STUDY AND REVISION GUIDE

Working for over 30 YEARS with Cambridge Assessment International Education

Cambridge IGCSE™

Physics

Third Edition

Mike Folland
Catherine Jones

Boost

HODDER EDUCATION

STUDY AND REVISION GUIDE

Working for over 25 YEARS WITH Cambridge Assessment International Education

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Contents

Answers to exam-style questions are available at:
www.hoddereducation.co.uk/cambridgeextras

Introduction

Welcome to the Cambridge IGCSE™ Physics Study and Revision Guide. This book has been written to help you revise everything you need to know and understand for your Physics exam. Following the Physics syllabus, it covers all the key Core and Extended content and provides sample questions and answers, as well as practice questions, to help you learn how to answer questions and to check your understanding.

How to use this book

Key objectives

The key skills and knowledge covered in the chapter. You can also use this as a checklist to track your progress.

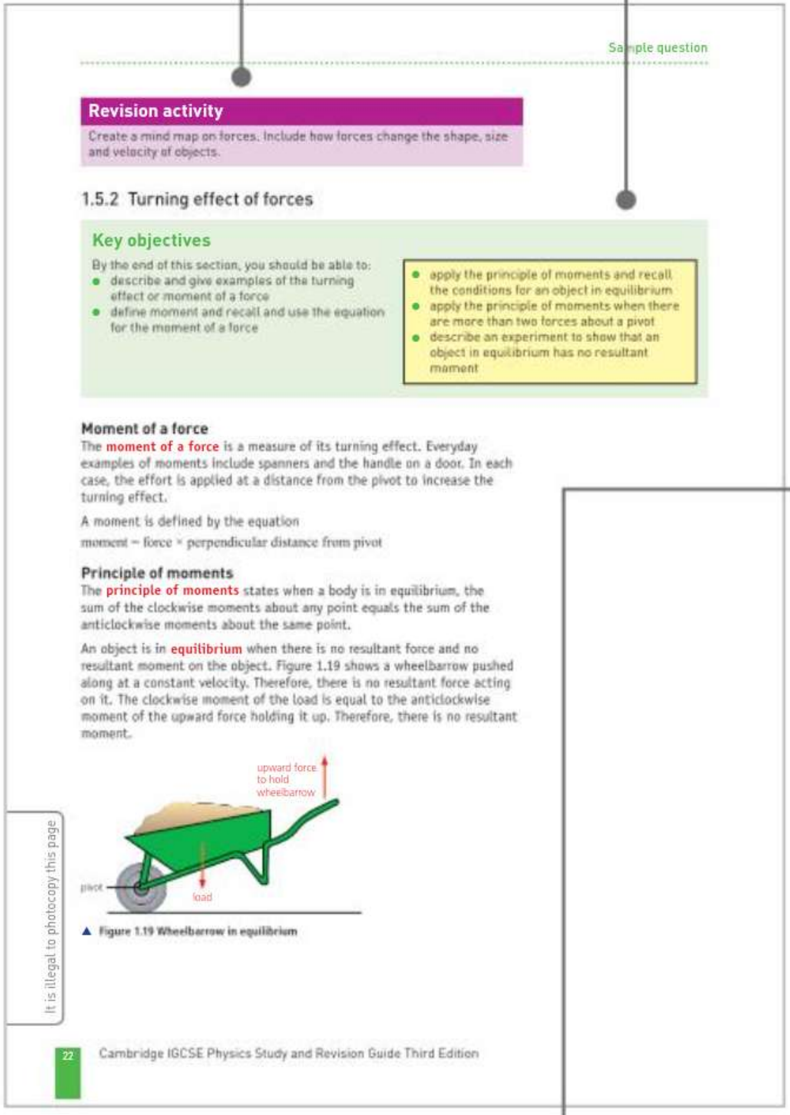
Skills

Key practical skills coverage will help you to consolidate your understanding of practical work you have undertaken in your lessons, and to describe and evaluate these skills effectively.

Key mathematical skills are covered to help you to demonstrate these skills correctly.

Revision activities

Examples of strategies to help you revise effectively.


Sample question

Revision activity

Create a mind map on forces. Include how forces change the shape, size and velocity of objects.

1.5.2 Turning effect of forces

Key objectives

By the end of this section, you should be able to:
- describe and give examples of the turning effect or moment of a force
- define moment and recall and use the equation for the moment of a force
- apply the principle of moments and recall the conditions for an object in equilibrium
- apply the principle of moments when there are more than two forces about a pivot
- describe an experiment to show that an object in equilibrium has no resultant moment

Moment of a force

The **moment of a force** is a measure of its turning effect. Everyday examples of moments include spanners and the handle on a door. In each case, the effort is applied at a distance from the pivot to increase the turning effect.

A moment is defined by the equation

moment = force × perpendicular distance from pivot

Principle of moments

The **principle of moments** states when a body is in equilibrium, the sum of the clockwise moments about any point equals the sum of the anticlockwise moments about the same point.

An object is in **equilibrium** when there is no resultant force and no resultant moment on the object. Figure 1.19 shows a wheelbarrow pushed along at a constant velocity. Therefore, there is no resultant force acting on it. The clockwise moment of the load is equal to the anticlockwise moment of the upward force holding it up. Therefore, there is no resultant moment.

▲ Figure 1.19 Wheelbarrow in equilibrium

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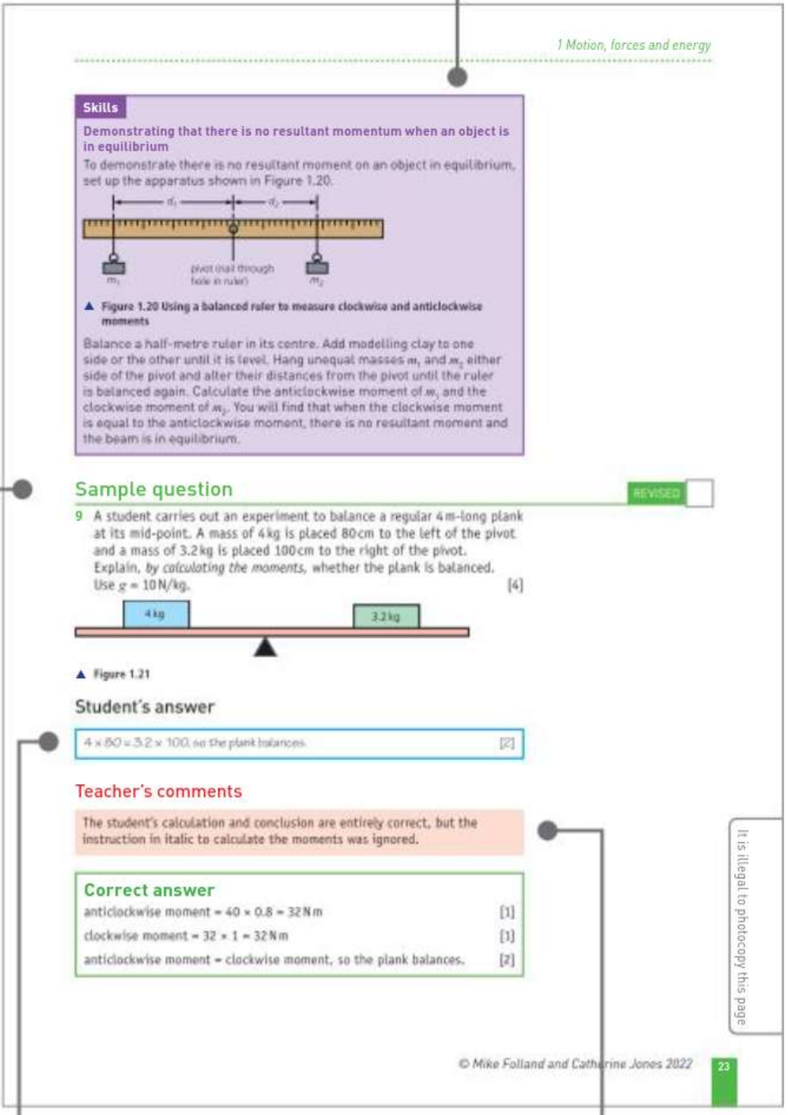
1 Motion, forces and energy

Skills

Demonstrating that there is no resultant momentum when an object is in equilibrium

To demonstrate there is no resultant moment on an object in equilibrium, set up the apparatus shown in Figure 1.20.

▲ Figure 1.20 Using a balanced ruler to measure clockwise and anticlockwise moments

Balance a half-metre ruler in its centre. Add modelling clay to one side or the other until it is level. Hang unequal masses m_1 and m_2 either side of the pivot and alter their distances from the pivot until the ruler is balanced again. Calculate the anticlockwise moment of m_1 and the clockwise moment of m_2. You will find that when the clockwise moment is equal to the anticlockwise moment, there is no resultant moment and the beam is in equilibrium.

Sample question REVISED

9 A student carries out an experiment to balance a regular 4 m-long plank at its mid-point. A mass of 4 kg is placed 80 cm to the left of the pivot and a mass of 3.2 kg is placed 100 cm to the right of the pivot. Explain, *by calculating the moments*, whether the plank is balanced. Use g = 10 N/kg. [4]

▲ Figure 1.21

Student's answer

4 × 80 = 3.2 × 100, so the plank balances [2]

Teacher's comments

The student's calculation and conclusion are entirely correct, but the instruction in italic to calculate the moments was ignored.

Correct answer

anticlockwise moment = 40 × 0.8 = 32 N m [1]

clockwise moment = 32 × 1 = 32 N m [1]

anticlockwise moment = clockwise moment, so the plank balances. [2]

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Sample questions

Exam-style questions for you to think about.

Student's answers

Typical student answers to see how the question might have been approached.

Teacher's comments

Feedback from a teacher, showing what was good, and what could have been improved.

Correct answers

Model student answers, based on the teacher's comments on the typical student answers.

Exam-style questions

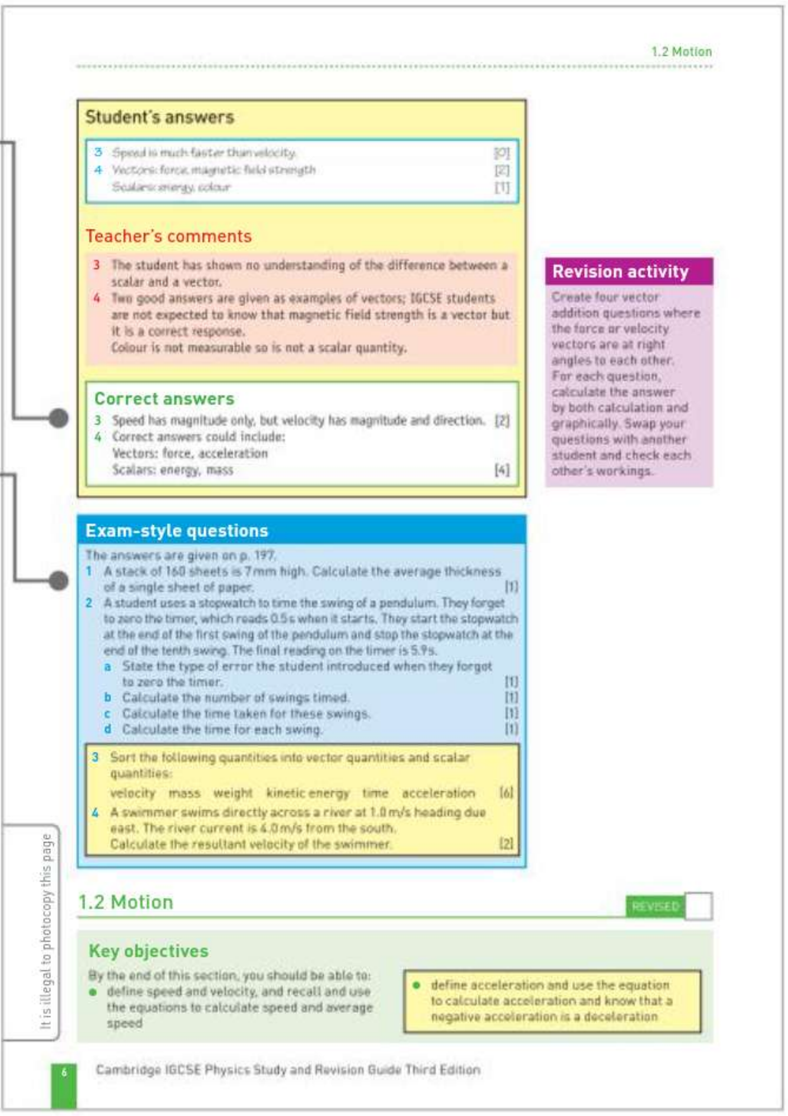
Practice questions, set out as you would see them in the exam paper, for you to answer so that you can check what you have learned.

