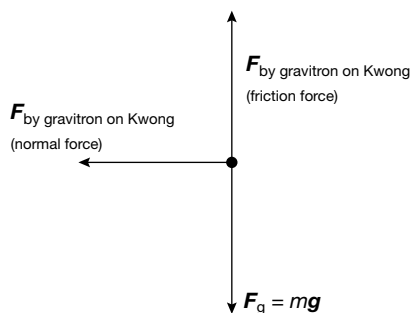
- a. 3.1 m b. 1.3 m s^{-1} c. 0.83 m s^{-1} d. 0 m s^{-1}

Sample problem 11

- a. 9.0 m s^{-2} towards the centre of the roundabout
 b. $1.1 \times 10^4 \text{ N}$ towards the centre of the roundabout

Practice problem 11

- a. 22.1 m s^{-2}
 b. 1326 N
 c.



Sample problem 12

12.4 m s^{-1}

Practice problem 12

1800 N

Sample problem 13

13.3 m s^{-1}

Practice problem 13

15°

Sample problem 14

53°

Practice problem 14

- a. 10.40° b. 498.2 N

6.5 Exercise

- a. 0.024 m s^{-2} towards the centre of the circle
 b. 1.6 N towards the centre of the circle
- a. 0.050 m s^{-2} towards the centre of the circle
 b. 1.75 N towards the centre of the circle
 c. 75 N towards the centre of the circle
 d. To move along the same path, the child and the train require the same *acceleration*. As the masses of the child and the train are different, different forces are needed to produce identical accelerations.
- To go around a bend, a motorcyclist needs a horizontal force acting on the bike towards the centre of the curve of the bend. This is provided by the road acting on the tyres. The force of the road on the tyres needs to act through the centre of mass of the cyclist, otherwise the force will act to tip the bike over. As the horizontal component of this force is acting towards the centre of the curve, the motorcyclist must lean into the curve to avoid falling off.
- a. 11.7 m s^{-1}
 b. 92.0 m s^{-2} towards the centre of the circle
 c. 4.60 N towards the centre of the circle
 d. 4.63 N
- a. 353 N towards the centre of the circle
 b. 353 N
 c. 5.0 m
- 82.6°

6.6 Non-uniform circular motion

Sample problem 15

- a. 8.9 m s^{-1} b. 1200 N c. 1800 N

Practice problem 15

- a. 1127 N
 b. 1715 N
 c. The normal force is $\frac{1715}{588} \approx 2.9$ times the force due to gravity.

Sample problem 16

- 6.6 m s^{-1}
- As the speed, v , increases, the normal force, F_N , gets smaller.
- The normal force is less than the force due to gravity, so the passenger will feel lighter.

Practice problem 16

- 2507 N
- 4.85 m s^{-1}

Sample problem 17

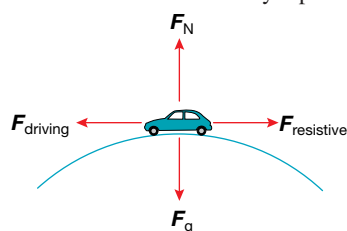
- 6.26 m s^{-1}
- 78.4 N up
- 80.4 N up
- 5.77 m s^{-1}
- 42.7 N down

Practice problem 17

- 5.0 m s^{-1}
- 12.5 N up
- 11.7 N
- 4.64 m s^{-1}
- 9.8 N down

6.6 Exercise

- When the ball is at the very bottom of the circle
 - When the ball is at the very top of the circle
- a.



- 7840 N
 - 6.26 m s^{-1}
- 4.85 m s^{-1}
 - 28.2 N up
 - 27.0 N
- 1568 N
 - 2205 N

6.7 Review

6.7 Exercise 1: Multiple choice questions

- D
- C
- A
- D
- B
- B
- C
- C
- B
- B

6.7 Exercise 2: Short answer questions

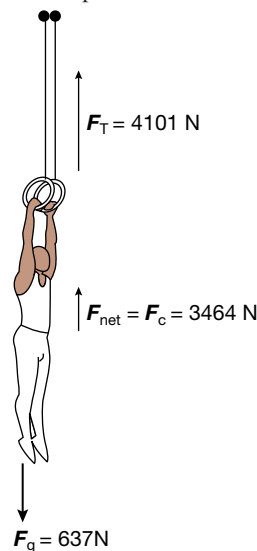
- The stationary car is pushed forward by the other vehicle. As a result, the seat pushes the body of an occupant forward. This happens almost instantaneously. However, without a headrest, there is nothing to push the occupant's head forward quickly. The head remains at rest until pulled forward by the spine (Newton's First Law of Motion). The head applies an equal and opposite force to the spine (Newton's Third Law of Motion), potentially causing serious injuries.
- To say that the passenger is thrown forward implies that a force accelerates the passenger. The car slows down rapidly in most collisions as a result of a large external force. The

passenger continues to move at the original speed of the car while the car slows down.

- The gravitational pull of you on the Earth.
- As no forces are acting in the horizontal direction, there can be no horizontal acceleration. Therefore, the horizontal component of velocity must remain constant.
- The time of a projectile's flight is the time it takes to hit the ground. Therefore, the projectile cannot take longer to complete one part of its motion than the other. Time is the only useful variable that is a scalar and is the same in both the vertical and horizontal directions.
- When a basketball falls from rest, there is initially no air resistance. As it accelerates downwards due to the Earth's gravitational pull, the air resistance increases. The magnitude of the net force, and subsequently its acceleration, decreases. The air resistance continues to increase as the acceleration continues downwards. Because the air resistance is small compared to the basketball's weight, the basketball will not reach its terminal velocity, unless dropped from an aeroplane or helicopter in flight!
- Newton's first law states that an object will continue to move in a straight line with constant speed unless an unbalanced force acts on it. Therefore, the mass will continue to move forwards without a propelling force, once in motion. The centripetal force acts to change the direction of the mass, not its speed.

6.7 Exercise 3: Exam practice questions

- 200 m
 - 14 m s^{-1}
 - 24 000 N
 - 32 000 N
- 0.050 m s^{-2}
 - 1.75 N towards the centre of the circle
 - 75 N towards the centre of the circle
 - To move along the same path, the child and the train require the same *acceleration*. As the masses of the child and the train are different, different forces are needed to produce identical accelerations.
- 5.89 m s^{-1}
 - 30.9 m s^{-2} towards the centre of the circle
 - 3.09 N towards the centre of the circle
 - 3.24 N
- 84.8°
 - 14.6 m s^{-1}
 - 3464 N upwards



7 Force, energy and mass in collisions and other interactions

7.2 Momentum and impulse

Sample problem 1

- $1.8 \times 10^4 \text{ kg m s}^{-1}$ in a direction opposite to the original direction of the car.
- $1.8 \times 10^4 \text{ N s}$ in a direction opposite to the original direction of the car.
- $3.0 \times 10^5 \text{ N}$
- $3.6 \times 10^5 \text{ N}$

Practice problem 1

- a. 2000 N s east b. 2500 N s east c. 2500 N s west

Sample problem 2

12 m s^{-1}

Practice problem 2

4.5 m s^{-1}

Sample problem 3

- $-1.44 \times 10^4 \text{ kg m s}^{-1}$
- 3600 kg m s^{-1}
- 3600 kg m s^{-1}
- 1.33 m s^{-1} in the direction of the initial velocity of the first car
- $16\,000 \text{ kg m s}^{-1}$ in the direction of motion of the tangled wreck
- $-16\,000 \text{ kg m s}^{-1}$ which is in the direction opposite that of the 1200 kg car

Practice problem 3

- 10 m s^{-1}
- $20\,000 \text{ N s}$ north
- $-20\,000 \text{ N s}$ (south)
- 6 m s^{-1}

7.2 Exercise

- Impulse is equal to the change in momentum.
- No. The system of the two cars is not isolated. There are unbalanced frictional forces acting on the cars during and immediately after the collision.
- 2.0 m s^{-1} south
 - The vertically downward momentum of the coal decreases to zero because there is an upward net force acting on it when it strikes the cart. The total momentum of the Earth–coal system has not changed.
 - 2.0 m s^{-1} south
- Student responses will vary. In most situations, an occupant in a larger car is safer. However, the design of the particular car, the nature of the collision and several other factors influence the likely effect of an accident on occupants. Detailed sample responses can be found in your digital formats.
- -10 N s^{-1}
 - 100 N away from the wall
 - 10 m s^{-1} away from the wall

7.3 Work done

Sample problem 4

253 312 J

Practice problem 4

62 576 J

Sample problem 5

12.5 J

Practice problem 5

7.5 J

7.3 Exercise

- 200 N
- 83 J
- 1347.5 J
- 4.0 J
- 350 J

7.4 Kinetic and potential energy

Sample problem 6

- a. $4.32 \times 10^4 \text{ J}$ b. $1.44 \times 10^5 \text{ N}$

Practice problem 6

- a. $8.0 \times 10^4 \text{ J}$ b. 4000 N

Sample problem 7

2.9 J

Practice problem 7

- a. 1.94 J b. 25 cm

Sample problem 8

- 200 N m^{-1}
- The gradient of the graph for spring A is greater than that for spring B. Therefore, spring A has a greater spring constant than spring B – in fact, it is twice the size.
- 2.0 J

Practice problem 8

- a. 100 N m^{-1} b. 4.0 J

Sample problem 9

1.0 m s^{-1}

Practice problem 9

- a. 0.128 J b. 5.1 cm

Sample problem 10

- a. 3100 J b. 13 m s^{-1}

Practice problem 10

- a. 14 700 J b. 22 m s^{-1}

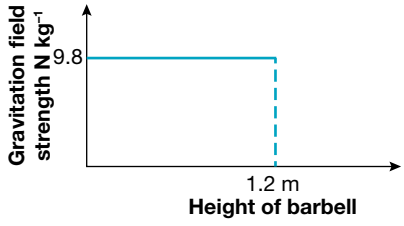
Sample problem 11

- a. 9.5 m s^{-1} .
- b. Total kinetic energy before the collision is given by:
- $$\frac{1}{2} \times 800 \times (20)^2 + \frac{1}{2} \times 700 \times (0)^2 = 160\,000 \text{ J.}$$
- Total kinetic energy after the collision is given by:
- $$\frac{1}{2} \times 800 \times (9.5)^2 + \frac{1}{2} \times 700 \times (12)^2 = 86\,500 \text{ J.}$$
- Kinetic energy is not conserved; therefore, the collision is not elastic.

Practice problem 11

- a. i. -0.25 m s^{-1} ii. -1.0 m s^{-1}
- b. $E_{\text{ki}} = 1400 \text{ J}$
- i. $E_{\text{kf}} = 162.5 \text{ J}$
- ii. $E_{\text{kf}} = 800 \text{ J}$
- As the final E_{k} is less than the initial E_{k} , both collisions are inelastic.

7.4 Exercise

1. a. No
- b. Sound, along with some heating of the ball, provides evidence that some of the ball's initial kinetic energy is transformed.
- c. Yes
2. a. 30 m s^{-1} east b. $\frac{1}{26}$
3. a. -9.8 N (9.8 N up) b. 38 N m^{-1}
- c. A d. 1.25 J
- e. Spring B
4. a.
- 
- b. 1764 J
- c. $1.8 \times 10^3 \text{ J}$
5. a. $4.1 \times 10^3 \text{ J}$ b. $5.5 \times 10^3 \text{ J}$
- c. $3.1 \times 10^5 \text{ J}$
6. a. $1.8 \times 10^5 \text{ J}$
- b. $1.8 \times 10^5 \text{ J}$
- c. $4.5 \times 10^5 \text{ N}$ opposite to the initial direction of motion of the car.
7. The depth of penetration would double.

7.5 Review

7.5 Exercise 1: Multiple choice questions

1. B
2. A
3. C
4. B
5. C
6. A
7. C
8. D
9. D
10. C

7.5 Exercise 2: Short answer questions

1. The fundamental purpose of airbags, collapsible steering wheels and padded dashboards in passenger vehicles is to increase the time interval during which the momentum of the vehicle's occupants changes during a collision.
2. Yes, an object can have energy but no momentum; for example, an object at rest but raised above ground level has gravitational potential energy, but no momentum because $v = 0$. No, an object cannot have momentum but no energy; if an object has momentum, then it must be moving, so: $v \neq 0$. Thus, $E_{\text{k}} = \frac{1}{2}mv^2 \neq 0$.
3. a. Noise, heating and any damage to the car indicate that some of the initial kinetic energy is transformed.
- b. Yes. On an icy road, friction is small enough for the system of the two cars to be considered isolated.
4. 0.8 m s^{-1} east
5. 39.2 J
6. a. $3.4 \times 10^6 \text{ J}$ b. $3.4 \times 10^6 \text{ J}$
7. a. $1.8 \times 10^4 \text{ J}$
- b. $2.8 \times 10^4 \text{ J}$
8. In each of cases (a), (b) and (c), the change in momentum is fixed. An increase in the time interval during which the momentum changes results in a smaller force applied to the occupants or cyclist as $\Delta p = F\Delta t$.

7.5 Exercise 3: Exam practice questions

1. a. 140 kg m s^{-1} east
- b. The centre of mass is 2.5 m east of Dean.
- c. 1.2 m s^{-1} east
- d. 1.2 m s^{-1} east
- e. 60 N s east
2. a. $9.7 \times 10^3 \text{ J}$ b. $1.4 \times 10^4 \text{ N}$
- c. $2 \times 10^6 \text{ N}$
3. a. $4.4 \times 10^5 \text{ J}$ b. 1000 J c. 16 J
- d. 1.7 J e. 0 J
4. a. 7350 J b. 16 m s^{-1} c. 0 J d. 232 N
5. a. $7.7 \times 10^{-3} \text{ m}$ b. 900 J
- c. 2.0 m s^{-1}
6. a. 2.9 m s^{-1} east
- b. $3.4 \times 10^4 \text{ N s}$ west
- c. The car experiences the greatest (in magnitude) change of velocity.
- d. $\Delta p_{\text{car}} = -\Delta p_{\text{truck}}$ since the total change in momentum is zero.
- e. Each vehicle experiences the same force (in magnitude).

8 Special relativity

8.2 Einstein's theory of special relativity

Sample problem 1

In the first scenario, the first car is travelling at 80 km h^{-1} relative to the second car.

In the second scenario, the first car is travelling at $100 - 20 = 80 \text{ km h}^{-1}$ relative to the second car.

In the third scenario, the first car is travelling at $100 - (-20) = 120 \text{ km h}^{-1}$ relative to the second car.

Practice problem 1

B

Sample problem 2

According to the measurements made in A, the rocket accelerated for 10 s at:

$$\begin{aligned}a &= \frac{\Delta v}{t} \\&= \frac{100 \text{ m s}^{-1} - 0 \text{ m s}^{-1}}{10 \text{ s}} \\&= \frac{100 \text{ m s}^{-1}}{10 \text{ s}} \\&= 10 \text{ m s}^{-2}\end{aligned}$$

From B:

$$\begin{aligned}a &= \frac{\Delta v}{t} \\&= \frac{150 \text{ m s}^{-1} - 50 \text{ m s}^{-1}}{10 \text{ s}} \\&= \frac{100 \text{ m s}^{-1}}{10 \text{ s}} \\&= 10 \text{ m s}^{-2}\end{aligned}$$

The acceleration is the same whether it is measured from frame A or frame B. It will still be 10 m s^{-2} regardless of the speed of the reference frame.