Extended syllabus

Content for the Extended syllabus (Supplement material) is shaded yellow.

Answers

Worked answers to the Exam-style questions can be found at: **www.hoddereducation.co.uk/cambridgeextras**


1.2 Motion

Student's answers

3 Speed is much faster than velocity. [0]
4 Vectors: force, magnetic field strength [2]
Scalars: energy, colour [1]

Teacher's comments

3 The student has shown no understanding of the difference between a scalar and a vector.
4 Two good answers are given as examples of vectors; IGCSE students are not expected to know that magnetic field strength is a vector but it is a correct response.
Colour is not measurable so is not a scalar quantity.

Correct answers

3 Speed has magnitude only, but velocity has magnitude and direction. [2]
4 Correct answers could include:
Vectors: force, acceleration
Scalars: energy, mass [4]

Revision activity

Create four vector addition questions where the force or velocity vectors are at right angles to each other. For each question, calculate the answer by both calculation and graphically. Swap your questions with another student and check each other's workings.

Exam-style questions

The answers are given on p. 197.
1 A stack of 160 sheets is 7 mm high. Calculate the average thickness of a single sheet of paper. [1]
2 A student uses a stopwatch to time the swing of a pendulum. They forget to zero the timer, which reads 0.5 s when it starts. They start the stopwatch at the end of the first swing of the pendulum and stop the stopwatch at the end of the tenth swing. The final reading on the timer is 5.9 s.
a State the type of error the student introduced when they forgot to zero the timer. [1]
b Calculate the number of swings timed. [1]
c Calculate the time taken for these swings. [1]
d Calculate the time for each swing. [1]
3 Sort the following quantities into vector quantities and scalar quantities:
velocity mass weight kinetic energy time acceleration [6]
4 A swimmer swims directly across a river at 1.0 m/s heading due east. The river current is 4.0 m/s from the south.
Calculate the resultant velocity of the swimmer. [2]

1.2 Motion

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Key objectives

By the end of this section, you should be able to:
- define speed and velocity, and recall and use the equations to calculate speed and average speed
- define acceleration and use the equation to calculate acceleration and know that a negative acceleration is a deceleration

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Exam breakdown

You will take three examinations at the end of your studies. If you have studied the Core syllabus content you will take Paper 1 and Paper 3, and either Paper 5 or Paper 6. If you have studied the Extended syllabus content (Core and Supplement) you will take Paper 2 and Paper 4, and either Paper 5 or Paper 6.

Paper 1: Multiple choice (Core)	Paper 3: Theory (Core)
45 minutes	1 hour 15 minutes
40 marks	80 marks
40 four-option, multiple-choice questions based on the Core subject content	Short-answer and structured questions based on the Core subject content
30% of your grade	50% of your grade

Paper 2: Multiple choice (Extended)	Paper 4: Theory (Extended)
45 minutes	1 hour 15 minutes
40 marks	80 marks
40 four-option, multiple-choice questions, based on the Core and Supplement subject content	Short-answer and structured questions, based on the Core and Supplement subject content
30% of your grade	50% of your grade

Paper 5: Practical test	Paper 6: Alternative to practical
1 hour 15 minutes	1 hour
40 marks	40 marks
Questions will be based on the experimental skills in Section 4	Questions will be based on the experimental skills in Section 4
20%	20%

How to prepare for your examinations

Here are a few summary points to guide you:

- Use this book – it has been written to help students achieve high grades.
- Learn all the work – low grades are nearly always attributable to inadequate preparation. If you can recall the work and show understanding of it, you will succeed. Do not leave things to chance.
- Practise skills such as calculations, equation writing, labelling diagrams and the interpretation of graphs.
- Use past papers to reinforce revision, to become familiar with the types of question and to gain confidence.
- Answer each question as instructed on the paper – be guided by the key words used in the question (describe, explain, state etc.). Do not accept a question as an invitation to write what you know about the topic.

Examination terms explained

The examination syllabus gives a full list of the command terms used by in the exam and how you are expected to respond. This is summarised below.

Command word	Explanation
Calculate	Work out from given facts, figures or information
Compare	Identify/comment on similarities and/or differences
Define	Give the precise meaning
Describe	State the points of a topic / give the characteristics and main features
Determine	Establish an answer using the information available
Evaluate	Judge or calculate the quality, importance, amount or value of something
Explain	Set out purposes or reasons / make the relationships between things evident / state why and/or how, and support with relevant evidence
Give	Produce an answer from a given source or use recall/memory
Identify	Name/select/recognise
Outline	Set out the main points briefly
Predict	Suggest what may happen, based on available information
Sketch	Make a simple freehand drawing, showing the key features, and taking care over proportions
State	Express in clear terms
Suggest	Apply knowledge and understanding to situations where there is a range of valid responses, in order to make proposals / put forward considerations

1 Motion, forces and energy

Key terms

REVISED

Term	Definition
Acceleration of free fall, *g*	For an object near to the surface of the Earth this is approximately constant and is approximately 9.8 m/s^2
Accuracy	An accurate measurement is one that is close to its true value
Air resistance	Frictional force opposing the motion of a body moving in air
Centre of gravity	The point at which all the mass of an object's weight can be considered to be concentrated
Density	The mass per unit volume
Energy	Energy may be stored as kinetic, gravitational potential, chemical, elastic (strain), nuclear, electrostatic or internal (thermal)
Equilibrium	When there is no resultant force and no resultant moment on an object
Extension	Change in length of a body being stretched
Friction	Force which opposes one surface moving, or trying to move, over another surface
Gravitational field strength	The force per unit mass
Mass	A measure of the quantity of matter in an object at rest relative to an observer
Moment of a force	Moment = force × perpendicular distance from the pivot
Non-renewable	Cannot be replaced when used up
Power	The work done per unit time and the energy transferred per unit time
Pressure	The force per unit area
Principle of conservation of energy	Energy cannot be created or destroyed; it is always conserved
Principle of moments	States when a body is in equilibrium; the sum of the clockwise moments about any point equals the sum of the anticlockwise moments about the same point
Random error	Error introduced by the person taking the measurement
Renewable	Can be replaced; cannot be used up
Speed	The distance travelled per unit time
Systematic error	Error introduced by the measuring device
Velocity	Speed in a given direction
Weight	A gravitational force on an object that has mass
Work	A measure of the amount of energy transferred. Work done = force × distance moved in the direction of the force. SI unit is the joule (J)
Acceleration	Change of velocity per unit time
Deceleration	A negative acceleration; velocity decreases as time increases
Efficiency	(useful energy output/total energy input) × 100% (useful power output/total power input) × 100%
Impulse	Force × time for which force acts
Limit of proportionality	The point at which the load–extension graph becomes non-linear
Momentum	Mass × velocity
Principle of conservation of momentum	When two or more bodies interact, the total momentum of the bodies remains constant provided no external forces act

Term	Definition
Resultant force	The rate of change in momentum per unit time
Resultant vector	A single vector that has the same effect as the two vectors combined
Scalar	A quantity with magnitude only
Spring constant	Force per unit extension
Terminal velocity	Constant velocity reached when the air resistance upwards equals the downward weight of the falling body
Vector	A quantity which has both magnitude and direction

1.1 Physical quantities and measurement techniques

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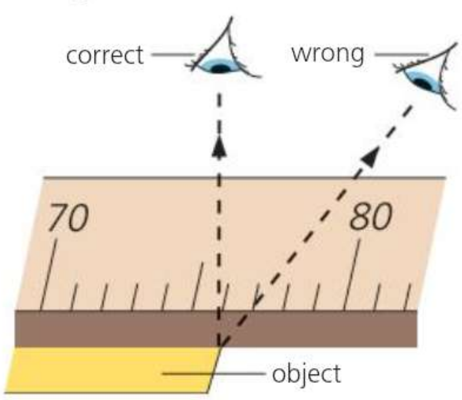
Key objectives

By the end of this section, you should be able to:

- describe how to measure length, volume and time using appropriate measuring instruments
- determine an average value for a small distance or short time by measuring multiples
- understand the difference between scalar and vector quantities and give examples of each
- determine the resultant of two vectors of force or velocity at right angles to each other either by calculation or graphically

Each time you measure a quantity you are trying to find its true value. How close you get to the true value is described as the **accuracy** of the measurement.

Length



▲ **Figure 1.1 The correct way to measure with a ruler**

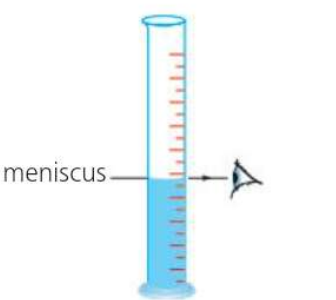
Length is the distance from one end of an object to the other. It is measured using a ruler. To measure length accurately your eye must be perpendicular to the mark on the ruler you are trying to read. This avoids parallax (see Figure 1.1).

Most rulers have millimetre markings. They give values to the nearest mm. For example, if you have to measure a small distance of 4 mm you only know the value to 4 ± 1 mm. To improve this measurement, you measure multiple distances and find an average distance.

Volume

Volume is the amount of space occupied. Figure 1.2 shows how to measure volume using a measuring cylinder. You measure the volume of a liquid by looking at the level of the bottom of the meniscus (see Figure 1.2). (For mercury, you should look at the level of the top of the meniscus.)

Measuring cylinders often measure in millilitres. Remember 1 ml = 1 cm^3.



▲ **Figure 1.2 The correct way to measure a volume of liquid**

Skills

Converting cm^3 to m^3

The SI unit of length is the metre. It is easy to convert lengths from cm into metres.

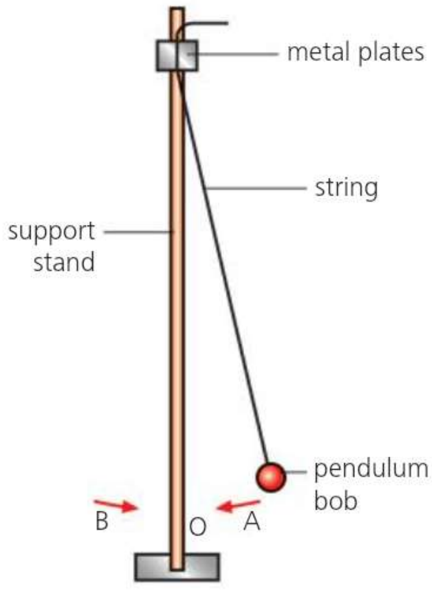
$$1\ \text{cm} = \frac{1}{100}\ \text{m} = 0.01\ \text{m} = 1 \times 10^{-2}\ \text{m}$$

The SI unit of volume is m^3. When you convert the units of volume, you have to divide by 100 for each dimension.

$$1\ \text{cm}^3 = \frac{1}{100 \times 100 \times 100}\ \text{m}^3 = 0.000\,001\ \text{m}^3 = 1 \times 10^{-6}\ \text{m}^3$$

Time

You need to be able to use analogue and digital stopwatches or clocks to measure time intervals. To improve the accuracy of the measurement of a short, repeated time interval, you can measure multiple times. For example, measuring the period of the pendulum in Figure 1.3. The period is the time taken for the pendulum to move from A to B and then back to A. You would measure the time for 10 such swings and then divide the time by 10.



▲ **Figure 1.3 A pendulum**

Errors in measurements

In any measurement there may be a measurement error. This is why results are not always the same. The error might be **random** (a **random error**) and cause an **anomaly** when you repeat the result. For example, an error introduced by your reaction time as you start and stop a stopwatch. The error may be a **systematic error**. For example, a newton meter might have a reading even when there is no force applied. This type of error is a zero error. In this case the same error is introduced to all the readings.

Scalars and vectors

Quantities can be divided into **scalar** or **vector**:

Scalars:

- only have magnitude (size)
- are added by normal addition

Examples of scalars you should know are distance, time, mass, speed, energy and temperature.

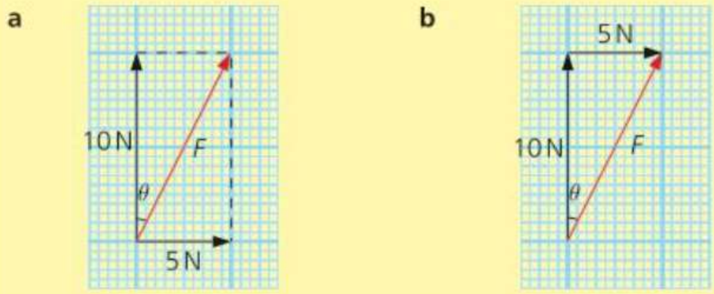
Vectors:

- have direction and magnitude (size)
- are represented by an arrow – the length of the arrow shows the magnitude of the vector and the direction shows the direction it acts
- are added by taking into account their direction

Examples of vectors you should know are force, weight, velocity, acceleration, momentum, electric field strength and gravitational field strength. Always state the direction of a vector, for example, the velocity is 10 m/s northwards.

Finding the resultant of two vectors

When you add vectors, you find the **resultant vector**. This is a single vector that has the same effect as the vectors you have combined. For example, if a force of 200 N pulls a boat to the east and a force of 800 N pulls it to the west, the resultant force is 600 N to the west. You may be asked to find the resultant of two vectors perpendicular to each other. Figure 1.4 shows a 10 N and a 5 N force acting at right angles to each other and their resultant vector F. The forces have been drawn using the parallelogram method and the triangle method.



Draw the vectors so they start at the same point. Draw in the sides of the parallelogram. The resultant is the diagonal.

Draw the vectors nose-to-tail. The resultant vector is the line drawn from the start to the finish.

▲ **Figure 1.4 Finding the resultant of two forces acting at right angles to each other**

As you can see from Figure 1.4, the resultant is the same whether you use the parallelogram method or the triangle method. Use whichever one you find easiest. There are two ways to find the value of the resultant vector:

1 By calculation: As it is a right-angled triangle, you can use Pythagoras' theorem to determine the magnitude of the vector.

$$F = \sqrt{10^2 + 5^2} = 11 \text{ N to 2 s.f.}$$

You can use trigonometry to find the angle θ.

$$\tan\theta = \frac{5}{10}, \theta = 27° \text{ to 2 s.f.}$$

Therefore, the resultant is an 11 N force acting at an angle of 27° to the 10 N force.

2 Graphically: By drawing the vectors to scale, you can then use a ruler to measure the length of the resultant vector. Do not forget to convert back using your scale and always write your scale down, e.g. 1 cm : 10 N. You can measure the angle using a protractor. Check this gives the same answer for the resultant force as by calculation using Figure 1.4.

Sample questions

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1 A student wishes to time how long it takes a ball to fall 1.5 m. Describe how to obtain reliable results for the measurements of time and height. [4]

Student's answer

Start the stopwatch as soon as the ball is released and stop when the ball hits the floor. Repeat three times. If there is an anomalous result, leave it out when you calculate the average time. Measure the height using a ruler and make a mark so that the ball is dropped from the same height each time. [3]

Teacher's comments

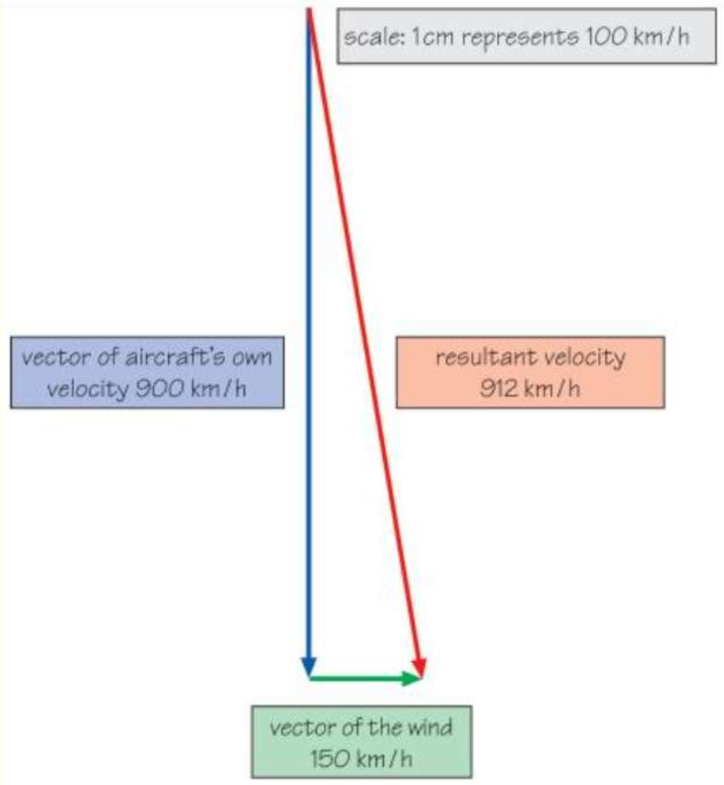
The question is answered well in terms of measuring the time. The student realises that they have to repeat because of the random errors when timing. They need to be more detailed in describing the distance measurement. The height is 1.5 m so a tape measure would be needed. It is not accurate to use two smaller rulers. Though they do include the idea of a mark so that the height is the same each time.

Correct answer

Use a tape measure to make a mark at the correct height of 1.5 m. Release the ball from this height each time. Start the stopwatch when the ball is released and stop it when the ball hits the floor. Repeat the experiment and discard any anomalous results before calculating the average time. [4]

2 An aircraft flies at 900 km/h heading due south. There is a crosswind of 150 km/h from the west. Graphically, find the aircraft's resultant velocity. [4]

Student's answer



▲ **Figure 1.5 (Diagram is not drawn to scale)** [3]

Teacher's comments

On the whole, the question is extremely well answered and the graphical work is accurate; stating the scale shows excellent work. The student assumed the top of the page was north. However, the student has omitted the direction part of the resultant velocity, stating only the magnitude.

Correct answer

Figure 1.5 should have an arrow pointing up the page labelled north. The answers shown in Figure 1.5 are correct except that the resultant velocity label should be resultant velocity 912 km/h at 9° east of due south. [4]

3 Speed and velocity are related quantities. Explain why speed is a scalar quantity and velocity is a vector. [2]

4 Name two more scalar quantities and two more vectors. [4]

Student's answers

3 *Speed is much faster than velocity.* [0]
4 *Vectors: force, magnetic field strength* [2]
Scalars: energy, colour [1]

Teacher's comments

3 The student has shown no understanding of the difference between a scalar and a vector.
4 Two good answers are given as examples of vectors; IGCSE students are not expected to know that magnetic field strength is a vector but it is a correct response.
Colour is not measurable so is not a scalar quantity.

Correct answers

3 Speed has magnitude only, but velocity has magnitude and direction. [2]
4 Correct answers could include:
Vectors: force, acceleration
Scalars: energy, mass [4]

Revision activity

Create four vector addition questions where the force or velocity vectors are at right angles to each other. For each question, calculate the answer by both calculation and graphically. Swap your questions with another student and check each other's workings.

Exam-style questions

Answers available at: www.hoddereducation.co.uk/cambridgeextras

1 A stack of 160 sheets is 7 mm high. Calculate the average thickness of a single sheet of paper. [1]
2 A student uses a stopwatch to time the swing of a pendulum. They forget to zero the timer, which reads 0.5 s when it starts. They start the stopwatch at the end of the first swing of the pendulum and stop the stopwatch at the end of the tenth swing. The final reading on the timer is 5.9 s.
   a State the type of error the student introduced when they forgot to zero the timer. [1]
   b Calculate the number of swings timed. [1]
   c Calculate the time taken for these swings. [1]
   d Calculate the time for each swing. [1]

3 Sort the following quantities into vector quantities and scalar quantities:
velocity mass weight kinetic energy time acceleration [6]
4 A swimmer swims directly across a river at 1.0 m/s heading due east. The river current is 4.0 m/s from the south.
Calculate the resultant velocity of the swimmer. [2]

1.2 Motion

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Key objectives

By the end of this section, you should be able to:
- define speed and velocity, and recall and use the equations to calculate speed and average speed
- define acceleration and use the equation to calculate acceleration and know that a negative acceleration is a deceleration

- sketch, plot and understand the motion shown on distance–time and speed–time graphs
- determine from data or the shape of a distance–time graph or speed–time graph when an object is at rest, moving with constant speed, accelerating or decelerating
- calculate speed from the gradient of a distance–time graph and distance travelled from the area under a speed–time graph
- know the approximate value of the acceleration of freefall, g, for an object close to the Earth's surface

- determine from data or the shape of a speed–time graph when an object is moving with constant acceleration and changing acceleration
- calculate acceleration from the gradient of a speed–time graph
- describe the motion of an object falling in a uniform gravitational field with and without air or liquid resistance

Speed

Speed is defined as the distance travelled per unit time. **Velocity** is speed in a given direction. If someone sees a runner moving at 5 m/s in a northerly direction, then the runner's speed is 5 m/s and their velocity is 5 m/s north. The speed, v, can be calculated from the distance travelled, s, in a very short time, t, using the equation:

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

In most cases, speed is calculated using a much longer time. This is then the average speed of the object. The average speed is calculated using the equation:

$$\text{average speed} = \frac{\text{total distance travelled}}{\text{total time taken}}$$

Acceleration

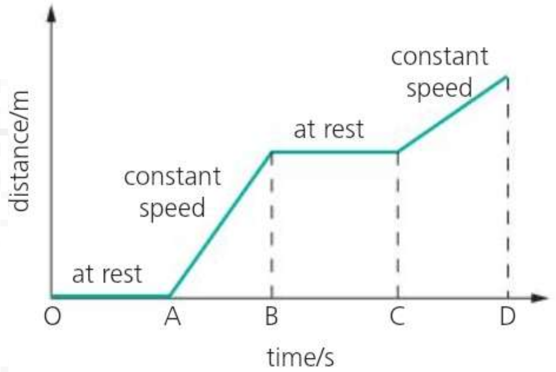
Acceleration is the change in velocity per unit time. The acceleration, a, for a change in velocity, Δv, when the time taken for the change is Δt is given by:

$$a = \frac{\Delta v}{\Delta t}$$

A negative acceleration is called a **deceleration**.

Distance–time graphs

Distance–time graphs show how an object's distance changes with time. Figure 1.6 shows the motion of an object plotted on a distance–time graph.



▲ **Figure 1.6 Distance–time graph**

The gradient of the graph for the section AB is greater than the gradient for section CD. This shows the object was moving at a faster constant speed at AB. The gradient of the distance–time graph is equal to the speed.

Skills

Calculating the gradient of a graph

To calculate the gradient of a graph, you need to read values for the change in y in a set change in x. See Figure 1.7.

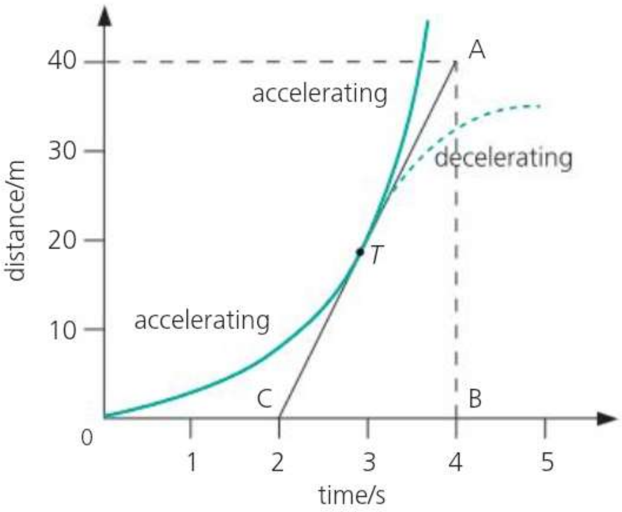
▲ **Figure 1.7 Calculating the gradient**

The gradient is then given by:

$$\text{gradient} = \frac{\text{change in } y}{\text{change in } x}$$

In Figure 1.7, the gradient = $\frac{(15 - 5)}{(4 - 0)}$ = 2.5.

If the speed increases, the object is accelerating. If the speed decreases, the object is decelerating. When the speed changes, the distance–time graph will curve. An upward curve shows the object is accelerating as the gradient is increasing. The solid green line in Figure 1.8 shows the object accelerating. A downward curve (the dashed green line in Figure 1.8) shows the object is decelerating.



▲ **Figure 1.8 Non-constant speed**

The speed at any point on a distance–time graph where the object is changing speed is given by the gradient of the tangent drawn at that point. In Figure 1.8, the speed at time T is equal to the gradient of the tangent (line AC) drawn at that point.

$$\text{gradient} = \frac{40-0}{4-2} = \frac{40}{2} = 20 \text{ m/s}$$

$$\text{speed at time } T = 20 \text{ m/s}$$

Determining the motion of an object from data

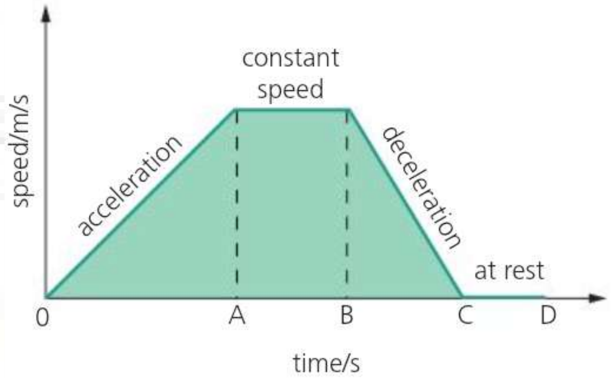
It is easy to interpret the motion from the shape of distance–time graphs, but you can also tell when you look at data in tables. When the object travels at a constant speed, the distance increases the same amount in equal times. When the object is stationary, the distance remains the same. When the distance increases in different amounts in equal times, the speed is changing. Table 1.1 shows how the distance of an object changes with time.