Practice problem 2

- The measured speed depends entirely on the relative motion of the person measuring the speed. Therefore, it depends on the observer's frame of reference.
- Newton's three laws of motion do not require the entering of a value of velocity at any point. However, the second law (net force = ma) includes a value for acceleration. If the value for acceleration is different, then the net force would be different. By the principle of relativity, physical laws need to give the same answer in all inertial reference frames.

Sample problem 3

Galileo proposed that all inertial frames of reference are equally valid. Maxwell's concept of electromagnetic waves suggested the presence of an absolute frame of reference — the luminiferous aether. That is, observers moving relative to the aether should experience light at different velocities, and therefore not all inertial frames of reference are equally valid, as stated by Galileo.

Practice problem 3

The light is moving at c relative to the aether, and the spacecraft is moving at $0.5c$ in the other direction; therefore, the light is moving away from the spacecraft at $1.5c$, assuming that light moves at c relative to the aether and that the Galilean understanding of relativity is correct.

Sample problem 4

The principle of relativity is applied to all laws of physics, not just the mechanics of Galileo and Newton.

The speed of light is constant for all observers. Before Einstein, the speed of light was assumed to be relative to its medium, the luminiferous aether.

Practice problem 4

Einstein found that the speed of light was invariant and that time, distance, simultaneity, mass and kinetic energy were all relative, and hence relative.

Sample problem 5

35.4 days

Practice problem 5

Even small increases in the acceleration would make the astronauts feel very heavy. Humans cannot withstand large accelerations for long periods of time. If the acceleration was large enough, they would be squashed flat, but, long before that, they would be rendered unconscious by the lack of blood flow through the brain.

Sample problem 6

The way to understand this situation is to move away from absolute space and time and understand that these are relative to the observer. When this is done, it is seen as possible for planet B to be at the centre of the light circle. However, this requires that A and B disagree about when two events occur. According to planet A, the different sides of the light circle reach the light-year radius at different times, but from planet B this must occur simultaneously.

Practice problem 6

- Invariant
- Relative

8.2 Exercise

- Velocity depends on the reference frame in which it is measured.
- A frame of reference is a set of length and time coordinates that an observer uses to measure an event.
- 100 km h^{-1}
- The acceleration due to the revolution of the Earth around the Sun is about $6 \times 10^{-2} \text{ m s}^{-2}$, which is tiny. According to the principle of relativity, if the Earth is not accelerating, the movement of the Earth cannot be felt no matter what its speed is.
 - Daily rotation about its axis and precession of the equinoxes (the motion of the Earth's axis), which has a period of about 22 000 years.
 - The accelerations are so tiny that they are difficult to detect.
- $2.9989 \times 10^8 \text{ m s}^{-1}$
- Newton's laws are an excellent approximation at speeds lower than light speed. For most of human history, there was no way of observing extremely high speeds, meaning that the limitations of Newton's laws were unidentifiable.
 - Newton's laws are still useful at the lower speeds that are seen in everyday life, providing accurate results at those speeds. They are also much easier to use and learn than Einstein's laws.
- It would seem impossible. An object travelling at a speed of $0.99c$ towards a stationary observer emits light in all directions. The light travels at speed c . According to Newtonian physics, the observer would measure the speed of

the light from the approaching object to be $1.99c$. However, the observer actually measures the speed of light to be c .

8. $3.0 \times 10^8 \text{ m s}^{-1}$.

8.3 Time dilation

Sample problem 7

5.774 minutes

Practice problem 7

4.329 minutes

Sample problem 8

5.774 minutes

Practice problem 8

1.8 minutes, or 1 minute and 48 seconds

Sample problem 9

$$t = 1.000\,000\,000\,000\,0022t_0$$

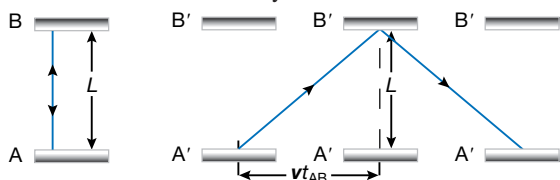
The difference between the rates of time in the two perspectives is so small that it is difficult to calculate, much less notice it.

Practice problem 9

$$2.6 \times 10^8 \text{ m s}^{-1}$$

8.3 Exercise

- Time dilation is the slowing of time for objects in motion relative to the observer. It can be detected with very sensitive instruments when comparing times on board aeroplanes with the time on the ground.
- The clock in motion relative to you
- As can be seen in the two figures, the distance the light travels in the moving clock is further than in the stationary clock. As the speed of light is constant, the time taken for the light to complete one cycle in the moving clock is longer. Therefore it 'ticks' more slowly.



- Proper time is t_0 , which is the time as measured in the reference frame of the event. Conversely, t is the time as measured in a different inertial reference frame.
- a. 1.048 28 b. 95.4 beats per minute

8.4 Length contraction

Sample problem 10

13.4%

Practice problem 10

- Madeline's measured distance will be shorter than Rebecca's.
- Rebecca's measurement is the proper length. The proper length is the length measured from the frame of reference at which objects are at rest.

8.4 Exercise

- Depth.
- No. Length contraction is only apparent while an object is in motion relative to an observer.
- a. Its length would be unchanged from the perspective of the alien on board.
b. The length of the spaceship from the perspective of the Sun would be 60% of its proper length.
c. c
- a. 2.82 s b. 0.7053 m
- 43.59 m

8.5 Seeing relativistic effects

Sample problem 11

- 1.56 microseconds
- 9.29
- 99.4% of the speed of light.
- 14.5 microseconds

Practice problem 11

- 1938 m b. 209 m

8.5 Exercise

- As a result of the muons travelling at very near light speed, their half-lives according to scientists on Earth are much longer than in their rest frame due to time dilation. This means that more of the muons have sufficient time to reach the Earth's surface before decaying.
- 5.97 km
- 7.839 microseconds
- In the early days of special relativity, few experiments were available to test whether the phenomena predicted by the theory matched up with measurements. Muons, however, were detectable, were travelling close to the speed of light and had features of their journey that were measurable, in particular the distance travelled and their half-life. The number of muons reaching the ground agreed with the predictions of special relativity but not classical physics.

8.6 Einstein's relationship between mass and energy

Sample problem 12

As $v \rightarrow c$,

$$\gamma \rightarrow \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}} \rightarrow \infty$$

So as $v \rightarrow c$, γ becomes infinitely large

$$m = m_0 \gamma, \text{ so}$$

$$\text{as } v \rightarrow c, \gamma \rightarrow \infty, m \rightarrow \infty.$$

An object travelling at c would have infinite mass.

$$\gamma = \frac{1}{\sqrt{1 - \frac{v^2}{c^2}}}$$

$$\text{If } v > c, \text{ then } \frac{v^2}{c^2} > 1 \text{ and } 1 - \frac{v^2}{c^2} < 0.$$

Speeds larger than c would produce a negative under the square root sign, so these speeds are not possible.

Practice problem 12

$$3 \times 10^{16} \text{ kg}$$

Sample problem 13

$$1.96 \times 10^{-26} \text{ kg}$$

Practice problem 13

$$3.83 \times 10^{-27} \text{ kg}$$

Sample problem 14

$$1.45 \times 10^9 \text{ m s}^{-1}$$

Practice problem 14

$$6.43 \times 10^8 \text{ m s}^{-1}$$

Since the maximum speed possible is $3.0 \times 10^8 \text{ m s}^{-1}$, the calculated speed is not possible, showing that Newton's laws are not useful when dealing with objects travelling at high speeds.

Sample problem 15

Using special relativity: $1.39 \times 10^{20} \text{ J}$

Using classical physics: $1.13 \times 10^{20} \text{ J}$

The kinetic energy is $\frac{1.39}{1.13} = 1.23$ times the value predicted by classical physics.

Practice problem 15

$$0.999\,999\,985\,4c$$

Sample problem 16

It is clear that the mass of the nucleus is different to the mass of the individual particles, but when the binding energy of the hydrogen-2 nucleus is included, the mass-energy of both is found to be the same. The separate particles have their mass and zero potential energy. The particles bound in the nucleus have a reduced mass and the binding energy of the nucleus.

Practice problem 16

$$5.33 \times 10^{-29} \text{ kg}$$

Sample problem 17

$$4.0 \times 10^{26} \text{ W}$$

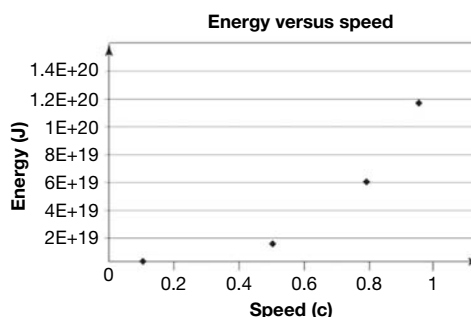
Practice problem 17

$$1.44 \times 10^{13} \text{ years}$$

8.6 Exercise

1. The mass of an object increases with its motion, according to the factor γ . Therefore an object's mass becomes infinite at the speed of light. Also, the length of the object would be zero at the speed of light, and time would cease. Mathematically, speeds beyond the speed of light would require taking the square root of a negative number in the equation for γ .
2. a. $4.5 \times 10^{17} \text{ J}$
c. $6.0 \times 10^{19} \text{ J}$
b. $1.4 \times 10^{19} \text{ J}$
d. $1.2 \times 10^{20} \text{ J}$

3.



4. Energy and mass are equivalent.
5. $5.4 \times 10^{41} \text{ J}$
6. $2.99 \times 10^{16} \text{ kg}$
7. The mass of the Sun is decreasing over time.
8. The electromagnetic radiation produced is in the form of gamma photons emitted when the deuteron fuses with the protons; it is also produced when the positrons emitted during fusion come into contact with electrons, annihilating both particles.

8.7 Review

8.7 Exercise 1: Multiple choice questions

1. A
2. C
3. A
4. A
5. C
6. A
7. D
8. C
9. B
10. D

8.7 Exercise 2: Short answer questions

1. Inertial reference frames are those that are not subject to acceleration. Non-inertial frames are accelerating.
2. There are no indications of movement with constant velocity. While accelerating, however, a force is required and you feel this as a push from your seat.
3. Head-on collisions are particularly dangerous because the velocity of one car relative to the other can be much greater than the velocity of each car individually. For example, two cars, both travelling at 50 km h^{-1} in opposite directions, collide head-on. The velocity of one car relative to the other is 100 km h^{-1} .
4. a. The laws of physics are the same in all inertial reference frames, and light speed is constant in a vacuum, for all observers.
b. In previous physics, the laws of electromagnetism were not the same in all inertial reference frames.
5. False. By the principle of relativity, the situation must be symmetrical so that any two inertial reference frames are indistinguishable. Both observers see the other frame as moving and, therefore, both see the other's time running slow.
6. a. The proper time is the time that passes in the frame of reference in question.
b. $0.78c$

7. Accelerating even relatively small masses to near light speed involves enormous amounts of energy. This is not currently feasible. Additionally, humans are not able to sustain large accelerations for extended periods of time. Reaching near light speeds with safe accelerations would take years.
8. $2.25 \times 10^{16} \text{ J}$
9. All the chemical products of combustion must add up to less than the mass of the initial coal because energy has been released.
10. $7.47 \times 10^{-31} \text{ kg}$

8.7 Exercise 3: Exam practice questions

1. a. $10 \text{ km h}^{-1} \text{ s}^{-1}$
b. $10 \text{ km h}^{-1} \text{ s}^{-1}$
c. Invariant
2. Einstein's second postulate states that the speed of light is the same for all observers. The Michelson–Morley experiment worked on the basis that the speed of light was relative to the aether, which the Earth was moving through. If this were the case, then the light would take the two paths in different times; however, as the speed of light is the same for all observers in all directions, the path the light takes does not matter. The light will take the same time if the paths have equal length. This would mean that the interferometer would detect no changes in the interference pattern as it was rotated.
3. The principle of relativity states that the laws of physics are the same for observers in all inertial reference frames. If all clocks in a reference frame at rest relative to the observer ticked at the same rate, they must all tick at the same rate if the reference frame is set in motion. The length of the tick is not absolute but the idea of time passing at a certain rate within a reference frame must be maintained or the laws of physics will be broken.
4. a. 3 light-years b. 4.3 years c. 6 years
5. a. 57 m b. 190 m
c. $6.33 \times 10^{-7} \text{ s}$ d. $2.67 \times 10^{-7} \text{ s}$
6. a. 117 kg b. $4.2 \times 10^{18} \text{ J}$
7. $2.25 \times 10^{20} \text{ J}$
8. $1.0 \times 10^4 \text{ m s}^{-1}$
9. a. ${}^1_1\text{H} + {}^1_1\text{H} \rightarrow {}^2_1\text{H} + {}^0_0\beta^+ + \text{neutrino}$
 ${}^2_1\text{H} + {}^1_1\text{H} \rightarrow {}^3_2\text{He} + \text{gamma}$
 ${}^3_2\text{He} + {}^3_2\text{He} \rightarrow {}^4_2\text{He} + 2{}^1_1\text{H}$
b. The mass is greater for the particles on the left than on the right. This is because some of the mass–energy stored as mass in the particles on the left-hand side is released as energy in the form of gamma photons or as the kinetic energy of the particles on the right-hand side.

9 Properties of mechanical waves

9.2 Explaining waves as the transmission of energy

9.2 Exercise

1. a. A periodic wave is a disturbance that repeats itself at regular intervals; a single pulse is, as the name suggests, a disturbance without repeats.
b. For transverse waves, the disturbance is at right angles to the direction the waves travel whereas for longitudinal waves, the disturbance is parallel to the direction the waves are travelling.

2. a. 2 seconds b. Transverse wave
3. 332 m s^{-1}

9.3 Properties of waves

Sample problem 1

$$340 \text{ m s}^{-1}$$

Practice problem 1

$$340 \text{ m s}^{-1}$$

Sample problem 2

$$0.609 \text{ m}$$

Practice problem 2

$$335 \text{ m s}^{-1}$$

9.3 Exercise

1. A wave will travel a distance of one wavelength during a time equal to one period.
2. Periodic sound waves travel at the same speed from a stationary source independent of how loud they are. Music from an orchestra, containing a variety of sound intensities, is heard synchronised at distances from the orchestra.
3. The marching band appears out of step with the music because the speed of light is significantly different to the speed of sound. Optical information arrives at an observer before audio information does.
4. Yes, you will, because the speed of sound is the same for low- and high-frequency sound waves produced by a stationary source such as a group of musicians at a concert.
5. 0.780 s
6. 1.02 m
7. 330 m s^{-1}
8. a. 1.33 m b. 5.86 m

$v \text{ (m s}^{-1}\text{)}$	$f \text{ (Hz)}$	$\lambda \text{ (m)}$
335	500	0.67
300	12	25
1500	5000	0.30
60	24	2.5
340	1000	0.34
260	440	0.59

10. In this instance, the source produces sound with a source frequency of 100 Hz. An observer moving towards the source will intercept more waves per second and so will measure a higher frequency; the observer moving towards the source measures 110 Hz. Likewise an observer moving away from the source will intercept fewer waves per second and will measure a lower frequency; the observer moving away from the source measures 90 Hz.

9.4 Diffraction of waves

Sample problem 3

There will be a large diffraction spread for the sound of wavelength 165 cm (200 Hz) because the wavelength is

large compared with the opening: $\frac{\lambda}{w} = \frac{165}{35} = 4.7$.