▼ **Table 1.1 Distance–time data**

Time/s	0	2	4	6	8	10	12	14
Distance/m	0	5	10	15	15	16	18	24
	Constant speed: Every 2 seconds distance increases by 5 m			Stationary: The distance remains the same		Changing speed: The distance travelled every 2 seconds is increasing		

Speed–time graphs

Speed–time graphs show the speed of an object over time. The area under the speed–time graph is the distance travelled (green shaded area in Figure 1.9).



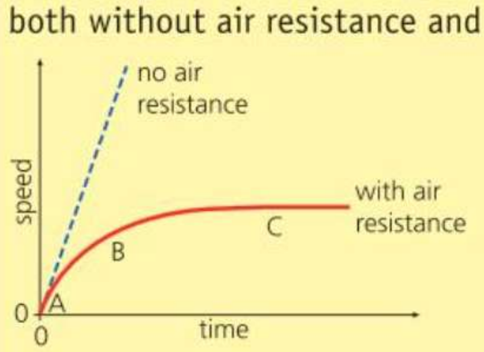
▲ **Figure 1.9 Speed–time graph showing acceleration, constant speed and deceleration**

In Figure 1.9, the object is accelerating between 0 and A, at constant speed between A and B and between B and C it is slowing down or decelerating.

The steeper the gradient of a speed–time graph, the greater the acceleration. In Figure 1.9 the deceleration is greater than the acceleration. The same change in speed happened in a much shorter time interval and the gradient is steeper.

Near the surface of the Earth the **acceleration of free fall** (g) is approximately constant and is equal to 9.8 m/s^2.

You can calculate the acceleration using the gradient of a speed–time graph. Figure 1.10 shows the speed–time graph for an object falling both without air resistance and with air resistance.



▲ **Figure 1.10 A body in free fall in the atmosphere**

Without air resistance the gradient of the graph is constant and equal to 9.8 m/s^2. However, with air resistance the acceleration decreases. You can see this because the gradient of the graph is decreasing. At point A in Figure 1.10, the speed is slow so there is negligible air resistance and the body has free fall acceleration. At point B, the speed is higher and there is some air resistance, so acceleration is less than free fall. At point C, the body has high speed and high air resistance, which is equal to its weight. Therefore, there is no acceleration – this constant speed is called the **terminal velocity**.

Sample question

REVISED

5 A runner completes an 800 m race in 2 min 30 s after completing the first lap of 400 m in 1 min 10 s. Find their average speed for the last 400 m. [3]

Student's answer

Total time = 2 mins 30 s = (2 × 60) + 30 = 150 s

$$\text{speed} = \frac{400}{150} = 2.67\,\text{m/s}$$ [2]

Teacher's comments

The student used the correct equation and the correct distance, but used the time for the whole race instead of the time for the last 400 m. The answer is quoted to 3 s.f.

Correct answer

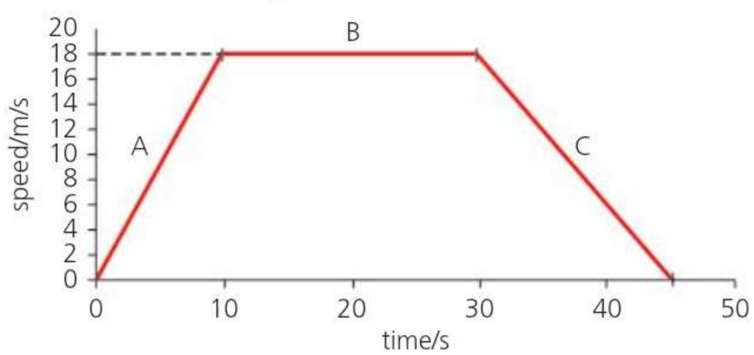
Time = 2 min 30 s – 1 min 10 s = 1 min 20 s = 80 s [1]

$$\text{speed} = \frac{400}{80} = 5.0\,\text{m/s}$$ [2]

Sample question

REVISED

6 A car is moving in traffic and its motion is shown in Figure 1.11.



▲ **Figure 1.11**

a Choose from the following terms to describe the motion in parts A, B and C: acceleration, deceleration, steady speed. [3]

b Calculate the total distance covered. [5]

c Calculate the acceleration in part C. [2]

Student's answers

a Part A: acceleration; part B: deceleration; part C: steady speed [1]

b distance = speed × time = 18 × 45 = 810 m [0]

c acceleration $a = \frac{\Delta v}{\Delta t} = \frac{18}{15} = 1.2\ m/s^2$ [1]

Teacher's comments

a The answers to parts B and C are the wrong way around.

b The equation used is distance = average speed × time, but this is not appropriate, as the average speed is unknown. The student should have worked out the area under the graph, which equals the distance covered.

c The calculation is correct but the student should have specified a negative acceleration. [1 mark given]

Correct answers

a Part A: acceleration; part B: steady speed; part C: deceleration [3]

b distance = area under graph [1]

Part A area = $\frac{1}{2} \times 18 \times 10 = 90$ m [1]

Part B area = 18 × 20 = 360 m [1]

Part C area = $\frac{1}{2} \times 18 \times 15 = 135$ m [1]

distance = total area = 90 + 360 + 135 = 585 m = 590 m to 2 s.f. [1]

c acceleration $a = \frac{\Delta v}{\Delta t} = \frac{-18}{15} = 1.2\ m/s^2$ [2]

Exam-style questions

Answers available at: www.hoddereducation.co.uk/cambridgeextras

5 Runner A runs 100 m in 20 seconds at a constant speed.

a Sketch this information on a distance–time graph. [3]

b Calculate their average speed. [2]

c Runner B is twice as fast. Add a line to your distance–time graph and label it B. Assume they also run at a constant speed and run 100 m. [2]

6 A bus accelerates at a constant rate from standstill to 15 m/s in 12 s. It continues at a constant speed of 15 m/s for 8 s.

a Sketch this information on a speed–time graph. [3]

b Use the graph to calculate the total distance covered. [2]

c Calculate the average speed of the bus. [2]

d Calculate the acceleration in the first 12 seconds. [2]

Revision activity

Create a revision poster on motion. Start in the middle of sheet with the four types of motion you have to recognise: a) at rest, b) moving with a constant speed, c) accelerating, d) decelerating. Draw distance–time and speed–time graphs to represent each type of motion. Include all the key words used to describe motion and how motion can be calculated. Link these to your graphs. Swap posters and see how another student has summarised the same information.

1.3 Mass and weight

REVISED

Key objectives

By the end of this section, you should be able to:

- define mass and weight and know that weights (and masses) can be compared using a balance
- define gravitational field strength, g, and use the equation relating g, weight and mass
- describe how the weight of an object depends on the gravitational field it is in

Mass is the amount of matter in an object. The unit of mass is the kilogram, kg.

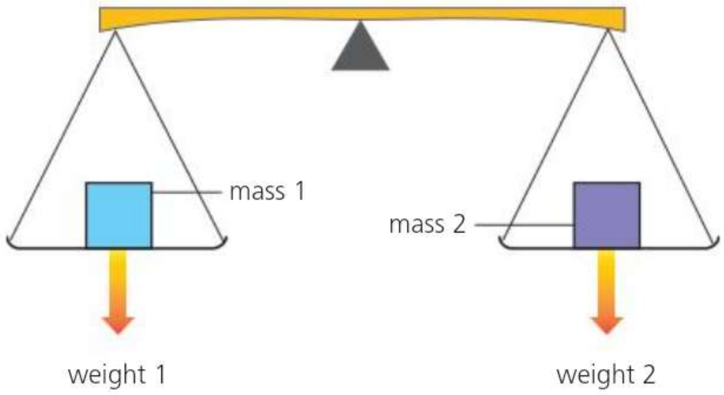
Weight is the gravitational force acting on an object that has mass. As it is a force, the unit of weight is the newton, N.

Weight, W, and mass, m, are related. The weight depends on the strength of the gravitational field the mass is in. **Gravitational field strength** is defined as the force acting per unit mass and is given by the equation:

$$g = \frac{W}{m}$$

Gravitational field strength has the same symbol g as the acceleration of free fall as they are equivalent. The units are different. Near the surface of the Earth, gravitational field strength is 9.8 N/kg and acceleration of free fall is 9.8 m/s^2.

A balance such as the one shown in Figure 1.12 compares an unknown weight with a known weight.



▲ **Figure 1.12 Balanced weights**

As mass determines weight, a balance also compares masses. In Figure 1.12, mass 1 = mass 2 because weight 1 = weight 2.

The mass of an object at rest is always the same as it depends on the matter in the object. However, the weight depends on the gravitational field the mass is in. A 1 kg mass has a weight of 9.8 N on Earth. Jupiter has a gravitational field strength of 25 N/kg. The same 1 kg mass would have a weight of 25 N on Jupiter.

Exam-style questions

Answers available at: www.hoddereducation.co.uk/cambridgeextras

7 A rover used to explore planets weighs 8820 N on Earth. On Mars the rover weighs 3330 N.

a Calculate the mass of the rover. [2]

b Calculate the gravitational field strength on Mars. [1]

Revision activity

Create flashcards for the definitions of the key terms in this section and the equation $g = \frac{W}{m}$.

1.4 Density

REVISED

Key objectives

By the end of this section, you should be able to:

- define density, and recall and use the equation relating density, mass and volume
- describe how to determine the density of a liquid, a regularly shaped solid and an irregularly shaped solid, including appropriate calculations
- use density data to determine whether an object will float or sink in a liquid
- use density data to determine whether one liquid will float on another liquid

Density is the mass per unit volume of a substance.

For a mass m with volume V the density ρ is given by the equation:

$$\rho = \frac{m}{V}$$

The units of density are kg/m^3.

Skills

Measuring the density of different substances

To find the density of a substance you must make accurate measurements of the mass and volume:

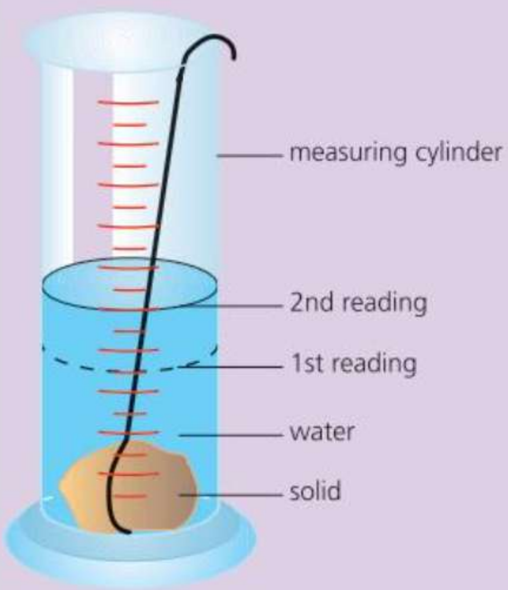
For a regularly shaped solid, measure the dimensions and work out the volume, then find the mass on a balance.

volume of a rectangular block = length × breadth × height

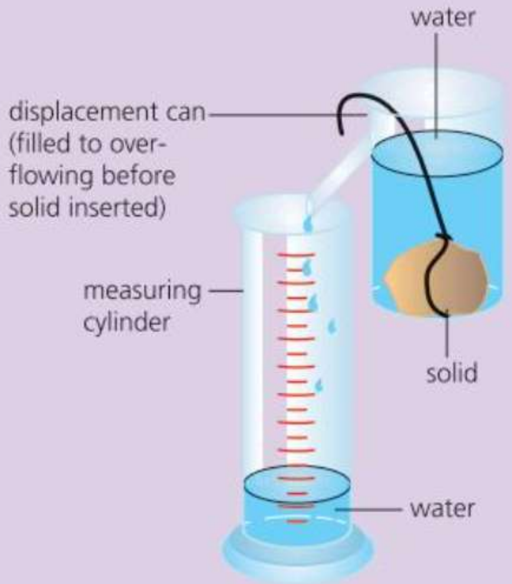
volume of a cylinder = $\pi r^2 h$

For an irregularly shaped solid, use a displacement method where the solid is placed in water (Figure 1.13). In method 1, the volume of the solid is the increase in the reading on the measuring cylinder (see Figure 1.13a). In method 2, where a displacement can is used, the volume of the solid is the volume of liquid displaced (see Figure 1.13b).