There will be a very small diffraction spread for the sound of wavelength 3.30 cm (10 000 Hz) because the wavelength is

small compared with the opening: $\frac{\lambda}{w} = \frac{3.3}{35} = 0.094$.

Practice problem 3

In the first instance, $\frac{\lambda}{w} = \frac{2.20}{0.800} = 2.75$ and so the amount of diffraction will be significant. With the 15 kHz sound, $\frac{\lambda}{w} = \frac{0.022}{0.800} = 0.0275$ and so this sound will not diffract significantly.

9.4 Exercise

- When a plane wave passes through a narrow opening, the wavefront changes direction, spreading out when moving away from the opening.
 - Sound produced by a speaker is subject to diffraction effects, because the speaker produces sound waves with wavelength λ originating from a narrow opening due to the speaker cone having a diameter d . The amount of diffraction scales according to the ratio $\frac{\lambda}{d}$.
- 1.70 m
 - Since the wavelength of the sound made by the patient is larger than the 1.0 m opening, diffraction effects would be significant. The sound intensity level due to the groan of the patient at points A and B would be similar.
 - The wavelength of the sound produced by the drill is $\frac{340}{5000} = 0.0680$ m. This wavelength is much smaller than the 1.0 m opening and thus diffraction effects would be negligible. The sound level intensity due to the drill would be much less at B than at A.
- 1500 Hz: 0.227 m b. 5.3 cm
 - 8500 Hz: 0.040 m
- Decreases b. Increases
 - Increases d. Decreases

9.5 Standing waves in strings

Sample problem 4

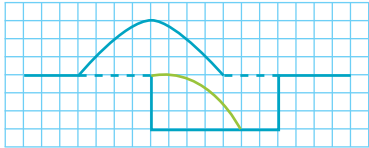
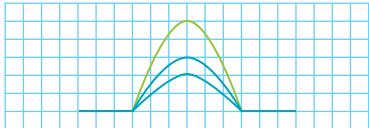
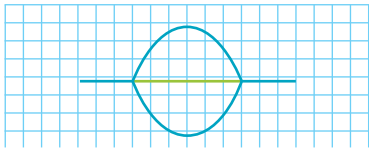
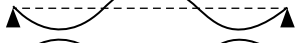
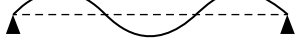
- Four
- 3rd harmonic
- 0.24 s
- 1.4 Hz and 3.0 m
- Three
- 1.0 m
- 4.2 m s⁻¹

Practice problem 4

- $f_1 = 2.0$ Hz
 $f_2 = 4.0$ Hz
 $f_3 = 6.0$ Hz

- First harmonic's wavelength as 3.0 m, the second harmonic's wavelength as 1.5 m and the third harmonic's wavelength as 1.0 m.

9.5 Exercise

- C
 - A and B
- Superposition is the addition of the amplitudes of two or more wave disturbances at a point in space and time. It occurs whenever there is a disturbance arising from two or more sources of waves.
- Constructive interference occurs when two or more wave disturbances superimpose (add together) to give a resultant amplitude larger than the amplitudes of either wave.
- 
 - 
 - 
- 1.5 m.
- 
 - 
 - 
 - 
- Constructive interference
 - 1.0 m
- 330 m s⁻¹
- 4.8 m s⁻¹
 - 0.60 m
 - 0.20 m
 - 8
- 6.0 m s⁻¹
 - 1.2 m
 - 0.08 m
 - 5
- $f_1 = 406$ Hz
 $f_2 = 813$ Hz
 $f_3 = 1219$ Hz
- 5th harmonic
 - Three nodes
 - 1.2 m
 - 240 m s⁻¹
 - 40 Hz

9.6 Interference of waves

Sample problem 5

- 9.00 m
- 9.50 m

Practice problem 5

- 8.0 m
- 8.5 m

Sample problem 6

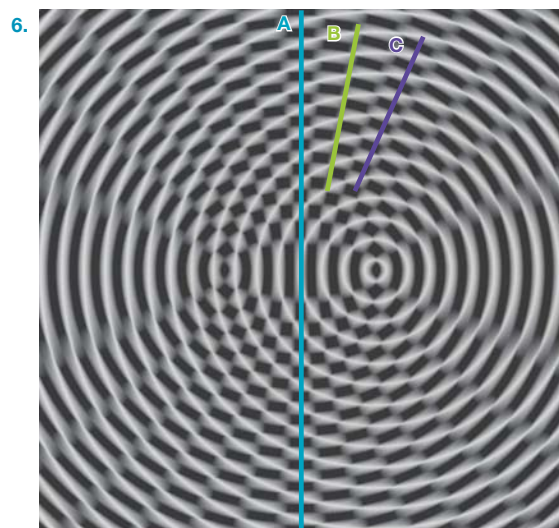
A very soft sound.

Practice problem 6

A very loud sound.

9.6 Exercise

- The interference pattern produced by two sound sources consists of regions of loud and soft sound. The former is due to constructive interference while the latter is due to destructive interference. You can determine a local maximum if the sound at that point is loud. Additionally, you can determine a local minimum if the sound at that point is soft.
- The phrase 'interference pattern' refers to the stationary wave pattern produced by the superposition of sound waves radiating away from two sources.
- Louder
 - Louder
 - Softer
- 0.500 m
 - 18.125 m
 - 3.000 m
- Alternating regions of constructive and destructive interference occurring along the path A through to I.
 - At point E, the sound is loud. This is due to constructive interference occurring at E:
 $|S_1E - S_2E| = 0$.
 - At point D, the sound is very soft. This is due to destructive interference occurring at D:
 $|S_1D - S_2D| = \frac{\lambda}{2} = 0.4000 \text{ (or } 40.00 \text{ cm)}$
- 19.60 m
- As the frequency increases, the wavelength will decrease. This results in the interference pattern compressing. As Suroor is standing on a local minimum, she will hear the loudness increase and then decrease as antinodal and nodal lines alternatively sweep across point D.



- Any point on the blue line (line A) gives a path difference of 0.
- Any point on the second nodal line is correct. Any point on the green line (line B) would be correct.
- Any point on the third antinodal line is correct. Any point on the violet line (line C) would be correct.
- The pattern would be more compressed. Nodal lines would be closer together.

9.7 Review

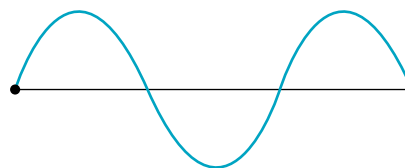
9.7 Exercise 1: Multiple choice questions

- B
- A
- D
- C

- D
- B
- D
- D
- A
- D

9.7 Exercise 2: Short answer questions

- Without a medium, there is nothing for the wave to distort, so it can't travel anywhere.
- 0.50 s
 - 1.3 m
 - The wavelength will decrease. Speed is unchanged.
- $1.08 \times 10^{-3} \text{ s}$
 - 0.370 m
- 20 Hz = 17 m; 20 kHz = 0.017 m
- The frequency will be smaller; hence, the pitch will be lower.
 - The frequency will be the same; hence, the pitch will be the same.
 - The frequency will be greater; hence, the pitch will be higher.
- Diffraction is less evident with smaller wavelengths.
 - Diffraction is more evident when the width of an opening is decreased.
- $f_1 = 82.41 \text{ Hz}$
 $f_2 = 164.8 \text{ Hz}$
 $f_3 = 247.2 \text{ Hz}$
 $f_4 = 329.6 \text{ Hz}$
 - 1.50 m
 - 124 m s^{-1}
 - Standing waves on a guitar string are composed of transverse travelling waves as the vibration is perpendicular to the direction of propagation of the travelling wave.
 - 25 cm
- 615 Hz
 - The fourth harmonic is a standing wave consisting of four antinodes as shown below:



- 713 m s^{-1}
 - 14.5 cm
- 12.0 m
 - 0.400 m
 - $|S_1C - S_2C| = 1.60 \text{ m} = 2 \times 0.800 = 2\lambda$. Since the path difference is a whole number of wavelengths, the point C is a point where constructive interference is occurring. Waves from S_1 and S_2 arrive at C in phase and thus add to give a resultant amplitude larger than either wave.
 - 11.8 m
 - $|S_1X - S_2X| = \frac{\lambda}{2}$
 - 2.0 m
 - 16 m s^{-1}

9.7 Exercise 3: Exam practice questions

- A longitudinal wave consists of the vibration of a medium parallel to the direction of propagation whereas for a transverse wave the vibration of the medium is perpendicular to the direction of propagation of the wave. An example of a longitudinal wave is a sound wave, and an example of a transverse wave is a vibrating string such as the string on a guitar.
 - Both types of waves transfer energy from one place to another via a medium. Both types of waves travel at a constant speed dependent on the properties of the medium. And both types of waves have the same parameters, namely frequency, amplitude and wavelength.
 - Tony is correct: all types of waves will exhibit diffraction effects. Sarah's statement is incorrect.
- 4.50 cm
 - 8.4 Hz
 - To the right by 3.8 cm
- $9.0 \times 10^2 \text{ m s}^{-1}$
 - $f_2 = 1060 \text{ Hz}$
 $f_3 = 1590 \text{ Hz}$
 $f_4 = 2120 \text{ Hz}$
- Along the line AB, evenly spaced regions of loud and soft sound exist. This is due to constructive interference located at the points marked L, and destructive interference located at points in-between. At any point marked L, waves from speaker 1 arrive in phase with waves from speaker 2 to produce a larger resultant amplitude, and hence a loud sound. At points in-between, the waves from speaker 1 arrive out of phase with those from speaker 2, resulting in cancellation and hence little sound.
 - 0.472 m
 - 0.472 m
 - 8.4 m

10 Light as a wave

10.2 Light and its properties

Sample problem 1

8 minutes 20 seconds

Practice problem 1

2.5 s

Sample problem 2

$9.5 \times 10^{12} \text{ km}$

Practice problem 2

$2.0 \times 10^8 \text{ m s}^{-1}$

This speed is less than the speed of light in a vacuum.

10.2 Exercise

- The longest time: 21 min
The shortest time: 4.4 min
 - The longest time: 258 min
The shortest time: 242 min
- 65°
 - 25°
- 45°

10.3 Bending of light

Sample problem 3

20°

Practice problem 3

1.29

Sample problem 4

- $2.0 \times 10^8 \text{ m s}^{-1}$
- $2.3 \times 10^8 \text{ m s}^{-1}$

Practice problem 4

- $1.24 \times 10^8 \text{ m s}^{-1}$
- $1.84 \times 10^8 \text{ m s}^{-1}$

10.3 Exercise

- Angle of incidence $40^\circ \Rightarrow \theta = 29^\circ$
Angle of incidence $50^\circ \Rightarrow \theta = 35^\circ$
The angle of refraction increases by 6° when the angle of incidence increases by 10° .
- 1.5
- 36°
 - The angle of refraction at the bottom face is the same as the angle of incidence at the top face: 65° .
Sample responses can be found in your digital formats.
- 23.8°
- $2.3 \times 10^8 \text{ m s}^{-1}$
 - $2.0 \times 10^8 \text{ m s}^{-1}$
 - $1.2 \times 10^8 \text{ m s}^{-1}$
- Acetone: 18.1°
Glycerol: 16.7°
Carbon tetrachloride: 16.8°
Glass: 16.0°
Because the layers are parallel, the light ray will emerge from the glass into the air at the angle it left the air: 25° .
 - When the light reflects off the mirror, the angle of reflection will equal the angle of incidence, so the light ray will leave the bottom medium at the same angle that it entered it (25°). The light path up through the layers will be the reverse of the path coming down through the layers. All the angles will be the same.
- 0.85 cm
- When the ray meets the opposite side of the glass sphere, the normal at this point passes through the centre of the sphere (i.e. it is a radius). This means that the triangle formed by the points on the glass sphere and the centre of the sphere is an isosceles triangle and that the angle of incidence at the opposite side of the sphere is 19.5° . This situation is the reverse of the entry into the sphere, so the angle of refraction is 30° .
- Refraction: the bending of light as it passes from one material into another.
Reflection: the leaving of light from a surface at the same angle that it approached the surface.
Dispersion: the spreading of light into colours as it is refracted.
Spectrum: the range of colours that light can be broken down into.
Refractive index: a measure of how much a material slows light down and therefore changes its direction.

b. In a triangle, the rays emerge at different angles and spread further apart the further they travel, so on a distant wall the colours are seen separately. With the rectangle, the colours stay the same distance apart regardless of how far they travel.

-

- ## 10.4 Total internal reflection

Sample problem 5

Practice problem 5

- ### Sample problem 6

- ### Practice problem 6

- a. Larger.
b. 65.5°
c. $1.92 \times 10^8 \text{ m s}^{-1}$.
Therefore, the speed of light in the new optic fibre is larger.

10.4 Exercise

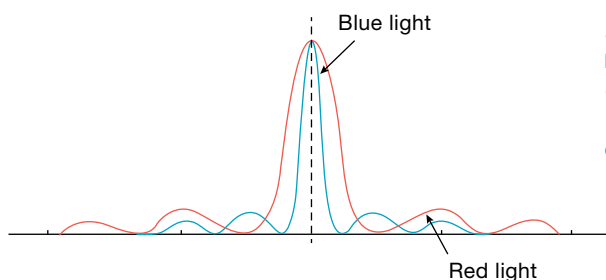
1. a. 24° b. 32.1°
2. a. 1.4 is the minimum value for total internal reflection to occur for an angle of incidence of 45° .
b. The rays would be inverted and swap positions (this is often used in binoculars to correct the normally inverted image). The initial ray of light would move down and refract off the surface shown, bouncing to the left at a right angle. The other ray of light would enter the block and refract at a right angle as well.
c. Both rays of light would be expected to emerge at the same time, as they have identical pathways (just mirrored).
3. 1.49
4. Above, the diver would see a circle containing a compressed 180° view of the world above the water. Towards the edge of the circle, the image would look distorted. Outside the circle, the diver would see the reflected, inverted image of the world beneath the surface of the water due to the total internal reflection of the light rays from beneath the water as they meet the water–air boundary.
5. The critical angle for light travelling from glass into water is 59.1° .
The angle of incidence at the glass–water boundary is 45° , which is less than the critical angle, so the ray is refracted into the water. The angle of refraction, is 55° .
6. 46 cm
7. a. $7.00 \times 10^{-8}\text{ m}$
b. Speed of light in the glass $= 3.0 \times 10^8\text{ m s}^{-1}$
Time difference $= 2.3 \times 10^{-16}\text{ s}$
This time is small, but in an optical fibre of 1.00 km , there would be 1.41×10^8 reflections, corresponding to a total time difference of $3.28 \times 10^{-8}\text{ s}$. This would limit the upper frequency of light pulses sent down the optical fibre. If the frequency was too high, the pulses would overlap. The problem can be overcome by using a narrower optical fibre or using an optical fibre whose refractive index gets smaller when the distance gets greater from the centre.

10.5 Diffraction of light

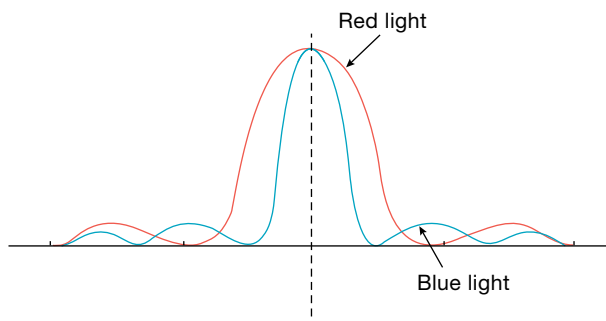
10.5 Exercise

1. The diffraction of light when passed through a narrow opening is strong evidence to support that light is a type of wave.
2. a. The first minimum occurs where the path difference for light rays travelling from different places on the opening reaches $\frac{\lambda}{2}$. This will be a region where the intensity of the light will be diminished due to destructive interference.

b.



c.



3. a. Diffraction depends on the wavelength or colour of light. White light is a mixture of the different colours in the spectrum, so when it diffracts while passing through a small slit, the colours that make up the white light form slightly different diffraction patterns.

- b. The positions of the minima are given by $\sin \theta = \frac{\lambda}{w}$. The red end of the spectrum has the longest wavelengths; therefore, θ for any minimum occurs at a greater angle than for blue light and other parts of the visible spectrum.

4. a. A blurred edge is evidence of diffraction and hence the wavelike nature of light.
b. Red light has a longer wavelength compared to green light and so the pattern would reveal more significant diffraction; the edge of the shadow would be more blurry (less sharp).
c. With a smaller object, the degree of diffraction observed would be more significant than before; the edge of the shadow would be less sharp.

10.6 Interference using light

Sample problem 7

- a. 1920 nm
b. 910 nm
c. The pattern is now more compact or compressed

Practice problem 7

- a. 1060 nm
b. The pattern will compress; adjacent maxima and minima will be closer together.
c. The pattern will be red and, since the wavelength for red light is greater than for green light, the pattern will dilate.
d. The pattern is indicative of the superposition of waves combining from two sources that are close to each other and in phase. Only wavelike sources produce such a pattern.

Sample problem 8

1.77 mm

Practice problem 8

- a. 650 nm
b. Red
c. If blue light was used, the pattern would be blue and compressed relative to the pattern produced by red light.
d. The line spacing could be made easier to measure if the screen was moved further from the pair of slits, since $\Delta x \propto L$.

10.6 Exercise

- a. Young's experiment clearly demonstrates the interference of light passing through two narrow closely spaced slits. This is strong evidence for the wavelike nature of light.

b. An interference pattern consists of evenly spaced bright and dark fringes. Bright fringes are produced by the constructive interference of light passing through each slit. This occurs when the path difference is $0, \lambda, 2\lambda, 3\lambda$, and so on. Dark fringes are produced by the destructive interference of light passing through each slit. This destructive interference occurs when the path difference is $\frac{\lambda}{2}, \frac{3\lambda}{2}, \frac{5\lambda}{2}$, and so on.
- a. The pattern on the screen is evidence for the wave nature of light as the pattern is fully explained by the process of interference. Interference is a property associated with waves but not particles.

b. There is bright light at point W so it is a point where constructive interference is taking place.

c. 0

d. 1060 nm

e. $\frac{\lambda}{2} = 265 \text{ nm}$
 $\frac{3\lambda}{2} = 795 \text{ nm}$
 $\frac{5\lambda}{2} = 1325 \text{ nm}$

f. There are two dark fringes between C and W.
- a. i. The bright band corresponds to constructive interference, where crests from the light waves coming through the two slits arrive together, and troughs in the light waves arrive together.
ii. The dark band is where destructive interference occurs. At all times, the sum of the waves from the two slits is zero, with the crests from one slit coinciding with the troughs from the other.

b. i. 0. ii. 317 nm iii. 1266 nm

c. The wavelength is smaller, so the bright fringes in the interference pattern would be closer together. As the path difference for the bright fringes equals $n\lambda$, a smaller wavelength means that each bright fringe would be closer to the central bright band.

d. The increase in distance between the slits would result in the bright bands being closer together.

e. Moving the screen further away would result in the interference pattern spreading out, increasing the distance between the bright bands.
- a. Constructive interference: Path difference = $0, 1.06 \mu\text{m}, 2.12 \mu\text{m}, 3.18 \mu\text{m}$, and so on.
b. Destructive interference: Path difference = $0.53 \mu\text{m}, 1.59 \mu\text{m}, 2.65 \mu\text{m}$, and so on.

5. Therefore, the distance from the central maximum to:
 The first bright band = 0.86 mm
 The second bright band = 1.72 mm
 The third bright band is = 2.58 mm or 2.58×10^{-3} m
6. a. 670 nm b. 2.5 cm
 7. 450 nm

10.7 Light as a transverse electromagnetic wave

Sample problem 9

- a. 1.8×10^{-15} s b. 5.4×10^2 nm

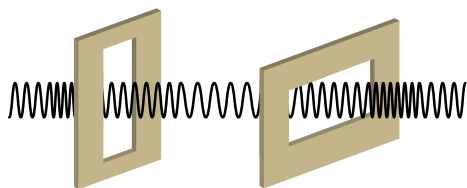
Practice problem 9

$$f = 6.7 \times 10^{14} \text{ Hz}$$

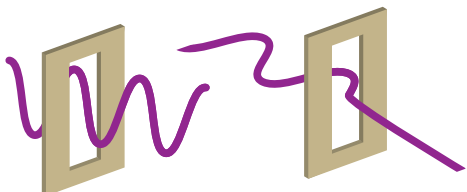
$$T = 1.5 \times 10^{-15} \text{ s}$$

10.7 Exercise

- 2.1×10^{-15} s
- $\lambda_1 = 3.0$ cm
 $\lambda_2 = 0.30$ mm
 Microwaves have wavelengths that range from fractions of a millimetre to a few centimetres.
- $f = 1.1 \times 10^{19}$ Hz
 $T = 9.0 \times 10^{-20}$ s
- Radio waves, microwaves, visible light, ultraviolet rays, gamma-rays
- a. 50 Hz b. 6.0×10^6 m
- The waves with the larger wavelength would be more susceptible to diffraction effects. AM radio waves have a longer wavelength as they have a lower frequency compared to FM radio waves. Hence, AM radio waves would show diffraction effects more readily.
- a. 4.6×10^{-7} m b. 3.1×10^{-7} m
 c. 6.5×10^{14} Hz d. 1.5×10^8
- All longitudinal waves consist of an oscillation parallel to the direction of propagation and are hence not able to be polarised. Only transverse waves are capable of being polarised due to the many different planes of oscillation possible.



Longitudinal waves:
no polarisation



Transverse waves:
polarisation can occur

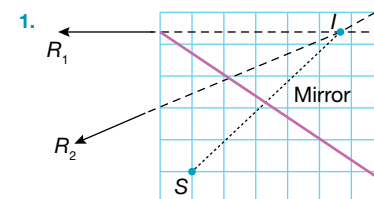
- Since the reflected light is horizontally polarised, the polarising filter could be set so that it is oriented in the vertical plane.
- A simple explanation involves projecting two pictures onto the screen filmed by cameras located close to each other, but giving a different perspective. One of the cameras uses vertically polarised light while the other uses horizontally polarised light. Viewing glasses have polarising filters to accept one plane of polarisation into one eye and the other plane into the other eye, giving two pictures from two perspectives, thus allowing a 3D image to be constructed by the brain.
- Both electric and magnetic fields are static about the charge. If the charge changes direction or accelerates in a straight line, a ripple is created in both fields, which is associated with an electromagnetic wave: All accelerated charged particles produce electromagnetic radiation consistent with Maxwell's model for electromagnetic waves.

10.8 Review

10.8 Exercise 1: Multiple choice questions

- D
- A
- B
- C
- D
- B
- B
- A
- D
- B

10.8 Exercise 2: Short answer questions



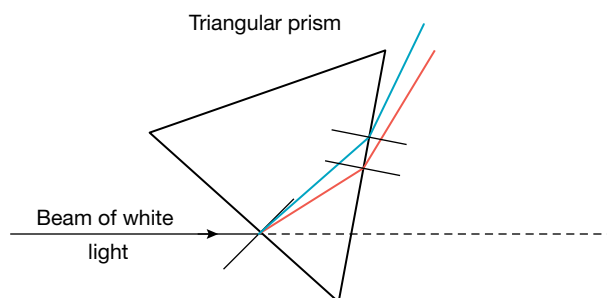
- a. Blue light: 4.6×10^{-7} m
 Yellow light: 5.8×10^{-7} m
 b. Blue light in the glass: 3.1×10^{-7} m
 Yellow light in the glass: 3.8×10^{-7} m
- 46 cm long.
- a. 1.36
 b. 23°
 c. 31°

When light passes from air into perspex (refractive index is greater than 1), it bends towards the normal; the angle of refraction is thus less than the angle of incidence. However, when light passes from perspex to air, it bends away from the normal; in this case, the angle of refraction is greater than the angle of incidence.

- a. $1.84 \times 10^8 \text{ m s}^{-1}$
 b. The speed of light in salt water is greater than the speed of light in carbon disulfide.
 c. Away from the normal.
 d. 57°

6. a. The word dispersion describes the splitting of white light into its constituent colours. This occurs when refraction into a medium has a refractive index that is dependent on colour, or frequency. Such media are known as dispersive media. In dispersive media, light of different colours will travel at different speeds and have different angles of refraction for the same angle of incidence.
- b. For red light: 15.61°
For blue light: 15.37°
Thus, the angle between the blue light and the red light is: 0.24° .

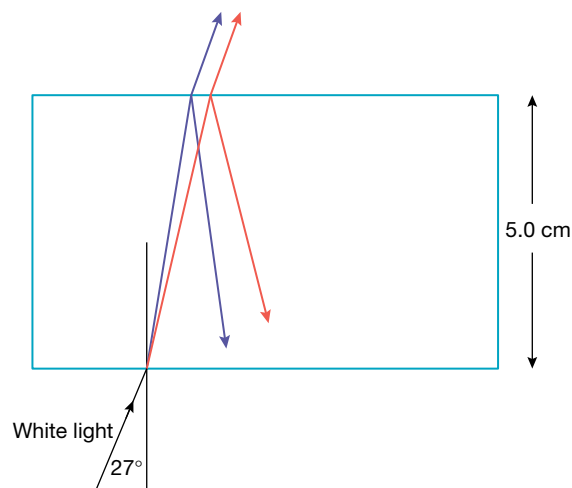
7.



8. a. Glass type Z has the smallest critical angle of the three materials.
- b. 39.6°
- c. 77.0°
9. When light passes around an obstacle or through a sufficiently narrow opening, it displays wavelike behaviour in the form of diffraction. Not only does the direction of light change but, in addition, interference effects, such as those shown in the diagram, produce bright and dark fringes around edges that are well explained by constructive and destructive interference.
10. The wavelength of light λ used can be increased, or the width of the opening w can be decreased.
11. Each colour in white light will produce its own diffraction pattern. Each colour will have a slightly different spread, with red spread the most and purple spread the least, due to variations in wavelength. Hence, the pattern has a spectrum of coloured fringes that are consistent with a typical diffraction pattern for waves passing through a narrow opening.
12. a. 500 nm
- b. 1000 nm or $1.0 \mu\text{m}$
13. The spacing between adjacent bright fringes Δx can be increased by a factor of 2:
- by increasing the distance of the screen from the slits by a factor of 2
 - by increasing the wavelength of the light used by a factor of 2
 - by decreasing the distance between the slits, the slit separation, by a factor of 2.
14. 3.08 m
15. Yes. Microwaves are a type of electromagnetic radiation. They consist of synchronised, in-phase transverse electric and magnetic field variations like all types of light. These waves are transverse in nature and hence capable of being polarised.

10.8 Exercise 3: Exam practice questions

1. a.



- b. 17.3°
- c. The time taken for red light to cross the prism is $2.671 \times 10^{-10} \text{ s}$
The time taken for the blue light is $2.70 \times 10^{-10} \text{ s}$
Therefore, blue light takes slightly longer.
2. a. Since $n_{\text{cladding}} < n_{\text{core}}$ there exists a critical angle. Ideally the refractive index of the cladding is only a little smaller than the core so that the critical angle is as large as possible.
- b. 1.52
- c. $1.9 \times 10^8 \text{ m s}^{-1}$
- d. 253 nm
3. a. $5.7 \times 10^{14} \text{ Hz}$
- b. $795 \text{ nm} = 7.95 \times 10^{-7} \text{ m}$
- c. $1.06 \times 10^{-6} \text{ m}$
- d. When the slit separation is increased, the pattern on the screen is compressed; the bright fringes are closer together.
- e. The pattern on the screen is strong evidence for the wave nature of light. The pattern is fully explained by appealing to the interference of waves passing through each slit. Bright regions on the screen correspond to constructive interference, where waves from each slit opening arrive in phase. Dark regions on the screen correspond to destructive interference, where waves from each slit opening arrive out of phase and cancellation occurs.
4. a. Electromagnetic waves refer to the waves that form from the interactions between an electric and a magnetic field. An electromagnetic wave is a wave that propagates at a unique speed in uniform media.
- b. For waves to be polarised, they must be transverse waves and not longitudinal waves. Electromagnetic waves are transverse waves so therefore can be polarised whereas sound waves are longitudinal and oscillate parallel to the direction of motion, so therefore cannot be polarised.

c.

	wavelength (m)	electromagnetic wave type
i.	1×10^3	radio waves
ii.	1×10^{-2}	microwaves
iii.	1×10^{-12}	γ -rays
iv.	1×10^{-8}	UV light

- d. The wave that would diffract the most significantly is the one with the largest wavelength. In this case, it would be radio waves.

11 Behaviour of light as a particle

11.2 Physics before the observation of the photoelectric effect

Sample problem 1

- a. i. 4.4×10^{-19} J ii. 1.5×10^{-27} N s
b. 1.02×10^{-27} N s

Practice problem 1

4.4×10^{14} Hz

Sample problem 2

- a. 3.86×10^{-19} J b. 8×10^{17} s $^{-1}$

Practice problem 2

1.4×10^{28} photons s $^{-1}$

Sample problem 3

- a. 8.0×10^{-17} J (or 500 eV)
b. kinetic energy
c. 8.0×10^{-17} J (or 500 eV)
d. 1.33×10^7 m s $^{-1}$
e. 1.2×10^{-23} N s

Practice problem 3

- a. 79 eV b. 79 V
c. 5.3×10^6 m s $^{-1}$ d. 4.8×10^{-24} N s

Sample problem 4

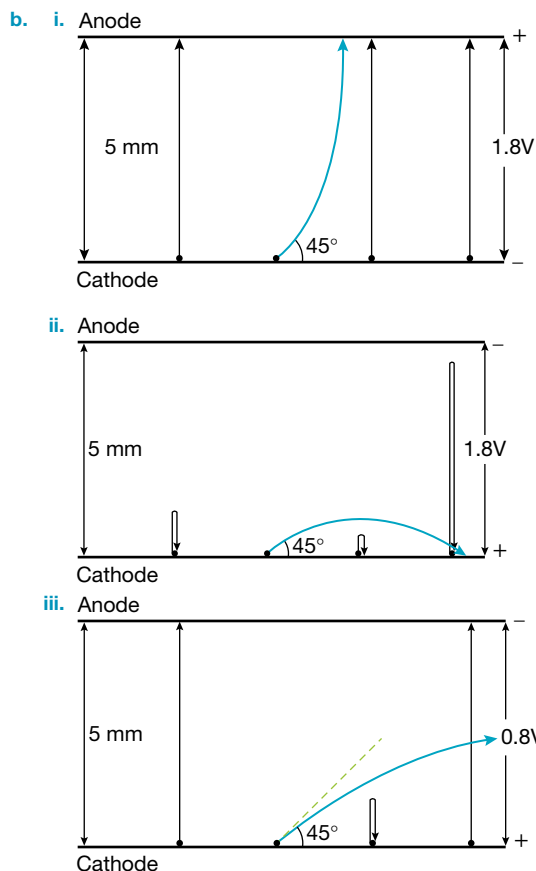
- a. 1.6 V b. 6.7×10^{-19} J

Practice problem 4

3.0 V

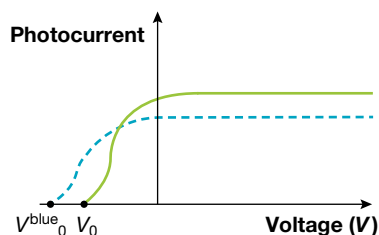
11.2 Exercise

1. a. 6.5×10^{-7} m b. 2.18×10^{-15} s
2. 52 photons
3. See table below, at the bottom of the page
4. 20 V
5. a. 5.3×10^5 m s $^{-1}$



11.3 The photoelectric effect

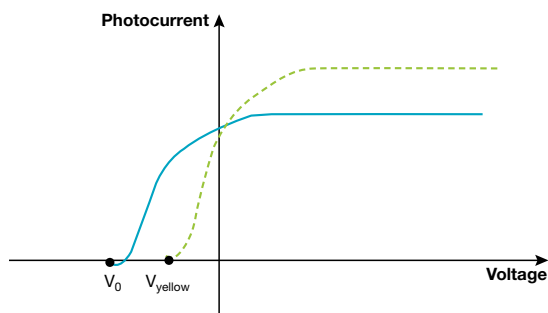
Sample problem 5



*3.e.