For a liquid, measure the volume in a measuring cylinder. To find the mass of the liquid, first find the mass of an empty beaker. Pour the liquid into the beaker and then find the total mass of the beaker and the liquid. Work out the mass of the liquid by subtraction of the mass of the beaker from the mass of the total.



▲ **Figure 1.13a Measuring the volume of an irregular solid method 1**



▲ **Figure 1.13b Measuring the volume of an irregular solid method 2**

Skills

Converting units

In your experiment, you probably measured the mass in grams and the volume in cm^3. This gives you a density in g/cm^3. To convert this to kg/m^3 you multiply by 1000.

For example, state which has the higher density: substance A at $0.8\,g/cm^3$ or substance B at $750\,kg/m^3$.

Both substances need to be in the same units of kg/m^3 so that you can compare them.

density of A = $0.8 \times 1000 = 800\,kg/m^3$

Therefore, substance A has a greater density.

Floating and sinking

An object will sink in a liquid if it has density greater than the density of the liquid.

When two liquids do not mix, the liquid with the lower density will float on top of the liquid with higher density.

Sample question

REVISED

7 The mass of an empty measuring cylinder is 185 g. When the measuring cylinder contains $400\,cm^3$ of a liquid, the total mass is 465 g. Find the density of the liquid. [4]

Student's answer

$\text{density} = \frac{465}{400} = 1.16\,g/cm^3 = 1.2\,g/cm^3$ to 2 s.f. [2]

Teacher's comments

The student put the appropriate quantities into the correct equation and gave the correct units, but used the total mass instead of working out and using the mass of the liquid itself.

Correct answer

mass of liquid = 465 − 185 = 280 g

$\text{density} = \frac{280}{400} = 0.70\,g/cm^3$ [4]

Exam-style questions

Answers available at: www.hoddereducation.co.uk/cambridgeextras

8 a Copy and complete the table by filling in the missing values. [3]

▼ Table 1.2

Substance	Mass/g	Volume/cm^3	Density/g/cm^3
A	540	200	
B	67.5		1.5
C		250	0.5

b State which of the substances would float in a liquid with a density of $1.2\,g/cm^3$. [1]

Revision activity

Create a mind map on density. Include how to calculate density, how to measure the density of a substance and how you use density to determine whether objects float.

9 A measuring cylinder containing 20 cm^3 of liquid is placed on a top-pan balance. The top-pan balance reads 150 g. More liquid is poured into the cylinder up to the 140 cm^3 mark and the top-pan balance now reads 246 g. A solid is gently lowered into the cylinder; the liquid rises to the 200 cm^3 mark and the top-pan balance reads 411 g. Calculate:

a the density of the liquid [3]

b the density of the solid [3]

10 A student has the same mass, 85 g, of two different liquids. Liquid A has a volume of 80 cm^3 and liquid B has a volume of 92 cm^3. Determine which liquid will float on top assuming the liquids do not mix. [3]

1.5 Forces

REVISED

1.5.1 Effects of forces

Key objectives

By the end of this section, you should be able to:

- know that forces may produce changes in the size and shape of an object
- describe an experiment to collect data for a load–extension graph and plot, sketch and understand the features of a load–extension graph
- define the spring constant, and recall and use the equation and define the limit of proportionality
- determine the resultant force when two or more forces are acting along the same line
- understand that an object will remain at rest or continue at a constant speed in a straight line unless a resultant force acts on it
- understand that a resultant force may change the velocity of an object by changing its speed or direction
- recall and use the equation $F = ma$ to calculate the resultant force, F, and the acceleration, a, and know that the force and acceleration are in the same direction
- state how solid friction opposes motion between two surfaces and produces heating
- understand there is friction acting on an object as it moves through gas (air resistance) or a liquid (drag)
- describe the motion of an object in a circular path and how the force is affected as the speed, radius of the circle and mass of the object change

Forces

Forces can change the size and shape of a body. You must be able to describe an experiment to measure the **extension** of an elastic solid, such as a spring, a piece of rubber or another object, with increasing load. The extension is the change in length of the object being stretched. For some materials, the load–extension graph is a straight-line graph through the origin. This means the load is directly proportional to the extension. This means doubling the force, doubles the extension. Not all load–extension graphs are linear, which means the force required to stretch the material changes as the material is stretched.

Spring constant

The **spring constant**, k, is defined as the force per unit extension. The units are N/m. The spring constant can be calculated using the equation:

$$k = \frac{F}{x}$$

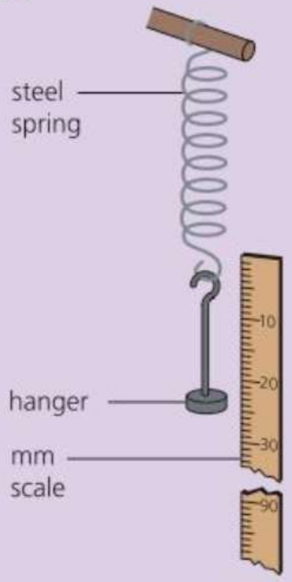
For a linear load–extension graph, the spring constant stays the same. The spring constant will be the gradient of the graph. On a load–extension graph the **limit of proportionality** is the point at which the graph is no longer linear.

Skills

Measuring extension of an object with increasing load

To investigate the load–extension graph for a spring, set up the apparatus shown in Figure 1.14.

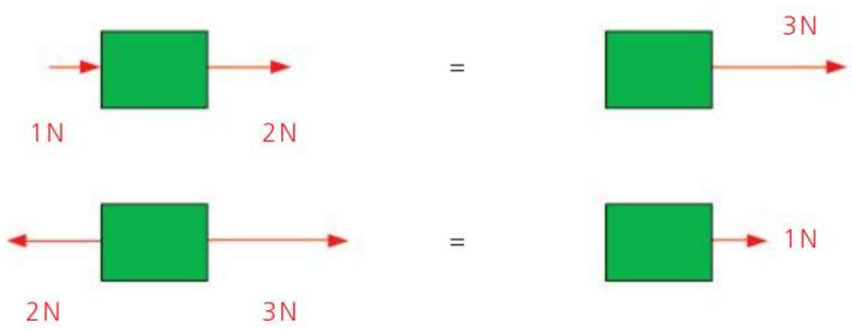
Place a 100 g mass carefully onto the hanger and record the position on the ruler of the bottom of the hanger. To help you read this accurately, attach a piece of card to the bottom of the hanger so that it lines up with the ruler. Record this measurement. Add another 100 g mass to the hanger and read the new reading on the ruler for the position of the hanger. The extension is the difference between the initial reading and this new reading. Repeat to a maximum of 500 g.



▲ **Figure 1.14 Measuring the extension of a spring with increasing force**

Forces and resultants

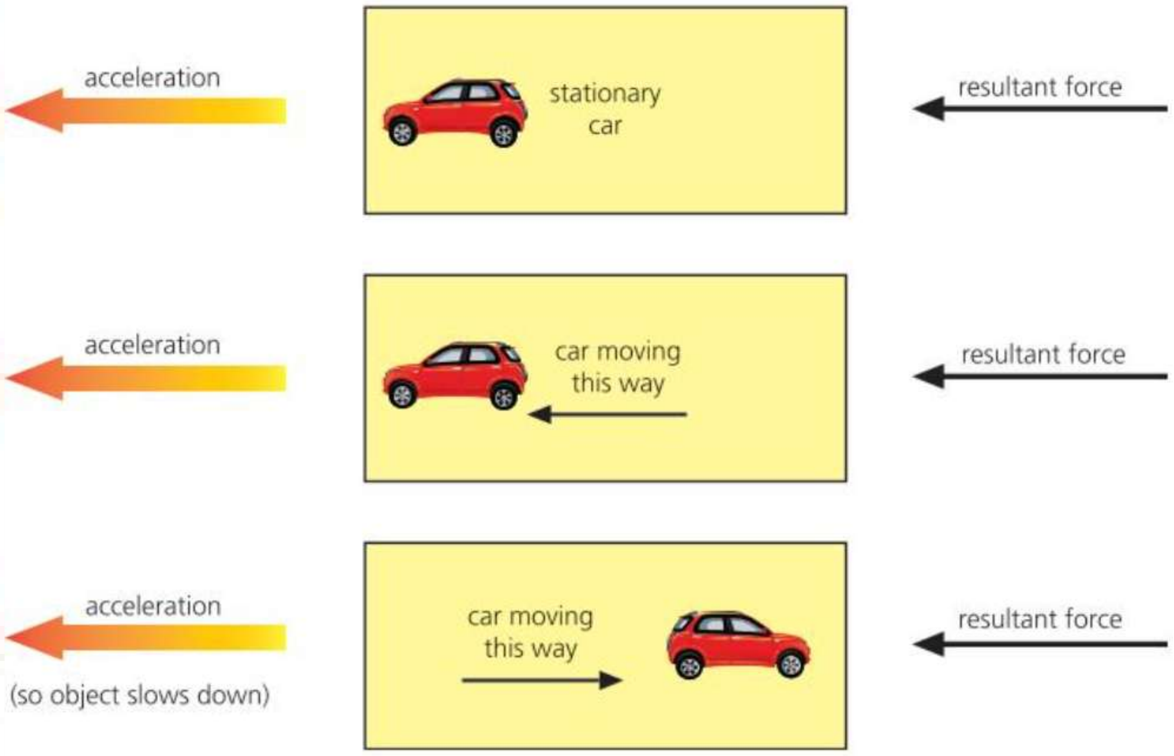
Force has both magnitude and direction. It is represented using an arrow to show the magnitude and direction the force acts. If more than one force acts on an object, you can find the resultant force. This is a single force which has exactly the same effect as all the forces added together. Figure 1.15 shows how to find the resultant of forces acting along the same line. If a question simply describes forces, it will help to sketch a force diagram showing the direction of each of the forces.



▲ **Figure 1.15 Use addition or subtraction to find the resultant of forces acting in a straight line**

If the resultant force acting on an object is zero, then the object will stay at rest or keep moving in a straight line at a constant speed.

If there is a resultant force acting on an object, then it changes velocity. This can mean a change in speed or/and a change in direction. Remember velocity is speed with direction.



▲ **Figure 1.16 A resultant force changes the motion of an object**

Friction

Solid **friction** is a force that opposes one surface that is moving or trying to move over another. Friction results in heating. When an object moves through a gas or liquid, there is a friction force opposing the motion. This friction force in liquid is called drag and in air is called **air resistance**.

Relationship between resultant force and acceleration

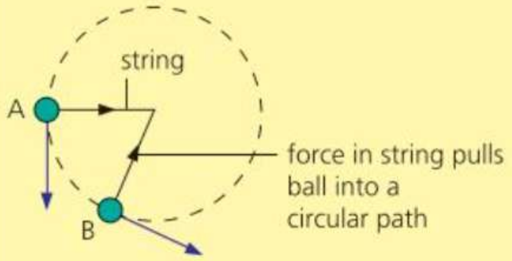
You need to know and be able to use the equation $F = ma$, where F is the resultant force and a is the acceleration. The acceleration is in the direction of the resultant force.

When the resultant force is perpendicular to motion, the object follows a circular path. Some examples of this are shown in Table 1.3.

▼ **Table 1.3 Examples of circular motion**

Object	Force	Circular motion
Planet in orbit	Gravitational force towards the Sun	Planet moves around the Sun
Car turning a corner	Friction force	Car drives around the corner
Ball on a length of string	String tension	Ball moves around in a circle on the end of the string

Although the object may be moving at a constant speed, it is still accelerating as it is continually changing direction. This means the velocity is changing. Remember velocity is a vector.



▲ **Figure 1.17 Diagram showing the direction of the force and velocity for a ball on a length of string**

The resultant force required to keep the object moving in the circle varies with the speed, radius and mass of the object:

- Increasing the speed, *increases* the force for the same mass and radius of circle.
- Increasing the radius, *decreases* the force for the same mass and speed.
- Increasing the mass, *increases* the force for the same speed and radius.

Sample question

REVISED

8 An empty lift weighs 2000 N. Four people enter the lift and their total weight is 3000 N. After the button is pressed to move the lift, the tension in the cable pulling up from the top of the lift is 4000 N.

a Work out the resultant force on the lift. [2]
b State how the lift moves. [2]
c Calculate the resultant acceleration (g = 9.8 N/kg). [3]

Student's answers

a Resultant force = 3000 + 2000 – 4000 = 1000 N [1]
b The lift will move down. [1]

c Mass of lift and people = $\frac{5000}{9.8}$ = 510.2 kg

Acceleration = $\frac{F}{m} = \frac{1000}{510.2}$ = 1.96 m/s² downwards [3]

Teacher's comments

a The student correctly worked out the size of the force but did not state the direction downwards.
b The words 'move down' are too vague.

c The student's answer is correct but has been quoted to 3 s.f.