Source	Wavelength	Frequency (Hz)	Energy	Momentum (N s)
Infra-red from CO ₂ laser	10.6 μ m	2.83×10^{13}	1.88×10^{-20} J, 0.117 eV	6.25×10^{-29}
Red helium–neon laser	633 nm	4.74×10^{14}	3.14×10^{-19} J, 1.96 eV	1.05×10^{-27}
Yellow sodium lamp	589 nm	5.09×10^{14}	3.37×10^{-19} J, 2.11 eV	1.125×10^{-27}
UV from excimer laser	194 nm	1.55×10^{15}	1.03×10^{-18} J, 6.42 eV	3.43×10^{-27}
X-rays from aluminium	0.990 nm	3.03×10^{17}	2.01×10^{-16} J, 1.25 keV	6.69×10^{-25}

Practice problem 5



Sample problem 6

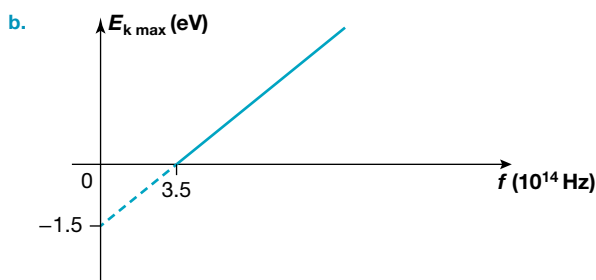
- 7.1×10^{14} Hz
- 4.7×10^{-19} J, 2.9 eV
- 2.00×10^{-19} J
- 2.7×10^{-19} J
- 7.4×10^{-7} m or 740 nm
- 1.5 V

Practice problem 6

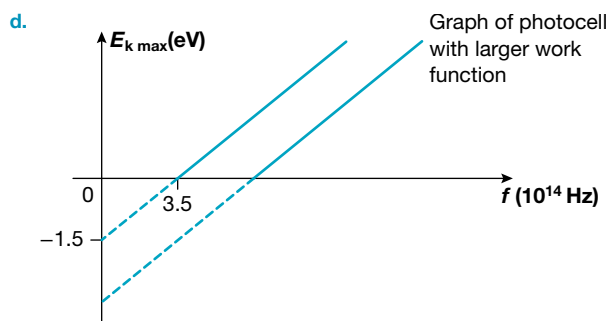
- 0.87 eV, 1.4×10^{-19} J
- 2.1 eV
- $f_0 = 4.96 \times 10^{14}$ Hz
 $\lambda = 605$ nm
- Light with wavelength 650 nm will consist of photons with energy:
 $E = 3.06 \times 10^{-19}$ J.
The energy is insufficient to overcome the work function ϕ (3.29×10^{-19} J) and thus the photoelectric effect will not occur. Alternatively, light of wavelength 650 nm has a frequency, in this case only 4.6×10^{14} Hz, which is below the threshold frequency (4.96×10^{14} Hz) for the photoelectric effect.

Sample problem 7

Wave length of light used (nm)	Frequency of light used $\times 10^{14}$ (Hz)	Photon energy of light used (eV)	Stopping voltage readings (V)	Maximum photo-electron energy (J)
663	4.52	1.88	0.450	7.20×10^{-20}
489	6.14	2.54	1.15	1.84×10^{-19}



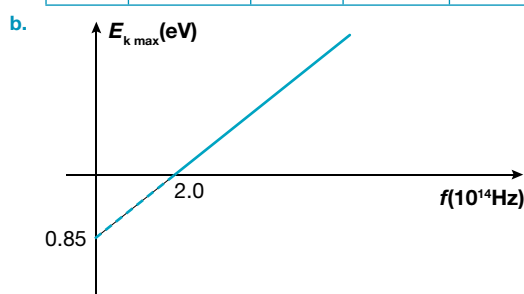
- 4.3×10^{-15} eV s, 6.9×10^{-34} J s
 - 3.5×10^{14} Hz
 - 2.4×10^{-19} J = 1.5 eV



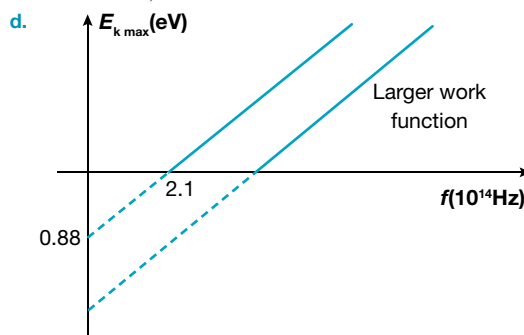
- 2.07 eV
- The photocurrent would double.
- 1.70 V

Practice problem 7

Wave length of light used (nm)	Frequency of light used $\times 10^{14}$ (Hz)	Photon energy of light used (eV)	Stopping voltage readings (V)	Maximum photo-electron energy (J)
390	7.70	3.19	2.36	3.78×10^{-19}
524	5.73	2.37	1.54	2.46×10^{-19}



- 6.73×10^{-34} J s, 4.2×10^{-15} eV s
 - 2.0×10^{14} Hz
 - 0.85 eV, 1.4×10^{-19} J



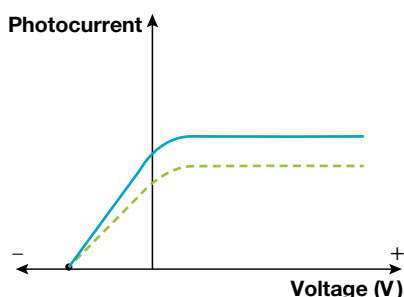
- 2.93×10^{-19} J = 1.8 eV
- The photocurrent would halve to 19 μ A.
- 1.59 V

11.3 Exercise

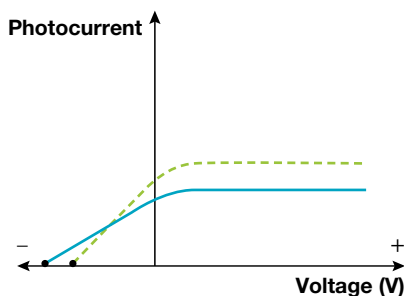
- 1.12 V
- The maximum current occurs when the accelerating voltage causes all ejected electrons to be collected at the anode. The voltage required for this is greater than zero because some electrons leave at an angle and their

parabolic path may miss the anode at lower voltages. When the voltage opposes the motion towards the cathode, electrons travelling towards the anode slow down. When the magnitude of the voltage is large enough, the electrons reverse direction and so do not contribute to the current. At a high enough retarding voltage, *all* electrons turn around before reaching the anode, so the current is zero.

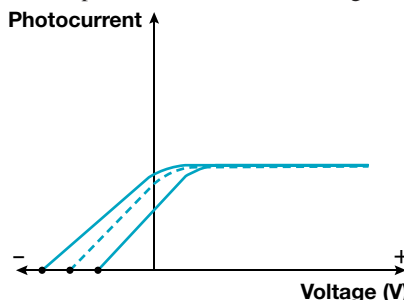
- b. The photoelectrons will have the same energy spread and, therefore, the same stopping voltage, but there will be more electrons ejected per second, resulting in a higher photocurrent.



- c. If the intensity is unchanged, the energy per second reaching the cathode is not changed, but since each photon has a greater energy, this means there are fewer photons per second reaching the cathode and the photocurrent will be reduced.

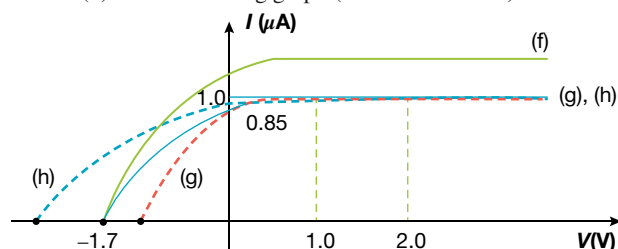


- d. This will change the maximum E_k of the electrons and therefore the stopping voltage, but since the same number of photons reaches the cathode each second, the maximum photocurrent will be unchanged.



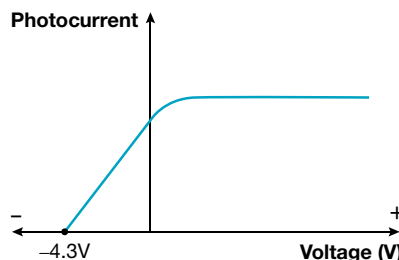
3. a. $0.85 \mu\text{A}$
b. $1.0 \mu\text{A}$
c. $1.0 \mu\text{A}$
d. Once the voltage has reached the point where all electrons are reaching the plate, the current in the photocell is determined solely by the intensity of the light source. There is no increase in light intensity; therefore, there is no increase in the photocurrent.

- e. 1.7 V or $1.7 \text{ eV} = 2.7 \times 10^{-19} \text{ J}$
f. See curve (f) in the following graph (green curve).
g. See curve (g) in the following graph (dotted red curve).
h. See curve (h) in the following graph (dotted blue curve).

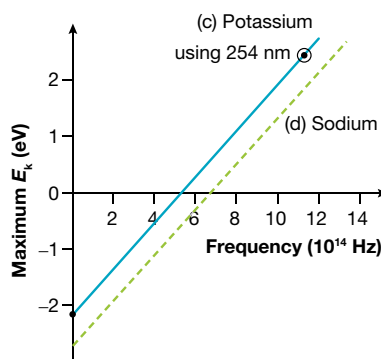


4. a. 0.67 V
b. $1.08 \times 10^{15} \text{ Hz}$
c. $9.17 \times 10^{14} \text{ Hz}$
5. a. $2.6 \text{ eV} = 4.1 \times 10^{-19} \text{ J}$
b. 2.1 V
c. $f = 1.1 \times 10^{15} \text{ Hz}$
 $\lambda = 265 \text{ nm}$
 $p = 2.50 \times 10^{-27} \text{ N s}$

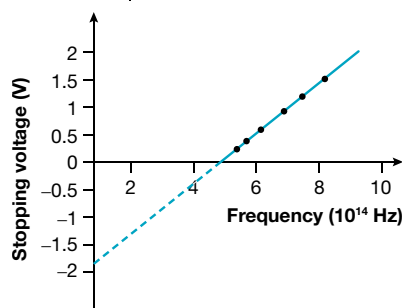
6. a. 1.5 eV or $2.4 \times 10^{-19} \text{ J}$
b. 2.5 V
c. 4.3 eV or $6.9 \times 10^{-19} \text{ J}$
d. Photocurrent



7. a. 2.59 eV or $4.14 \times 10^{-19} \text{ J}$
b. 2.59 V
c. and d.



8.



- a. $4.6 \times 10^{14} \text{ Hz}$.
b. $6.5 \times 10^{-7} \text{ m}$
c. $3.0 \times 10^{-19} \text{ J} = 1.9 \text{ eV}$
d. $6.56 \times 10^{-34} \text{ J s}$

11.4 Limitations of the wave model

11.4 Exercise

- If light behaved like a wave, when the intensity of light is increased, the stopping voltage would also increase, as energy is being delivered at a faster rate (and electrons would have higher kinetic energy).
- Sample answers:
 - For a given frequency of light, the photocurrent is dependent in a linear fashion on the brightness or intensity of light.
 - The energy of photoelectrons is independent of intensity of light and only linearly dependent on frequency.
 - There is no significant time delay between incident light striking a photocell and the subsequent emission of electrons, and this observation is independent of intensity.
 - A threshold frequency exists below which the photoelectric effect does not occur, and this threshold is independent of intensity.
- When treating light as a wave, there is no threshold frequency as energy transfer to electrons from a light source is cumulative and, eventually, emission will occur. However, when light is treated as a particle, there is a threshold frequency, as photons with energy less than the work function cannot free electrons from the photocell, and they will not be emitted.
- Light is thought to behave in two different ways — as both a particle and a wave. These two models are not competing models — they exist in duality and work together to explain the behaviour of light. Light behaves as both a ‘particle’ and a ‘wave’, so using the frequency from one model to calculate the energy of another model is quite reasonable. Using the wave model, you can relate the frequency and wavelength with the speed of light and, using the particle model, you can relate Planck’s constant and frequency with the speed of light. The frequency is in fact useful in both models so, while it seems contradictory, it is incredibly useful for the calculations.

11.5 Review

11.5 Exercise 1: Multiple choice questions

- C
- A
- D
- C
- B
- A
- C
- B
- D
- A

11.5 Exercise 2: Short answer questions

- $6.5 \times 10^{-7} \text{ m}$
 - $4.6 \times 10^{14} \text{ Hz}$
 - $E = 3.1 \times 10^{-19} \text{ J}$ (or 1.9 eV)
 $p = 1.0 \times 10^{-27} \text{ N s}$
- $1.42 \times 10^{28} \text{ photons s}^{-1}$
- $4.51 \times 10^{-19} \text{ J} = 2.81 \text{ eV}$
 - $2.11 \times 10^{-19} \text{ J} = 1.32 \text{ eV}$
 - 1.5 V

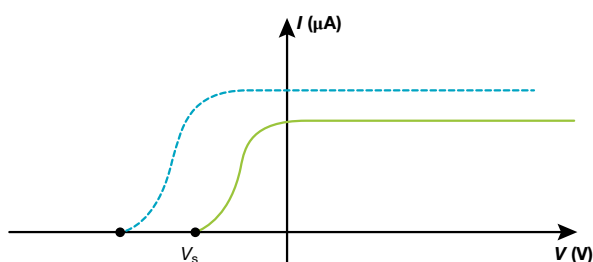
- Photons with a frequency below the threshold frequency will not have sufficient energy for electrons on the surface, or below the surface, to overcome the work function ϕ . The photoelectric effect will not occur.
 - $2.32 \times 10^{-19} \text{ J} = 1.45 \text{ eV}$
 - $3.15 \times 10^{-18} \text{ J} = 19.7 \text{ eV}$
- $4.2 \times 10^{-15} \text{ eV s} = 6.7 \times 10^{-34} \text{ J s}$
 - $0.98 \text{ eV} = 1.6 \times 10^{-19} \text{ J}$
- The stopping voltage will stay the same because the same frequency and hence the same energy photons will be incident on the photocell. Emitted electrons will have the same energy and hence will be stopped by the same stopping voltage. The photoelectron current will be increased due to an increased intensity of the light used. More photons strike the surface per second and hence more electrons will be emitted per second.
 - In this case, the stopping voltage will be greater as the photon energy increases and hence the energy of emitted electrons increases. The photocurrent will be the same as the photon intensity is the same.
 - A smaller work function ϕ will mean that emitted electrons will be emitted with greater energy when photons of the same frequency are used. This will accordingly require a larger stopping voltage. The photocurrent will be unchanged.
- One reason is that the photocurrent is proportional to the brightness of the light, lending support to the idea that light is a stream of particles. The greater the number of particles striking a surface per second, the greater the number of electrons emitted per second. A wave model does not make any obvious predictions concerning brightness and current. Further sample responses can be found in your digital resources.

11.5 Exercise 3: Exam practice questions

Wave length of light used (nm)	Frequency of light used $f \times 10^{14} \text{ (Hz)}$	Photon energy of light used (eV)	Maximum energy of photo-electrons E_e (eV)
575	5.22	2.16	0.47
373	8.04	3.33	1.60

- $h = 4.0 \times 10^{-15} \text{ eV s} = 6.4 \times 10^{-34} \text{ J s}$
 - $f_0 = 4.0 \times 10^{14} \text{ Hz}$
 - $\phi = 1.6 \text{ eV}$
- $4.93 \times 10^{-7} \text{ m}$ or 493 nm
- The photocurrent is also doubled to approximately $36 \mu\text{A}$.
 - The stopping voltage is unchanged at 1.59 V .
- Sample answer: Increasing the intensity of the light does not affect the energy acquired by emitted electrons — as indicated by the stopping voltage remaining unchanged; a threshold frequency exists, below which the photoelectric effect does not occur. Light behaving like a wave: Single-slit diffraction, double-slit interference and the slowing down of light as it bends towards the normal in refraction.

5.



12 Light and matter

12.2 Matter as particles or waves

Sample problem 1

- a. $6.6 \times 10^{-28} \text{ m}$ b. $7.3 \times 10^2 \text{ m s}^{-1}$

Practice problem 1

Proton: $\lambda = 2.0 \times 10^{-11} \text{ m}$

Electron: $\lambda = 3.6 \times 10^{-9} \text{ m}$

The electron has a de Broglie wavelength that is approximately 180 times larger than that of the proton.

Sample problem 2

Tennis ball: $3.7 \times 10^{-34} \text{ m}$

Electron: $2.4 \times 10^{-10} \text{ m}$

The de Broglie wavelength of the tennis ball is of the order of 10^{-34} m and that of the electron is of the order of 10^{-10} m .

The distances between atoms in a crystal are of the order of 10^{-10} m , so diffraction and interference could be observed when these electrons are scattered from a crystal. It is not surprising that diffraction and interference effects are never observed with tennis balls, due to the extremely small wavelength, 10^{-34} m , that they have.

Practice problem 2

0.40 m s^{-1}

Sample problem 3

26 V

Practice problem 3

$2.1 \times 10^6 \text{ m s}^{-1}$

Sample problem 4

- $5.0 \times 10^{-11} \text{ m}$
- The de Broglie wavelength of $5.0 \times 10^{-11} \text{ m}$ is a similar value to the $7.1 \times 10^{-11} \text{ m}$ wavelength of the X-rays.

Practice problem 4

- $5.4 \times 10^2 \text{ V}$
- The photon has a wavelength that is approximately 100 times larger compared to the de Broglie wavelength of the electron.

Sample problem 5

- a. $3.3 \times 10^{-24} \text{ N s}$

The photon and the electron have the same momentum.

- Photon: $9.9 \times 10^{-16} \text{ J}$ or 6.2 keV
Electron: $6.0 \times 10^{-18} \text{ J}$ or 37 eV
The electron has substantially less kinetic energy than the photon, even though they have the same momentum.
- Light and matter with the same wavelength will have the same momentum, and vice versa. However, when photons and electrons have the same momentum, they will not necessarily have the same energy.

Practice problem 5

- Both the photon and the electron will have the same momentum because they have the same associated wavelength.
 $6.6 \times 10^{-24} \text{ N s}$
- Photon: $1.98 \times 10^{-15} \text{ J}$ or 12.4 keV
Electron: $2.4 \times 10^{-17} \text{ J}$, or approximately 150 eV.
The electron again has substantially less kinetic energy than the photon even though they have the same momentum and wavelength.

12.2 Exercise

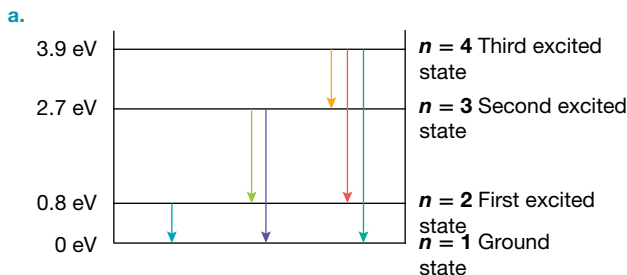
- $1.3 \times 10^{-14} \text{ m}$
 - $1.7 \times 10^{-10} \text{ m}$
 - $6.6 \times 10^{-35} \text{ m}$
- $8.0 \times 10^{-16} \text{ J}$
 - $2.5 \times 10^{-10} \text{ m}$
- Light exhibits both wave and particle behaviour, depending on the experiment you are performing at the time.
- $p = 2.3 \times 10^{-24} \text{ kg m s}^{-1}$
 $\lambda = 2.9 \times 10^{-10} \text{ m}$
 - Significant diffraction occurs when $\frac{\lambda}{d} \approx 1$. As the wavelength is a little greater than the atomic spacing, diffraction will be significant.
- 3000 eV or $4.8 \times 10^{-16} \text{ J}$
 - $p = 3.0 \times 10^{-23} \text{ N s}$
 $\lambda = 2.2 \times 10^{-11} \text{ m}$
 - The scientist would not expect to observe any diffraction effects since the wavelength of the electrons is too small.
 - The scientist should make the accelerating voltage smaller. This would reduce the energy of the electrons and hence reduce the momentum, increasing the wavelength.
 - $2.2 \times 10^{-11} \text{ m}$; $3.0 \times 10^{-23} \text{ N s}$.
 - $5.6 \times 10^4 \text{ eV}$, $9.0 \times 10^{-15} \text{ J}$
- $1.1 \times 10^3 \text{ m s}^{-1}$
- The proton will have the shorter wavelength, and the electron will have the larger wavelength.
 - Electron: $3.9 \times 10^{-11} \text{ m}$
Proton: $9.1 \times 10^{-13} \text{ m}$
- 38 V
- The electron has the smaller wavelength.

12.3 Emission and absorption spectra

Sample problem 6

Arranged in ascending order, the six photon energies are 1.5 eV, 1.7 eV, 1.8 eV, 3.3 eV, 3.5 eV and 5.0 eV.

Practice problem 6



b. $\Delta E = 3.9 \text{ eV}$
 $f = 9.4 \times 10^{14} \text{ Hz}$

c. $\Delta E = 1.9 \text{ eV}$
 $f = 4.6 \times 10^{14} \text{ Hz}$

Sample problem 7

$9.7 \times 10^{-8} \text{ m}$.

This is ultraviolet radiation.

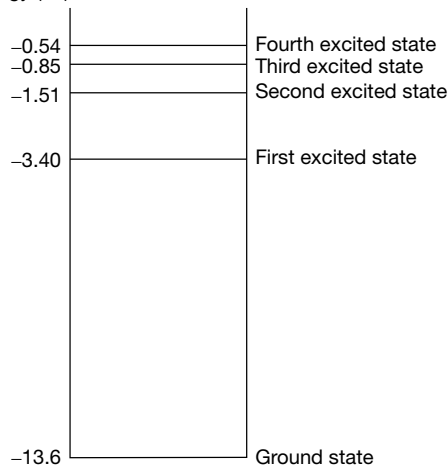
Practice problem 7

The lowest frequency is related to the smallest energy change.
The wavelength is $1.9 \times 10^{-6} \text{ m}$

12.3 Exercise

- A fire glows with a continuous range of wavelengths, and, in a red fire, the red wavelengths have the greatest intensity. Neon in a discharge tube glows red because the electrons in the neon atoms are excited to specific energies. When the electrons return to the ground state, they produce light of a few fixed wavelengths, mainly in the red part of the spectrum.
- Emission lines are produced when electrons return from an excited state to a lower energy state. The energy is released in the form of photons of particular frequencies. Absorption lines are produced when light from a continuous spectrum passes through a gas. This light excites some of the electrons in the atoms making up the gas, so photons with the energies allowed by the atoms will be removed from the continuous spectrum. As the energy required to raise an electron to a more excited state is equal to the energy released when the electrons drop back to the lower state, the emission lines and absorption lines for a particular element will be the same.
- Possible answers include refracting the light through a prism. Spectral yellow will remain yellow, whereas a mixture of green and red light will separate into two beams.
- Ground state: -10.4 eV ;
First excited state: -5.5 eV ;
Second excited state: -3.7 eV ;
Third excited state: -1.6 eV .
- a. The term 'ground state' defines the lowest energy state of an electron.

b. energy (eV)

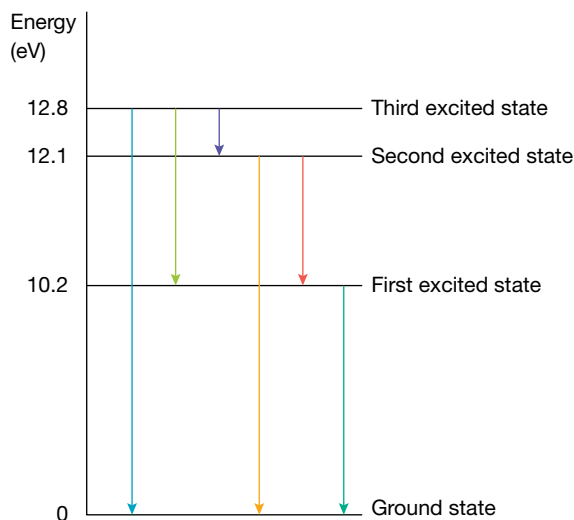


- c. The Balmer series is a collection of transitions from the 3rd, 4th, 5th and 6th excited states to the 2nd excited state in a hydrogen atom. They are grouped because each transition produces a photon in the visible part of the electromagnetic spectrum.

6.

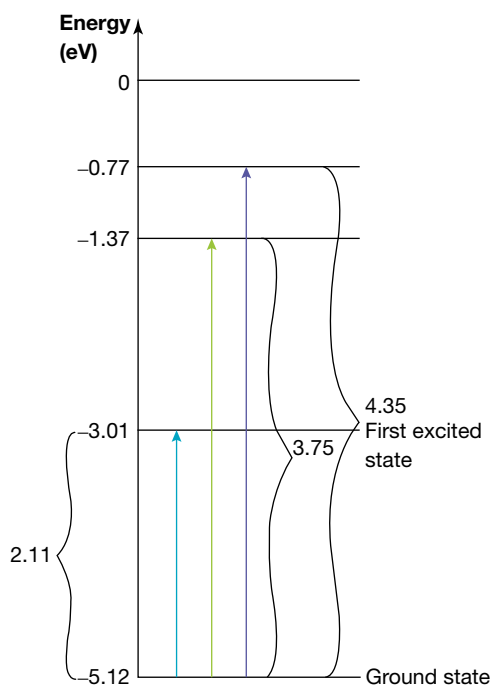
	λ (nm)	f (Hz)	E (J)	E (eV)	p (N s)
Red light	633	4.74×10^{14}	3.14×10^{-19}	1.96	1.05×10^{-27}
Electron	0.877	—	3.14×10^{-19}	1.96	7.56×10^{-25}
Blue light	405	7.41×10^{14}	4.91×10^{-19}	3.07	1.64×10^{-27}
Electron	405	—	1.48×10^{-24}	9.24×10^{-6}	1.64×10^{-27}

7. a and b



- c. $E_1 = 0.7 \text{ eV}$
 $E_2 = 2.6 \text{ eV}$
 $E_3 = 12.8 \text{ eV}$
 $E_4 = 1.9 \text{ eV}$
 $E_5 = 12.1 \text{ eV}$
 $E_6 = 10.2 \text{ eV}$

- d. The least energetic photon has an energy of 0.7 eV:
 $\lambda = 1.78 \times 10^{-6} \text{ m}$ ($1.8 \times 10^{-6} \text{ m}$)
 The greatest energy photon has an energy 12.8 eV:
 $\lambda = 9.7 \times 10^{-8} \text{ m}$ ($9.7 \times 10^{-8} \text{ m}$)
8. The dark lines in an absorption spectrum correspond to upward transitions from the ground state to excited states of atoms of a gaseous sample. The particles absorb those specific frequencies of light, and thus a continuous spectrum has these colours missing.
9. a and b



- c. First excited state:
 $5.9 \times 10^{-7} \text{ m}$
 Second excited state:
 $3.2 \times 10^{-7} \text{ m}$
 Third excited state:
 $2.9 \times 10^{-7} \text{ m}$
 The energy change from the first excited state is responsible for the yellow glow.

12.4 Making light

12.4 Exercise

- 1.90 eV
- a. Light of this wavelength corresponds to the photon energy, $E = \frac{hc}{\lambda} = 4.7 \times 10^{-19} \text{ J}$
 Electrons in helium absorb these photons, indicating there is an energy level within the helium atom that is $4.7 \times 10^{-19} \text{ J}$ above the ground state of the atom.
- b. 2.96 eV
- a b c d. continuous spectrum; temperature related; polychromatic; incoherent; non-polarised
- e. discrete spectrum; temperature independent; polychromatic; incoherent; non-polarised
- f. discrete spectrum; temperature independent; generally monochromatic; incoherent; can be polarised but still developmental
- g. discrete spectrum; temperature independent; monochromatic; coherent; generally polarised

- Different LEDs have different-sized band gaps resulting in different changes of energy for electrons moving in the LED. Hence, they emit photons of different energy.
- 2.1 eV
- $6.9 \times 10^{-7} \text{ m}$
- All photons of the same frequency in a beam of coherent light have the same phase. Each photon's wave character is synchronised with all the other photons in the beam.

12.5 Experiments exploring the duality of waves and particles

Sample problem 8

- $p = 1.0 \times 10^{-27} \text{ N s}$ in the direction of the beam
 The momentum perpendicular to the beam is 0 N s before incidence on the single slit.
- $\Delta p_x \geq 1.6 \times 10^{-28} \text{ N s}$
 On the other side of the slit, the photon has an uncertainty in its momentum perpendicular to the beam of at least $1.6 \times 10^{-28} \text{ N s}$.
- Before they reach the slit, photons have momentum parallel to the beam and zero momentum perpendicular to the beam. They all travel in a straight line towards the single slit. When they appear on the other side of the slit, they still have the same momentum in the direction of the beam, but they now have an uncertainty in their momentum perpendicular to the beam. Importantly, this uncertainty allows for the photons to have some motion either to the left or to the right of the slit.
 The uncertainty is $1.6 \times 10^{-28} \text{ N s}$, which is about $\frac{1}{6}$ of the momentum of a photon in the beam. As a result, diffraction will be readily observable.