Correct answers

a Resultant force = 3000 + 2000 – 4000 = 1000 N downwards [2]
b The lift will accelerate downwards. [2]

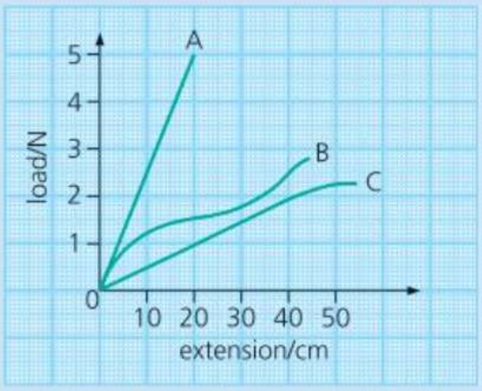
c Mass of lift and people = $\frac{5000}{9.8}$ = 510.2 kg

Acceleration = $\frac{F}{m} = \frac{1000}{510.2}$ = 2.0 m/s² downwards [3]

Exam-style questions

Answers available at: www.hoddereducation.co.uk/cambridgeextras

11 Figure 1.18 shows load–extension graphs for three different objects.



▲ **Figure 1.18**

Study the graphs carefully and answer the following questions:

a Describe the behaviour of each object and identify which could be a spring. [6]

b Calculate the spring constant for graph A. [2]

c Identify the limit of proportionality on graph C. [1]

12 A car is driving along a horizontal road with a constant velocity. The driver applies the brakes and the car comes to a stop.

a State the resultant force acting on the car when it is driving with a constant velocity. [1]

b State the direction of the resultant force acting on the car as the brakes are applied. [1]

13 A rocket of weight 980 N is propelled upwards by a thrust of 1800 N. The air resistance is 500 N.

a Calculate the resultant force on the rocket. [2]

b Describe how this resultant force changes the motion of the rocket. [2]

c Calculate the acceleration of the rocket (g = 9.8 N/kg). [3]

Revision activity

Create a mind map on forces. Include how forces change the shape, size and velocity of objects.

1.5.2 Turning effect of forces

Key objectives

By the end of this section, you should be able to:

- describe and give examples of the turning effect or moment of a force
- define moment and recall and use the equation for the moment of a force
- apply the principle of moments and recall the conditions for an object in equilibrium
- apply the principle of moments when there are more than two forces about a pivot
- describe an experiment to show that an object in equilibrium has no resultant moment

Moment of a force

The **moment of a force** is a measure of its turning effect. Everyday examples of moments include spanners and the handle on a door. In each case, the effort is applied at a distance from the pivot to increase the turning effect.

A moment is defined by the equation:

$$\text{moment} = \text{force} \times \text{perpendicular distance from pivot}$$

Principle of moments

The **principle of moments** states when a body is in equilibrium, the sum of the clockwise moments about any point equals the sum of the anticlockwise moments about the same point.

An object is in **equilibrium** when there is no resultant force and no resultant moment on the object. Figure 1.19 shows a wheelbarrow pushed along at a constant velocity. Therefore, there is no resultant force acting on it. The clockwise moment of the load is equal to the anticlockwise moment of the upward force holding it up. Therefore, there is no resultant moment.

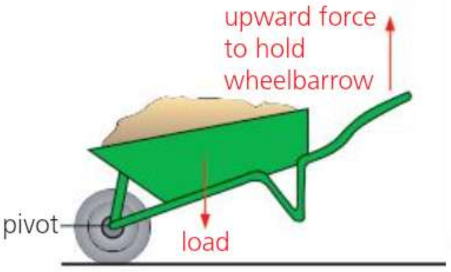


Figure 1.19 Wheelbarrow in equilibrium

Skills

Demonstrating that there is no resultant moment when an object is in equilibrium

To demonstrate there is no resultant moment on an object in equilibrium, set up the apparatus shown in Figure 1.20.

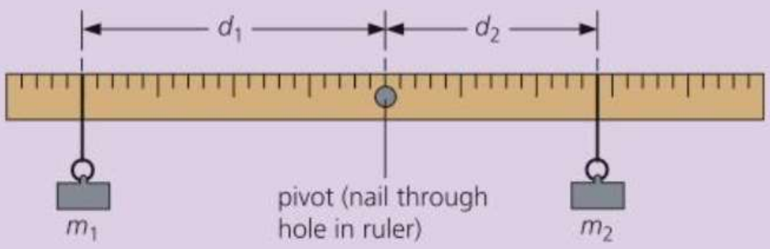


Figure 1.20 Using a balanced ruler to measure clockwise and anticlockwise moments

Balance a half-metre ruler in its centre. Add modelling clay to one side or the other until it is level. Hang unequal masses m_1 and m_2 either side of the pivot and alter their distances from the pivot until the ruler is balanced again. Calculate the anticlockwise moment of m_1 and the clockwise moment of m_2. You will find that when the clockwise moment is equal to the anticlockwise moment, there is no resultant moment and the beam is in equilibrium.

Sample question

REVISED

9 A student carries out an experiment to balance a regular 4 m long plank at its mid-point. A mass of 4 kg is placed 80 cm to the left of the pivot and a mass of 3.2 kg is placed 100 cm to the right of the pivot. Explain, *by calculating the moments,* whether the plank is balanced. Use g = 10 N/kg. [4]

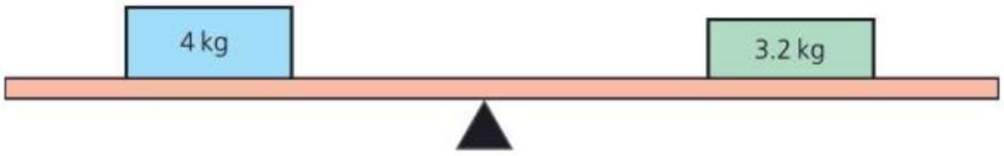


Figure 1.21

Student's answer

4 × 80 = 3.2 × 100, so the plank balances. [2]

Correct answer

anticlockwise moment = 40 × 0.8 = 32 N m [1]

clockwise moment = 32 × 1 = 32 N m [1]

anticlockwise moment = clockwise moment, so the plank balances. [2]

Teacher's comments

The student's calculation and conclusion are entirely correct, but the instruction in italic to calculate the moments was ignored.

Exam-style questions

Answers available at: www.hoddereducation.co.uk/cambridgeextras

14 A 450 N child sits 1.2 m from the pivot of a seesaw.
  a Calculate the moment of the child. [1]
  b A second child sits 1.5 m from the pivot on the opposite side. The seesaw is in equilibrium. Calculate the weight of the second child. [2]

15 A seesaw has a total length of 4 m and is pivoted in the middle. A child of weight 400 N sits 1.4 m from the pivot. A child of weight 300 N sits 1.8 m from the pivot on the other side. A parent holds the end of the seesaw on the same side as the lighter child. Calculate the magnitude and direction of the force the parent must exert to hold the seesaw level. [4]

Revision activity

Write four questions on moments with their solutions. Swap your questions with a partner and try each other's questions. Check the answers against each other.

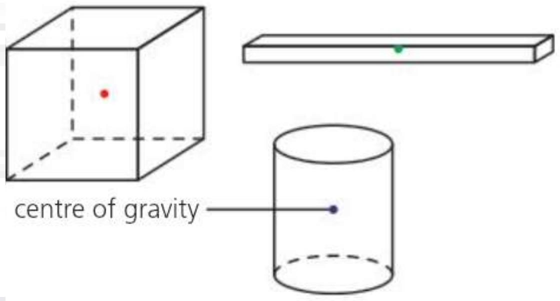
1.5.3 Centre of gravity

Key objectives

By the end of this section, you should be able to:
- define centre of gravity and describe how its position relates to the stability of simple objects
- describe an experiment to find the centre of gravity of an irregularly shaped piece of card.

Centre of gravity

A body behaves as if its whole weight were concentrated at one point, called its **centre of gravity**. If you hang an object so it can swing freely, it will end up with its centre of gravity directly beneath the point of suspension. In a regular object of uniform shape and density, the centre of gravity will be in the geometric centre.

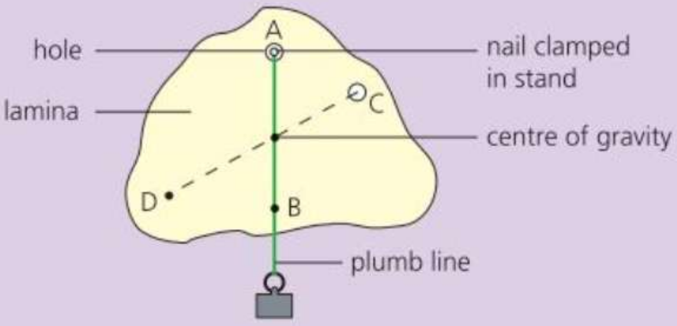


▲ **Figure 1.22 Centre of gravity is in the geometric centre of uniform shape and density objects**

Skills

Finding the centre of gravity

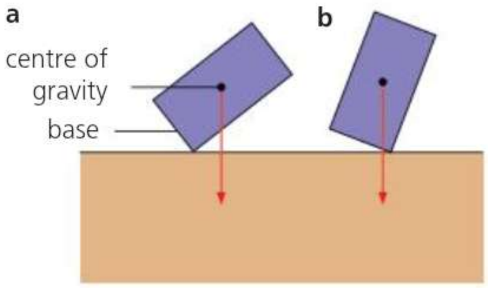
To find the centre of gravity of an irregularly shaped plane lamina (thin sheet) of cardboard, simply make a hole in the card. Use the hole to hang the card from a nail held in a clamp stand. The card must be able to swing freely so that it comes to rest with the centre of gravity directly below the nail. Tie a plumb line to the nail and mark its position on the card AB as shown in Figure 1.23. Make a second hole in the card and repeat the procedure making the line CD. Where the lines cross is the centre of gravity.



▲ **Figure 1.23 How to find the centre of gravity of an irregularly shaped lamina**

Toppling

The position of the centre of gravity affects the stability of an object. If an object is pushed, it will topple if the vertical line from the centre of gravity falls outside the base as in Figure 1.24a. It will not topple if the vertical line stays within the base as in Figure 1.24b.



▲ **Figure 1.24 An object will topple if the vertical line from its centre of gravity falls outside the base. a The object topples and b the object will remain standing**

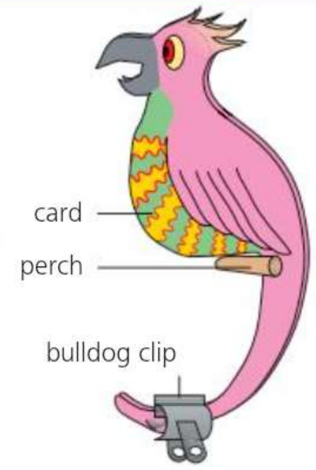
To increase the stability of an object:

- lower the centre of gravity
- increase the area of its base

Sample question

REVISED

10 Explain why the model parrot will only stay on its perch if the bulldog clip is in place. [2]



▲ **Figure 1.25**

Student's answer

The bulldog clip lowers the centre of gravity. [1]

Teacher's comments

The centre of gravity is lowered but the student did not mention its position relative to the perch.

Correct answer

The bulldog clip moves the centre of gravity to directly below the perch, so the parrot is stable. [2]

Exam-style questions

Answers available at: www.hoddereducation.co.uk/cambridgeextras

16 Describe how a Bunsen burner is designed so that it is very hard to topple. [2]

1.6 Momentum

REVISED

Key objectives

By the end of this section, you should be able to:

- define momentum, impulse and resultant force, and recall and use the correct equations to calculate them
- apply the principle of conservation of momentum to solve simple problems

Momentum (p) is the product of mass (m) and velocity (v):

$$p = mv$$

The units of momentum are kg m/s. Momentum is a vector quantity and so the direction is important.

Conservation of momentum

In any interaction between bodies, the total momentum is conserved. This is known as the **principle of conservation of momentum**. This includes explosions in rockets as well as collisions. In an explosion such as a cannon firing, the total momentum before firing is zero. After firing, the cannonball moves forward and the cannon rolls backwards. Their momentum is equal and opposite.