Practice problem 8

$$5 \times 10^{-25} \text{ N s}$$

12.5 Exercise

- Δx is the uncertainty in position along the x -axis.
 Δp_x is the uncertainty in momentum along the x -axis.
 This product is greater than Planck's constant h divided by 4π .
- $2.6 \times 10^{-25} \text{ N s}$
- a. $5.3 \times 10^{-20} \text{ N s}$
 b. $1.5 \times 10^{-9} \text{ J}$ or $9.6 \times 10^9 \text{ eV}$ (or 9.6 GeV)
 c. Electrons with energy in this range are not observed.
 In addition, electrons with momentum $5.3 \times 10^{-20} \text{ N s}$ would have a velocity,
 $v = 6.0 \times 10^{10} \text{ m s}^{-1}$.
 This velocity is faster than the speed of light.
- In general terms, as the uncertainty in momentum gets smaller, the uncertainty in position increases. Thus if an object were able to be perfectly still, that is with exactly zero momentum, then the object would have associated with it a very large uncertainty in its location.
- At zero kelvin, the motion of a collection of objects will have ceased. If their momenta are zero, then, somewhat paradoxically, an uncertainty approaching infinity would exist in their location. Confining a system is associated with uncertainty in momentum, and thus an exact zero kelvin state is not attainable.
- The pattern spreads out because reducing the size of the slit decreases Δx , which is associated with an increase in Δp_x in

a beam passing through an opening. The increase in Δp_x determines a spreading out of the beam.

7. No significant diffraction would be observed because the uncertainty in the sideways momentum Δp_x in relation to the momentum of the person p walking through the door is essentially equal to zero.

Sample responses can be found in your digital formats.

8. Classical laws contain no relationship between Δx and Δp_x ; where an object is and what it is doing are independent of each other in classical physics. However, in quantum mechanics, location and movement are not independent and the uncertainties associated with each of these variables make up the Heisenberg uncertainty principle. On the very small scale, it becomes necessary to be mindful of this principle, which effectively places a boundary on what can be known simultaneously about a system.

12.6 Review

12.6 Exercise 1: Multiple choice questions

1. B
2. D
3. C
4. B
5. A
6. C
7. D
8. C
9. D
10. B

12.6 Exercise 2: Short answer questions

1. a. $\lambda_\gamma = 5.8 \times 10^{-7} \text{ m}$
 $\lambda_e = 2.6 \times 10^{-10} \text{ m}$
 The photon has the longer wavelength.
 b. $p_\gamma = 1.2 \times 10^{-27} \text{ N s}$
 $p_e = 2.6 \times 10^{-24} \text{ N s}$
 The electron has the larger momentum.
 c. $E_\gamma = 3.5 \times 10^{-19} \text{ J}$
 $E_e = 3.6 \times 10^{-18} \text{ J}$
 The electron has the larger energy.
2. a. $p_\gamma = 1.6 \times 10^{-27} \text{ N s}$
 $p_e = 9.3 \times 10^{-25} \text{ N s}$
 The electron has the larger momentum.
 b. $\lambda_\gamma = 4.1 \times 10^{-7} \text{ m}$
 $\lambda_e = 7.1 \times 10^{-10} \text{ m}$
 The photon has the longer wavelength.
 c. As the energy of the photon and electron increases, the momentum of both also increases, but the momentum of the photon increases at a faster rate than the momentum of the electron since $p_\gamma \propto E_\gamma$ but $p_e \propto \sqrt{E_e}$. The wavelengths of both the photon and the electron will decrease as their momentum increases, as wavelength is inversely proportional to momentum.
3. The observation that a beam of electrons directed at a thin crystal will diffract is strong evidence for the wavelike behaviour of individual electrons in the beam. Objects modelled as particles do not display diffraction.

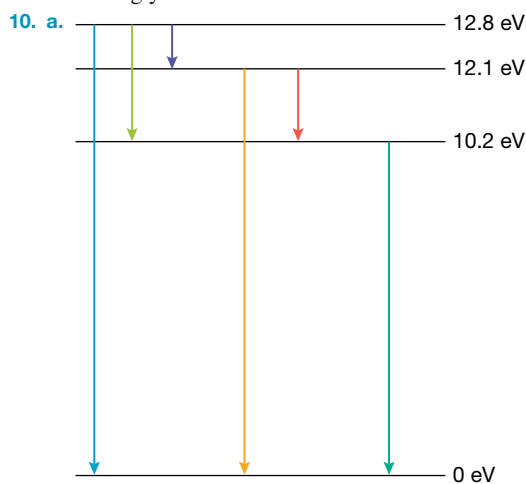
4. In a typical emission spectrum, a series of discrete coloured lines is observed. These lines occur due to atomic transitions from one energy level to a lower energy level within each excited atom. In an absorption spectrum, a continuous spectrum consisting of all colours with black lines is observed. The missing colours (where the black lines are positioned) occur when atoms in their ground state are excited into a higher energy state by the absorption of photons of specific energy consistent with the dark lines in an otherwise continuous spectrum.

5. $1.5 \times 10^4 \text{ V}$

6. The light emitted from an incandescent source consists of a continuous spectrum dependent only on the temperature of the source. The light emitted from a neon discharge tube consists of a number of coloured lines giving rise to a discrete spectrum. These lines are determined by the specific energy levels associated with that atom.

7. $7.3 \times 10^{-7} \text{ m}$

8. In a diode, electrons move across a junction, referred to as a p-n junction, and undergo an energy loss. This loss of energy by an electron is associated with the emission of a single photon with that amount of energy. Different types of LEDs are capable of producing different energy losses as electrons move across the junction, producing photons of different energy and hence different colour.
9. X-rays can be used to generate diffraction patterns when the rays are passed through samples. A diffraction pattern can be used to deduce the atomic structure of the samples. An example is the atomic structure of DNA, which was deduced by X-ray diffraction. Synchrotron radiation is accordingly used in medical research.



- b. 12.8 eV, 2.6 eV, 0.70 eV, 12.1 eV, 1.90 eV and 10.2 eV
 c. The photon with the least energy is 0.70 eV. Its wavelength is $\lambda_\gamma = 1.8 \times 10^{-6} \text{ m}$
11. a. i. 1.8 eV
 ii. $f = 4.3 \times 10^{14} \text{ Hz}$ $\lambda_\gamma = 6.9 \times 10^{-7} \text{ m}$
 b. $1.4 \times 10^{-7} \text{ m}$
12. When the width of the slit Δx is decreased, the uncertainty in the x -direction momentum Δp_x increases in accordance with the uncertainty principle. The diffraction pattern will spread out due to the increased uncertainty Δp_x .

12.6 Exercise 3: Exam practice questions

- The pattern indicates that both X-rays and electrons exhibit diffraction, which is a property associated with waves.
 - The rings of equal diameter indicate that the X-rays and electrons used have the same wavelength. In the case of X-rays, it is the wavelength of the electromagnetic radiation; in the case of electrons, it is the de Broglie wavelength.
 - 3.8×10^{-7}
- Both beams of electrons will produce a diffraction pattern. In the second experiment, the momentum of the electrons p will be twice as great compared to the first, but the uncertainty in momentum in the direction perpendicular to the motion of the electrons Δp_x will be the same. The diffraction pattern will be more compressed compared to the first experiment.

Essentially this is because the ratio $\frac{\Delta p_x}{p}$ is halved from experiment 1 to experiment 2.

- Spectrum 1 is source A.
 - Spectrum 2 is source C.
 - Spectrum 3 is source B.

- 4.30×10^{14} Hz
 - 2.8×10^{-7} m

- In the first model, the electron modelled as a particle is in a circular orbit and thus accelerating. Classical theory predicts that the accelerating electron would continuously emit light and hence spiral into the nucleus. Atoms are inherently unstable using this model and not consistent with observation. The second model treats the electron as a type of standing wave — a resonance. The standing wave is considered stable and does not emit a photon. Only transitions from a higher energy state to a lower energy state are associated with the emission of a single photon. This second model is consistent with observations of emission spectra.

13 Practical investigation

13.2 Key science skills in physics

Sample problem 1

Research question

Does the type of salt added to water impact the time it takes for water to boil?

Aim

To determine if different types of salts impact the time it takes for water to boil.

Hypothesis

If table salt, sea salt, Himalayan pink salt or chicken salt is added to water, then the time taken for the water to boil will decrease when salt is added, with pure table salt causing the largest decrease in time.

Practice problem 1

Research question

Does the type of clothing material affect the speed at which a person will roll down a hill?

Aim

To determine if different clothing materials impact the speed a person rolls down a hill.

Hypothesis

If an individual wears a smooth fabric such as silk, then they will have a faster speed when rolling down a hill compared to wearing a rougher fabric (such as wool).

13.2 Exercise

- To be a testable question, the question must be practicable, it must link the independent and dependent variables, and it must be investigable through the scientific method. Sample responses are:
 - How does the type of surface of a tennis court affect the height at which a ball bounces?
 - How does the addition of extra resistors in parallel in electric circuits affect the current travelling through the resistors?
 - What differences are there between the strength of the magnetic fields for iron and nickel?
- A logbook is important as it shows evidence of each step of an investigation, allowing work to be validated as your own.
- B.
- Decide on a topic
 - Formulate a question
 - Create an aim and hypothesis
 - Select equipment
 - Create a clear and reproducible method that will produce precise, accurate, valid and reliable results
 - Complete a risk assessment
 - Submit a practical proposal to your teacher.
- To investigate how the shape of a parachute affects the time it remains floating in the air.
 - If circular, square and triangular parachutes are dropped from a similar height, then the circular parachute will take the longest to hit the ground due to a larger surface area and increased air resistance when released from the same height.

13.3 Variables

13.3 Exercise

- The dependent variable is measured by the investigator and is influenced by the independent variable. The independent variable is manipulated and changed by the investigator.
- To make sure that the dependent variables measured are only influenced by the independent variable and not unfairly influenced by other factors. If variables are not controlled, trends and patterns cannot be accurately determined as

another factor other than the one being investigated may have influenced the results.

3. a. These variables are independent as they are being manipulated and changed by Belinda and Paul as part of their investigation.
- b. i. Categorical ii. Numerical
iii. Numerical iv. Categorical
v. Numerical vi. Categorical
- c. Examples include Speed of the ball after impact, distance travelled by the ball after impact.

13.4 Concepts specific to investigations (key terms and representations)

Sample problem 2

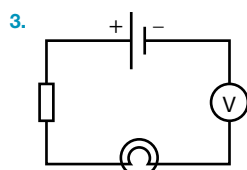
- a. 1.496×10^8 km b. 1.67×10^{-24} g

Practice problem 2

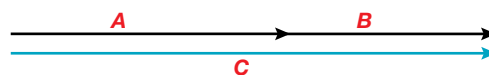
- a. 6.37×10^6 m
- b. 3.0×10^8 m s⁻¹
- c. 3×10^{-10} m

13.4 Exercise

1. Key terms can be defined either within the body of a report or in a glossary at the end, with the key words set in bold font throughout the body and defined in the glossary.
2. Representations are useful in scientific reporting as they allow researchers to show complex and abstract concepts in a form that is easy to understand, enhancing the clarity in scientific communication.



4. a. 7.15×10^4 km
b. 9.46×10^{12} km (the number of significant figures is not specified, so you may have chosen to list them all in this answer).
c. 8×10^{-7} m
5. $A + B = C$



13.5 Scientific research methodologies and techniques

Sample problem 3

- a. Student 2
- b. Student 1
- c. Student 3 had the most accurate data and student 2 had the most precise data.

Practice problem 3

- a. Student 1
- b. Student 1
- c. The student with the most precise data was student 2, and the student with the most accurate data was also student 2.

13.5 Exercise

1. Reliability is linked to the repeatability and reproducibility of an investigation and whether someone can follow your protocol and get similar results. Validity, however, is concerned with the credibility of the data, that is, whether the data shows what the investigation was designed to do.
2. Yes — an experiment needs to be replicated in order for it to be seen as reliable.
3. Results would not be considered reliable if repetitions of an investigation lead to vastly different results.
4. Sample answers:
 - Not correctly testing the variable outlined in the hypothesis
 - Misinterpreting measurements
 - Not controlling variables correctly
 See table below, at the bottom of the page.*
5. A valid experiment is free from any form of bias and involves correctly controlled variables, and provides an answer to the question under investigation. Therefore, it must be reliable, as other investigators should get the same results when controlling the same variables and following the same methodology. However, a method can be reliable (obtaining the same results every time) but not address the hypothesis and the question, therefore making the investigation invalid.

*4.

	Independent variables		Dependent variables
	NUMERICAL	CATEGORICAL	
(a) Performance of a parachute	- Size of the parachute - Angle at which the parachute is thrown - Height from which the parachute is dropped - Speed of the wind	- Type of material used - Shape of the parachute - Conditions in which the parachute is dropped (e.g. rainy, windy, indoors)	- Time to reach the ground - Speed - Force of impact on the ground
(b) The temperature inside cars	- Outside temperature - Time left outside	- Colour of the car - Brand of car - Type of material of seats - Location of car	- Temperature - Heat energy
(c) Movement of a ball down a hill	- Angle of the slope - Size of the ball	- Type of ball - Surface of the hill	- Time to reach the bottom - Speed of ball

- Precision is a measure of how close various measurements are to one another. Accuracy is how close a quantity is to the expected (and known) result.
- A strength of quantitative data is that it provides a clearer understanding of trends and patterns in results. A weakness is that it can be harder and more time-consuming to collect. A strength of qualitative data is that it is often easy and quick to collect. A weakness is that it can be subjective (e.g. one person might class a colour as blue, and another might state that it is purple).
- Primary data comes from the initial source, often through direct investigation, which allows for patterns to be observed more clearly without the impact of another source. Secondary data has often been interpreted, evaluated and analysed, so there is the possibility that the message has been misinterpreted and may not be specific to the investigation that was conducted.

13.6 Health and safety guidelines

13.6 Exercise

- The contents of batteries are corrosive, so care is needed in the case of leakages. A battery can heat up easily, which can lead to the rupture of the case. Appropriate precautions include keeping batteries in a dry location, checking for leaks and being careful not to cut open a battery.
 - Light globes can reach high temperatures, which may lead to burns. Light globes are made of glass, so they may break or chip, leading to lacerations. Appropriate precautions include reporting and sweeping up broken glass, and not touching lights globe while they are in use.
 - Matches are sources of ignition and can lead to burns. Safety precautions include keeping matches dry, lighting a match before turning on a gas source and ensuring the match is properly extinguished after use.
 - Measuring cylinders, being made of glass, can break or chip, leading to possible cuts or lacerations. Appropriate precautions include immediately reporting and sweeping up broken glass and discarding any that are damaged, as they are prone to breaking once damaged.
 - Iron fillings are small with sharp edges that may cause injury, particularly to the eyes. Safety glasses should be worn.
- Ethics may be important when confidentiality is involved, as in the conducting of an opinion survey.
- Sample answers:
 - Identifying hazards with equipment or chemicals
 - Suggesting standard handling procedures
 - Outlining the correct disposal of chemicals
 - Outlining any first aid that may be required
 - Providing information for the investigation, including the location, time and date
- Information about devices used such as specific voltages, information about allergies, details for emergency hotlines, clear information about how many students will be in each group and at each bench.
- In any plan drawn, you should show the emergency gas and electricity shut-offs, the locations of fire blankets and extinguishers, the exits, windows, locations of safety glasses, lab coats and gloves, and the locations of the fume cupboards, taps, eye wash station and emergency shower.

Other safety features may also include the locations of locked cupboards, the locations of cleaning equipment (including spill kits) and the location where broken glass should be disposed.

13.7 Methods of organising, analysing and evaluating primary data

Sample problem 4

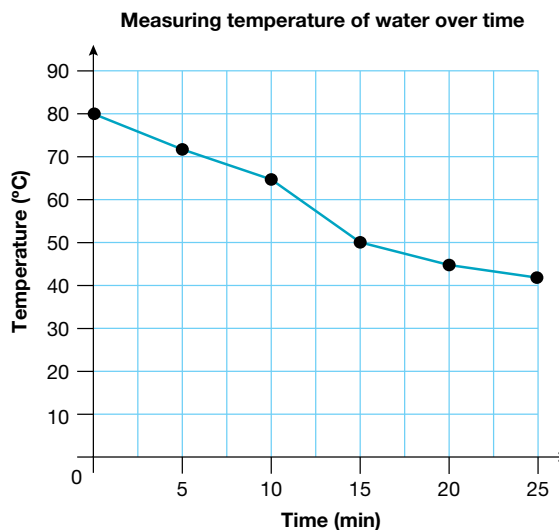
- 128.93 ± 0.005 g.
- 47 ± 0.25 °C.

Practice problem 4

0.8 ± 0.05 g.

13.7 Exercise

- A random error is a chance variation in measurements and usually affects the precision of data. Random errors can be eliminated by repeating the experiment. A systematic error usually affects the accuracy of an experiment and is often due to equipment errors; therefore, systematic errors cannot be improved by repeating the experiment using the same equipment.
Sample responses can be found in your digital formats.
- Taking multiple results and averaging them, or by using more precise equipment (e.g. if measuring 23 mm, use a ruler with marks every 1 mm, rather than a measuring tape that has marks every 1 cm).
- A bar graph would be most appropriate, as one variable is qualitative (athlete) and the other is quantitative (height of jump).
 - A line graph would be most appropriate as a variable (voltage of battery) is being observed over time.
 - A line graph would be most appropriate as both variables (temperature and height) are quantitative and a line graph would allow for trends to be seen. However, a scatterplot with a line of best fit may also be appropriate.
 - A histogram would be most appropriate as frequency and intervals would be used (due to the large number of options for an ATAR score).
- The following line graph would be an appropriate choice.



The graph shows that, as time passes, the temperature decreases, showing a negative correlation between time and temperature. The rate of temperature decrease changes over time, being faster between 10 and 15 minutes (with a drop of 15 °C) and slower between 20 and 25 minutes (with a drop of 3 °C). This may be due to minor changes in room temperature, which impacted results.

5. An outlier should be mentioned and discussed, with an outline of possible reasons. However, outliers are usually excluded when calculating averages or determining lines of best fit.
6. a. 9.5 ± 0.25 cm b. 8.5 ± 0.125 cm
c. 11.9 ± 0.05 cm
7. a. 60 W b. 40 W c. 180 W d. 20 W

13.8 Models and theories to understand observed phenomena

13.8 Exercise

1. Models can be useful for the following reasons:
 - They allow the visualisation of objects and concepts that can't be seen (e.g. atoms).
 - They make abstract concepts tangible.
 - They provide explanatory frameworks for a variety of chemical concepts, allowing for more in-depth exploration.
2. Some limitations of models include the following:
 - They can oversimplify complex situations, as models cannot show every detail.
 - They can misrepresent the concept in the real world, when conditions are not as carefully controlled.
 - The ever-changing nature of models and research means that models aren't definite.
3. A model is a representation of a phenomenon, whereas a theory is a well-supported explanation of a phenomenon. Often, a model is used to represent a theory.
4. Theories allow you to understand phenomena as they are based on investigations and observations, providing a structured idea that can be applied to different concepts.

13.9 Nature of evidence and key findings of investigations

13.9 Exercise

1. Hypotheses are supported by the evidence present at the time. However, the nature of evidence is that, as new knowledge becomes available, the evidence can be interpreted differently. Therefore, a hypothesis cannot be proven but, rather, supported with the current evidence and how it is interpreted at a given point in time.
2. Three examples of strong evidence include:
 - quantitative data obtained when investigating a single variable
 - data that has not been influenced by bias
 - data that has been obtained through a reliable method and repeated and obtained by other investigators.
3. Key findings communicated in your discussion should include information about trends and patterns in your data, the relationship to chemical concepts and theory, and a clear answer to the question of your investigation.
4. Linking results to concepts can show how results and theory can be used to support phenomena observed in a practical

investigation. It gives an investigation more validity and helps to better back up conclusions and findings.

13.10 Conventions of scientific report writing and scientific poster presentation

Sample problem 5

- a. 12 412 μL b. 261.53 dg c. 8 700 000 000 nm

Practice problem 5

- a. 4.5215 km b. 213 000 ns

Sample problem 6

0.87 g mL^{-1}

Practice problem 6

0.463 g L^{-1}

13.10 Exercise

1. a. 1.5 A b. 520 m c. 0.000 150 s
2. a. 65 200 cm b. 8 673.628 mg
3. a. The introduction is used to summarise key background concepts, explain other research that has been done in the field, outline key terms, explain the purpose of your investigation (and why you chose the question) and to outline the hypothesis being explored.
b. The discussion is used to outline any trends and patterns in your data; describe any outliers and how they were treated; evaluate your results and link them to theory; discuss any errors, uncertainties and limitations; describe the precision, accuracy, reliability and validity of your investigation; and suggest improvements and future investigations.
c. The conclusion acts to sum up your investigation and to provide a clear answer to your question, linking back to your aim and your hypothesis.
4. *In-text:* (O'Keeffe et. al, 2020)
Reference list: O'Keeffe, D, Lofts, G, Anderson, M, Pentland, P, Phillips, R, Robertson, P, Livett, M, Pearce, J, (2020). *Jacaranda Physics 2*, 4th edition, Milton: John Wiley & Sons.
5. a. 4 significant figures b. 3 significant figures
c. 3 significant figures d. 5 significant figures
6. a. 15.8 m
b. 770 m^2

13.11 Review

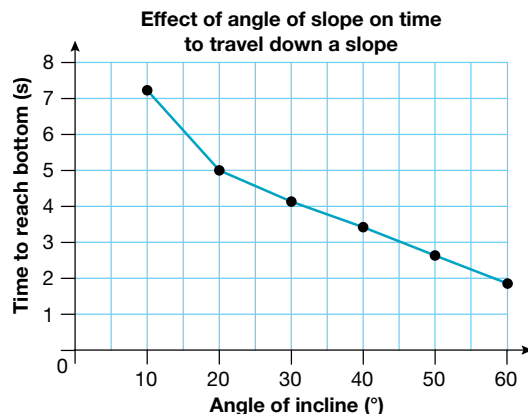
13.11 Exercise 1: Multiple choice questions

1. B
2. B
3. A
4. D
5. C
6. A
7. D
8. C
9. A
10. B

13.11 Exercise 2: Short answer questions

1. a. The angles at which the different colours deviate, the number of colours that appear from the prism and the wavelengths of the light.
b. You would use a protractor to measure the angles or a spectrometer to measure the wavelength.
c. The colour of the light that comes through the prism the type of prism used and the material the prism is made of.
d. These are through visual observation — a spectrometer will also allow the colours to be more easily seen.
2. a. An independent variable is manipulated by the investigator. Dependent variables are measured and are the result of changes to the independent variable.
b. Qualitative data is categorical (e.g. eye colour, type of metal), whereas quantitative data is numerical (e.g. distance, voltage).
c. A control group provides a point of comparison because it does not have the independent variable applied to it, whereas the experimental groups are impacted by the independent variable.
d. Primary sources are the initial sources of data collection, often through direct investigations. Secondary sources are summaries of primary data that has been collected by another individual.
e. Uncertainty is concerned with the limit to the precision of a piece of equipment. Error is concerned with factors affecting the accuracy of the experiment and how close results are to their true values.
3. a. 4 significant figures
b. 6.24×10^{-2}
4. a. To determine how the temperature of the hotplate and the size of a water droplet affects how long the water droplet can last on a hot plate.
b. IV: Choice of eye dropper (numerical — discrete, as the investigation was based on using more than one eye dropper, each of which provided a water droplet of unique size) and the temperature setting (numerical — discrete, as the hot plate was set to a specific temperature setting for each droplet).
DV: Time each drop lasted (numerical — continuous, as the time could be any value above 0 seconds).
c. It can be seen that, the larger the size of a water droplet, the longer the droplet can last on the hot plate. Regarding the hot plate temperature, the higher the temperature setting, the shorter the time the droplet will last.
d. Chris tested too many variables and did not show how he controlled the variables. He also chose a method of selecting water droplet size as being determined by which eye dropper he used; this means things such as the shape and diameter of the droplet were not well controlled. He did not record the exact temperature of the surface of the hot plate — the different settings might not have been equal distances apart. For example, settings 1 and 2 could have been 10 °C apart, but settings 5 and 6 could have been 20 °C apart.
e. Other independent variables could be different types of water (tap water versus bottled), water with different initial temperatures, and water droplets with different surface areas.
f. Using a ruler to calculate the droplet size would be appropriate in this case.

5. a. The graph should have a clear heading, scale and labelled axis, such as the one shown here:



- b. As the angle of incline increases, the time for the object to reach the bottom decreases, so it travels faster. This decrease in time is mostly linear, with the exception of when the angle is increased from 10° to 20°, where the change in time was much more significant (2.2 seconds difference between the two angles). On average, the time to reach the bottom of the ramp decreased by approximately 0.8 seconds for every 10° that the angle of the slope was increased.
- c. Increasing the angle of incline of a ramp, making it steeper, decreases the time for an object to slide down the ramp and reach the bottom.

13.11 Exercise 3: Exam practice questions

1. a. The time taken for the droplet to be absorbed.
b. Any two of the following:
 - The size of the water droplet placed on the speaker (both the volume and area)
 - The speaker and generator used
 - The source of the water
 - The watch glass used
 - The conditions in the room (e.g. room temperature).
- c. (i) the eye dropper, with clear graduation (lines of measurement), and (ii) a stopwatch.
Some factors that may affect the accuracy of the equipment include: Bubbles affecting measured volume, inaccuracies in measuring volume, time and point the droplet is absorbed.
- d. Responses will vary. Sample responses can be found in your digital formats. Students need to ensure that the method is reproducible, including quantities and controlled variables.
2. a. To investigate how changing the mass using slotted weights at the end of a string affects the period of a pendulum.
b. The hypothesis must clearly link the independent variable and the dependent variable, and must be tentative and testable. Sample response: If an increasing number of slotted weights is added to the end of the string on a pendulum, then the period will decrease, as the added mass will allow the pendulum to move faster.
c. Qualitative data: (i) if the object is moving fast or slow, (ii) the direction of movement or (iii) speeding up/slowing

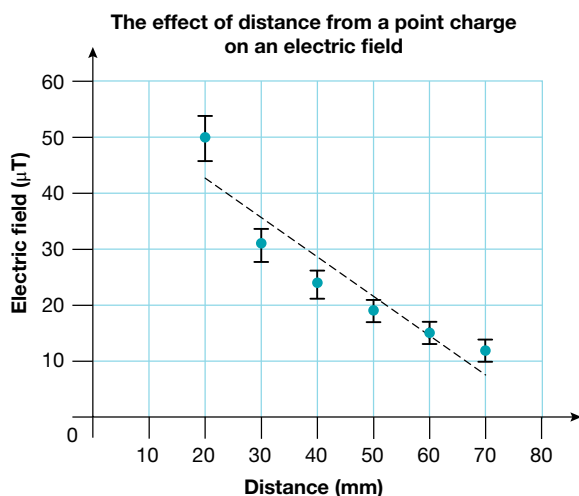
down. Quantitative data: (i) the time taken for one period, (ii) the speed of the object.

- d. Factors that may lead to different results between students include:

- Different precision in their timing of the measurements
- Different slotted masses used
- Different angle at which the slotted masses attached to the pendulum are released
- Different lengths of string.

- e. Sample response available in your digital formats. Students need to ensure that the method is reproducible, including quantities and controlled variables.

3. a.



- b. Some trends shown in the data include the following:
- A negative correlation/downward trend exists, in which the electric field decreases as the distance increases.
 - The data point at 20 mm is an outlier.
 - The trend is not perfectly linear.
 - The electric field drops approximately $7 \mu\text{T}$ for every 10 mm.
 - As the electric field gets smaller, the error bars get smaller.
- c. Error bars allow the uncertainty in the measurements to be more easily observed, indicate whether the reported data is close to the true value and therefore whether the interpretation of data could be affected.

4. a. Errors that may have occurred include the following:

- *Faulty scales:* Make sure that all scales have been calibrated, or record the mass using three different scales and get an average.
- *Imprecise ruler:* Record the compression using three different rulers and get an average.

- *Compression or mass being incorrectly recorded:* Repeat the experiment multiple times and take an average or get another student to check the measurement.

- b. Brian: 0.20 J

Michael: 0.25 J

- c. In applying Hooke's Law, the spring constant should be the same, regardless of the mass used. Brian's data only deviated by 4.3 N m^{-1} , whereas Michael's data deviated by 8.9 N m^{-1} . Therefore, Brian's data is more accurate than Michael's data.

- d. 4850 N cm^{-1}

5. a. The student hasn't identified both independent variables in their hypothesis nor have they mentioned the dependent variable (voltage), so their hypothesis is not testable.

A example of a hypothesis may be: If caesium, rubidium, potassium and sodium are used in a photocell with increasing frequencies of incident light, then caesium will have the highest recorded stopping voltage, and the stopping voltage will increase as the frequency increases.

- b. An ammeter would display the current as 0 A when it is between -0.5 A and 0.5 A . Therefore, an accurate reading of the current at 0 A would be impossible to take.
- c. The tolerance or uncertainty of a device is half the smallest measurement displayed; therefore, the tolerance is 0.05 V. This means there is a level of uncertainty with the data and the results obtained by each individual are not as accurate as they could be (for example, for caesium at the lowest frequency, the result may actually be 2.05 V or 1.95 V, leading to some inaccuracy in the data and the conclusion drawn).

- d. Sample answers:

- The inability to get a completely accurate reading
- The inability to control light other than the incident light (i.e. the inability to control the light in the classroom)
- A lack of a calibration procedure
- A lack of repetition in the investigation.

- e. Line graph with the data for the four types of metals superimposed. This is the best choice as both the frequency and voltage are quantitative.

- f. Sample conclusion: It was found that caesium has the highest stopping voltage, following by rubidium, potassium and, finally, sodium, when used in a photocell. It was also found that increasing the frequency of the incident light increased the stopping voltage. The hypothesis in this investigation was supported, as caesium has the highest stopping voltage compared to the other metals at the same frequency.

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