Force and momentum

The **impulse** of a force is defined as the product of the force (F) and the time over which the force acts (Δt).

$$\text{impulse} = F\Delta t$$

In any interaction, the impulse exerted on a body = change of momentum.

$$F\Delta t = \Delta(mv) \quad \text{or} \quad F\Delta t = \Delta p$$

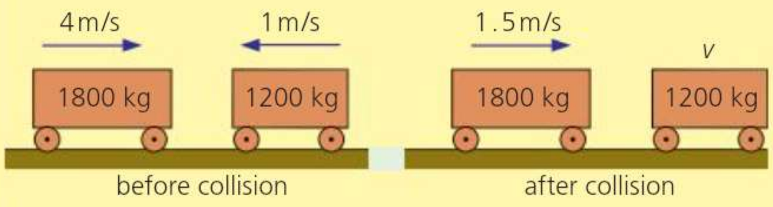
Earlier in this section, you used the equation $F = ma$ for resultant force. This relationship gives you another equation for resultant force and a new definition. **Resultant force** is the change in momentum per unit time:

$$F = \frac{\Delta p}{\Delta t}$$

Sample question

REVISED

11 A truck of mass 1800 kg moving with a velocity of 4 m/s to the right collides with a truck of mass 1200 kg moving with a velocity of 1 m/s to the left. The truck of mass 1800 kg has a velocity of 1.5 m/s to the right after the collision. Find the final velocity of the 1200 kg truck. [4]



▲ **Figure 1.26**

Student's answer

momentum before collision = $1800 \times 4 + 1200 \times 1 = 7200 + 1200$
$= 8400$ kg m/s [0]

momentum after collision = $1800 \times 1.5 + 1200v = 2700 + 1200v$ kg m/s [1]

momentum is conserved: $2700 + 1200v = 8400$ [1]

$1200v = 5700$

$v = \frac{5700}{1200} = 4.75$ m/s $= 4.8$ m/s to 2 s.f. [1]

Teacher's comments

The student made a good attempt at the question. The working was well set out. However, the student did not realise that direction is significant, as momentum is a vector quantity.

Correct answer

Consider that the positive direction is to the right and assume that v is also to the right.

momentum before collision = (1800 × 4) − (1200 × 1) = 7200 − 1200
= 6000 kg m/s [1]

momentum after collision = (1800 × 1.5) + 1200v = 2700 + 1200v kg m/s [1]

momentum is conserved: 2700 + 1200v = 6000 [1]

1200v = 3300

$v = \frac{3300}{1200}$ = 2.75 m/s = 2.8 m/s to 2 s.f. to the right [1]

Exam-style questions

Answers available at: www.hoddereducation.co.uk/cambridgeextras

17 A railway truck of mass 6000 kg moving at 6 m/s collides with a truck of mass 10 000 kg moving at 2 m/s in the same direction. The two trucks couple and move on together at 3.5 m/s.
  a Carry out a calculation to confirm that momentum is conserved. [2]
  b Determine whether kinetic energy is conserved in the collision. [3]
  c Comment on your answer to part b. [1]

18 During a kick, a 450 g football accelerates from 0 to 25 m/s. The foot and the ball are in contact for 0.02 s. Calculate the force on the ball. [2]

Revision activity

Write the words 'force', 'velocity', 'momentum' and 'time' on a blank page. Try to link the words with an explanation, e.g. link momentum and velocity and write 'momentum = mass × velocity' on the linking line. See how many links you can make. You can add other words from this topic so far. Compare your work with a partner and see if there are any links you missed.

1.7 Energy, work and power

REVISED

1.7.1 Energy

Key objectives

By the end of this section, you should be able to:

- recall the different energy stores and describe how energy is transferred between these stores
- know the principle of conservation of energy,and apply and interpret simple energy flow diagrams
- recall and use the equations to calculate kinetic energy and the change in gravitational potential energy
- interpret complex energy flow diagrams including Sankey diagrams

Energy stores

Energy may be stored in many different ways.

▼ **Table 1.4 Energy stores and their descriptions**

Stores of energy	Description	Equations
Kinetic energy	Energy due to motion, e.g. a car moving, a stone falling, a person running	$E_k = \frac{1}{2}mv^2$
Gravitational potential energy	Energy due to position, e.g. any object above the Earth's surface such as a book on a high shelf or water in a mountain lake	$\Delta E_p = mg\Delta h$
Chemical energy	Food, fuel and batteries are stores of chemical energy. The energy is released by chemical reactions.	
Elastic (strain) energy	Energy stored due to the stretching or bending of materials, e.g. stretching a rubber band, compressing or extending a spring	

Stores of energy	Description	Equations
Nuclear energy	The energy stored in the nucleus of an atom. It can be transferred by nuclear reactions such as fission in nuclear reactors or fusion in the Sun	
Electrostatic energy	Energy stored by charged objects	
Internal energy	Also called thermal energy	

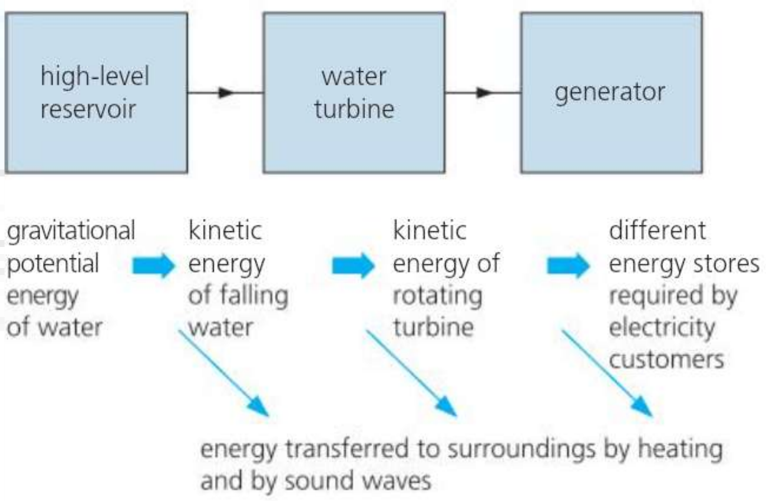
Δ is the Greek letter delta. It is used to represent change in a variable, in this case, the change in the gravitational potential store with a change in height.

Energy transfers

The **principle of conservation of energy** states that energy cannot be created or destroyed. However, energy can be transferred between stores by:

- forces (mechanical working)
- electrical currents (electrical working)
- heating through conduction, convection and radiation (Topic 2.3)
- waves (electromagnetic, sound and other waves)

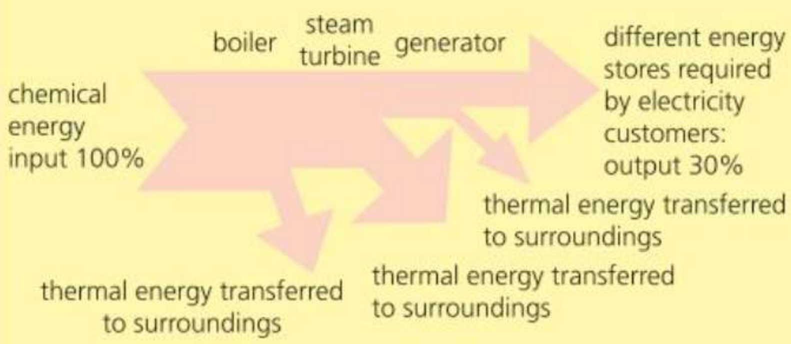
You can represent these energy transfers using a simple energy flow diagram such as in Figure 1.27.



▲ **Figure 1.27 Energy transfers in a hydroelectric power scheme**

At each stage of energy transfer, some energy is transferred less usefully. As you can see in Figure 1.27, not all the energy in the gravitational potential store is transferred to the energy stores required by electricity customers. Some of the energy is transferred to the surroundings.

In a Sankey diagram, the thickness of the bars represents the amount of energy transferred at each stage. This is useful to see the proportion of energy usefully transferred at each stage in a process. As you can see in Figure 1.28, only 30% of the energy input is transferred to the energy stores required by electricity customers.



▲ **Figure 1.28 Energy transfers in a hydroelectric power scheme**

Conservation of energy

As an object falls it loses gravitational potential energy and gains kinetic energy. If it falls from rest and you ignore air resistance, the kinetic energy on reaching the ground is equal to the loss in gravitational potential energy:

$$E_k = \Delta E_p \text{ or } \frac{1}{2}mv^2 = mg\Delta h$$

This is also true if you throw a ball vertically upwards in the air. As the ball will stop for a moment when it reaches its maximum height, the gain in gravitational potential energy is equal to the loss in kinetic energy.

Sample question

REVISED

▲ **Figure 1.29**

12 A person winds up the spring of the clockwork radio shown in Figure 1.29 using the muscles in their hand and arm. The internal spring then unwinds to provide energy to power the radio.

- **a** Describe the energy transfer between the muscles in the person's arm and the spring. [3]
- **b** Describe the process by which energy is transferred by the circuits in the radio. [1]
- **c** Name two ways energy is transferred from the radio. [2]

Student's answers

- **a** *Chemical energy is stored in their muscles and it is stored as elastic energy in the spring.* [2]
- **b** *Electrical working.* [1]
- **c** *The energy transfer is radio and sound waves.* [1]

Teacher's comments

- **a** The student has identified both stores of energy but not how the energy was transferred. In this case. by mechanical working.
- **b** Correct answer.
- **c** Energy is transferred by sound waves but radio waves transfer energy to the radio and not from.

Correct answers

- **a** Chemical energy stored in their muscles is transferred to elastic energy in the spring by mechanical working. [3]
- **b** Electrical working. [1]
- **c** Energy is transferred from the radio by sound waves and by heating. [2]

Revision activity

Make flashcards for each energy store and type of energy transfer. Use the cards to create energy transfer diagrams for different processes, e.g. a wind turbine, a solar cell, dropping a ball, throwing a ball, a pendulum, a torch. Compare your diagrams with a partner.

1.7.2 Work

Key objectives

By the end of this section, you should be able to:

- understand that mechanical work or electrical work done is equal to the energy transferred
- recall and use the equation to calculate mechanical work

In any energy transfer, **work** is done. Mechanical work is done when a force moves though a distance. The greater the force, the more work is done. The greater the distance moved, the more work is done.

work done = force × distance moved in the direction of the force

Know and be able to use the following equation:

$$W = Fd = \Delta E$$

where W is work done and ΔE is energy transferred.

To calculate work, you must identify the force and the distance moved in the direction of the force. If you walk up the stairs, you transfer energy to the gravitational potential store by mechanical work. The force is your weight ($W = mg$) and the distance is the vertical height of the stairs.

1.7.3 Energy resources

Key objectives

By the end of this section, you should be able to:

- describe the different ways useful energy is obtained or electrical power is generated, and the advantages and disadvantages of each method
- understand what is meant by the efficiency of energy transfer
- understand that the Sun releases energy through nuclear fusion and this is the main source of energy for most of the energy resources
- know that research is being carried out to find out if it is possible to have large-scale nuclear fusion to produce electricity
- define efficiency, and recall and use equations to calculate efficiency

Energy resources

There are many different energy resources. They can either be:

- **non-renewable** – cannot be replaced when used up
- **renewable** – can be replaced which means they cannot be used up

When choosing an energy resource, you have to consider its availability, reliability, scale and environmental impact. Most schemes involve a generator. When a generator is turned it produces electricity (Topic 4.5). Table 1.5 summarises this for the different energy resources.

▼ **Table 1.5 Energy resources**

Source	How the useful energy is obtained or electrical power generated	Renewable (R) or non-renewable (NR)	Availability	Reliable	Possible scale	Environmental impact
Fossil fuels	Chemical energy store in the fuels is released when they are burnt. This heats water in a boiler, making steam. The steam turns a turbine, which in turn drives a generator.	NR	Oil and gas running low; coal for the next 200 years	Yes	Large	Burning produces carbon dioxide (causes global warming) and sulfur dioxide (causes acid rain).
Water	Hydroelectric–gravitational potential energy in the water behind the dam. As the water flows through the dam, turbines are turned, which in turn drive generators.	R	Only some areas of the world have suitable sites	Yes	Medium	Loss of habitat for wildlife; land used for farming or forestry may be lost due to flooding for the dam.
	Tidal – same principle as hydroelectric	R	Only some areas of the world have suitable sites	Yes	Small	Destroys habitats for wildlife and causes problems in shipping routes
	Waves – energy of the waves is used to drive a generator.	R	Useful for island communities	Yes	Small	Problems to shipping
Geothermal	Cold water is pumped into hot rocks below the Earth's surface. The steam is used to turn a turbine, which then drives a generator.	R	Only certain parts of the world have rocks near enough to the surface that are hot enough for this to work.	Yes	Medium	Some (open-loop) designs have air emissions, although at a much lower level than burning fossil fuels: carbon dioxide (causes global warming) and hydrogen sulfide which changes to sulfur dioxide (causes acid rain). However, closed-loop designs do not.
Nuclear	Nuclear fission releases energy which is used to generate steam, which turn turbines which drive a generator.	NR	Available to countries with nuclear power stations	Yes	Large	Radiation; radioactive waste some of which has to be stored for thousands of years (Topic 5.2)
Radiation from the Sun	Solar cells – light used to generate electricity	R	Anywhere	No	Small	Large areas of solar cells to generate more electricity cover areas of land which could be used for food production.

Source	How the useful energy is obtained or electrical power generated	Renewable (R) or non-renewable (NR)	Availability	Reliable	Possible scale	Environmental impact
	Solar panels – infrared radiation heats water directly. Solar furnace – Using mirrors to focus the energy on a boiler, producing steam which turns a turbine which drives a generator.	R	Anywhere – but more effective closer to the equator	No	Small	
Wind	Turbine turned directly by the wind.	R	Coastal and upland sites best	No	Medium and small	Noisy; wind farms at sea can cause problems for shipping. Hazard to migrating birds.
Biomass	Chemical energy store in the biofuels.	R	Anywhere		Small	Produces carbon dioxide but is carbon neutral as carbon dioxide absorbed as biomass grows. Land used for food production may be lost to biofuel growth.

The Sun is the source of all energy resources except geothermal, nuclear and tidal. Energy is released by nuclear fusion in the Sun (Topic 5.1). Research is being done to try to reproduce fusion on Earth at a large scale. Currently it is not possible.

Efficiency

As you know, when energy is transferred form one store to another it is not all usefully transferred. How much energy is transferred usefully is described as the **efficiency**. In an efficient energy transfer, more of the energy input becomes useful energy output. A coal-fired power station has an efficiency of about 30%. This means that for every 100 J of energy released from burning coal only 30 J will be transferred to the electricity customers. However, a wind turbine at peak wind can have an efficiency of 50%. More of the energy has been usefully transferred.

Calculating efficiency

The **efficiency** of a device is the percentage of the energy supplied to it that is usefully transferred. You can calculate the efficiency using

$$\text{efficiency} = \frac{\text{useful energy output}}{\text{total energy input}} \times 100\%$$

or

$$\text{efficiency} = \frac{\text{useful power output}}{\text{total power input}} \times 100\%$$

Efficiency can never be more than 100%. This is because of the principle of conservation of energy.

Skills

Expressing efficiency

Efficiency can be expressed as a percentage or as a fraction written as a decimal number. To convert from a percentage to a fraction, simply divide the percentage efficiency by 100. For example, 45% is 0.45. As efficiency is always less than 100%, the number is always less than 1.

For example, a wind turbine is described as having an efficiency of 20%. Calculate the total energy input if the electrical energy transferred from the turbine is 300 J.

$$\text{efficiency as a decimal number} = \frac{20}{100} = 0.2$$

$$\text{efficiency} = \frac{\text{useful energy output}}{\text{total energy input}}$$

$$0.2 = \frac{300}{\text{total energy input}}$$

$$\text{total energy input} = \frac{300}{0.2} = 1500\ \text{J}$$

Sample question

REVISED

13 For each of the following two statements, give one strength and one weakness and write a conclusion.

a A supporter of nuclear power states that it should be more widely used as there is no pollution. [3]

b A supporter of coal-fired power stations states that nuclear power plants cannot be controlled and might explode like atomic weapons. [3]

Student's answers

a *Nuclear power stations are constantly leaking radiation, which heats up the atmosphere.* *[0]*

b *Nuclear power stations might be damaged in an earthquake or attacked by terrorists. This means there is a constant risk of a serious release of radioactive material.* *[2]*

Teacher's comments

a The student has made *no* real attempt to address the issues or draw a conclusion. If there are three marks for a question, try to make three points.

b This answer is incomplete, but the student has made two relevant points and made a basic conclusion.

Correct answers

Possible answers could be:

a Nuclear power stations produce no carbon dioxide or other air pollution, which is a powerful argument in their favour.
Nuclear power stations produce waste, some highly radioactive, which is very hard to dispose of, as it has a half-life of many centuries. This is a powerful argument against nuclear power.
Because of concerns about the production of greenhouse gases and global warming, the lack of air pollution is a substantial benefit. The issue of radioactive waste is a serious problem. The overall judgment is a matter of opinion with different countries reaching different decisions. [3]

b There have been examples of nuclear power plants overheating causing meltdown of the radioactive core, which has caused considerable release of radioactive substances into the environment. This happened in the Chernobyl incident as a result of an unauthorised test and in Japan following tsunami damage.
However, the statement exaggerates the dangers, as the nuclear material is arranged in a manner that could not cause an explosion like that of a nuclear weapon. In addition, as experience is gained, the likelihood of future incidents decreases.
Again, the two arguments have to be weighed against each other and the overall judgement is a matter of opinion with different countries reaching different decisions. [3]

Revision activity

Draw a table to summarise the advantages and disadvantages of each energy resource.

1.7.4 Power

Key objectives

By the end of this section, you should be able to:

- define power and recall and use equations to and calculate power

Power is the work done per unit time and the energy transferred per unit time. Remember work done is a measure of the energy transfer. The unit of power is the watt, W.

$$\text{power} = \frac{\text{work done}}{\text{time taken}} \quad \text{or} \quad \text{power} = \frac{\text{energy transferred}}{\text{time taken}}$$

$$P = \frac{W}{t} \quad \text{or} \quad P = \frac{\Delta E}{t}$$

Sample question

REVISED

14 The two cranes shown in Figure 1.30 are lifting loads at a port. Crane A raises a load of 1000 N to a height of 12 m in 10 s. Crane B raises the same load of 1000 N to the same height of 12 m but takes 12 s.

▲ **Figure 1.30**

a Compare the work done by the two cranes. [2]
b Compare the power of the two cranes. [2]
c Calculate the energy transferred and the power of each crane. [4]

Student's answers

a *Both cranes do the same amount of work because the force and distance moved are the same.* [2]
b *Crane B has more power because the amount of work done is the same but the time is greater.* [0]
c *energy transferred by each crane = 1000 × 12 = 12 000*
power of A = 12 000 × 10 = 120 000
power of B = 12 000 × 12 = 144 000 = 140 000 to 2 s.f. [1]

Teacher's comments

a Correct answer.
b The student has confused the relationship; the shorter the time taken, the greater the power.
c The calculation of energy transferred is correct, except that the unit (J) has been omitted. Both power calculations are incorrect because the wrong equation has been used; the unit of power (W) has also been omitted.

Correct answers

a Both cranes do the same amount of work because the force and distance moved are the same. [2]
b Crane A has more power because the amount of work done is the same but less time is taken. [2]
c Energy transferred by each crane = 1000 × 12 = 12 000 J

$$\text{Power of A} = \frac{12\,000}{10} = 1200\ \text{W}$$

$$\text{Power of B} = \frac{12\,000}{12} = 1000\ \text{W}$$ [4]

Exam-style questions

Answers available at: www.hoddereducation.co.uk/cambridgeextras

19 Copy and complete the table below to show the energy transfers in different devices. [5]

Device	Energy store at the start that decreases	Energy transfer process	Energy store at the end that increases
battery-powered fan	chemical energy		kinetic energy
roller coaster			kinetic energy
catapult	elastic energy		

20 A bungee jumper of mass 60 kg jumps from a bridge tied to an elastic rope that becomes taut after they fall 10 m. Consider the jumper when they have fallen another 10 m and are travelling at 15 m/s.

a State a store of energy that has decreased. [1]

b State two stores of energy that have increased. [2]

c Calculate the change in gravitational potential energy of the bungee jumper when they have fallen 20 m. [2]

d Calculate how much energy is stored in the rope. Ignore air resistance. [3]

21 Calculate the maximum height reached by a 60 g ball thrown vertically up in the air. The speed of the ball when it left the hands is 12 m/s. [3]

22 A 15 kg box is moved. In each case, calculate how much work is done.

a The box is dragged along the floor with a force of 25 N for 2 m. [1]

b The box is lifted onto a shelf 1.5 m high. [2]

23 Supporters and opponents are discussing a proposed new wind farm of 20 large wind turbines. The supporters say that the wind farm will use energy from a renewable source, not pollute and provide reliable energy. The opponents admit it will use energy from a renewable source, but say that it will not be reliable and it will pollute.

a Comment on the arguments of the supporters and the opponents. [4]

b Is it correct to say 'that the wind farm will use energy from a renewable source'? [2]

c Write down one other source of renewable energy and one source of non-renewable energy. [2]

24 Calculate the efficiency of a solar cell if the power input from the Sun is 1080 W and the power output is 432 W. [2]

25 A motor lifts a load of 40 N a distance of 1.4 m. The energy input to the motor is 70 J. Calculate the efficiency of the motor. [3]

26 a Calculate the power if a microwave transfers 96 000 J in 2 minutes. [2]

b Calculate the average power if a 750 N person climbs stairs 15 m high in 30 s. [2]

27 In a small-scale hydroelectric power scheme, 24 kg of water falls every second through a vertical height of 60 m from the reservoir to the turbine. The electrical output is 11 kW. Calculate the efficiency of the scheme. [3]

Revision activity

Write five questions on power and their answers. Include at least one where you have to rearrange the equation. Swap questions with a partner and check you agree with the solutions.

1.8 Pressure

REVISED

Key objectives

By the end of this section, you should be able to:

- define pressure, and recall and calculate pressure using the correct equation
- describe how pressure varies with force and area in everyday examples
- describe how pressure in a liquid varies with depth and density of the liquid
- recall and use the equation to calculate the change in pressure in a liquid

Pressure

Pressure is defined as the force per unit area. To calculate the pressure, you need to use the following equation:

$$p = \frac{F}{A}$$

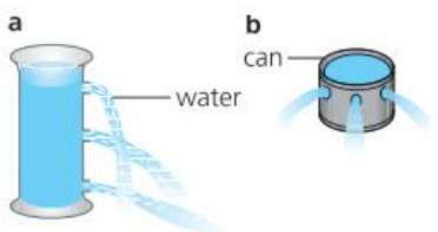
The unit of pressure is the pascal (Pa). A force of 1 N on an area of 1 m^2 exerts a pressure of 1 Pa.

The greater the area in contact as a force is applied, the less the pressure. For example, snowshoes and skis have a large surface area to stop the person wearing them sinking into the snow. They have the same weight as a person wearing normal shoes, but the pressure is less. A nail is designed with a small area of contact so that there is a high pressure when a force is applied. This allows the nail to be hammered into the wood.

Liquid pressure

Pressure beneath a liquid surface depends on the depth and the density of the liquid.

- The greater the depth in a given liquid, the greater the pressure. This is because as you increase in depth there is a greater weight of liquid above you. Figure 1.31a shows how the pressure is greater at the bottom of the column of liquid. Figure 1.31b shows that at one depth the pressure acts equally in all directions.
- At a given depth, the greater the density of the liquid, the greater the pressure. This is because a higher density liquid has a greater weight per unit volume. Remember the density is the mass per unit volume.



▲ **Figure 1.31 Pressure in a liquid**

You should know and be able to use the following equation:

$$\Delta p = \rho g \Delta h$$

where Δp is the change in pressure between the surface and that depth, ρ is the density of the liquid, g is the acceleration due to gravity and Δh is the depth below the surface of the liquid.

Skills

How many significant figures to use for the final answer

Remember only the final answer in the calculation should be rounded. Use the number in the calculator as you go through a calculation with more than one stage. The final answer should be the same number of significant figures (s.f.) as the number of the significant figures in the values used to calculate, e.g. if you know the depth is 5.00 m and the density is 1020 kg/m^3, then you know the depth and density to 3 significant figures. However, if you use g = 9.8 m/s^2, you only know the value to 2 significant figures. This means your final answer should be quoted to 2 significant figures.

For example, calculate the pressure exerted on the floor by a 12 kg sack with an area of 0.015 m^2.

$W = mg = 12 \times 9.8 = 117.6$ N

$\text{pressure} = \frac{F}{A} = \frac{117.6}{0.015} = 7840\text{ N} = 7800\text{ N to 2 s.f.}$

(All values used only given to 2 s.f.)

Sample question

REVISED

15 Some students are playing a ball game in the sea and the ball is pushed 60 cm below the surface of the water
(Density of seawater = 1.025 × density of freshwater.)

- **a** Explain how the pressure on the ball at a depth of 60 cm below the surface of the sea compares with the pressure just below the surface. [2]
- **b** Explain how the pressure on the ball at a depth of 60 cm below the surface of the sea compares with the pressure 60 cm below the surface of a freshwater lake. [2]
- **c** Calculate the pressure on a point on the ball 60 cm below the surface of the sea (density of freshwater = 1000 kg/m^3). [2]

Student's answers

- *a* *The pressure increases.* [1]
- *b* *The pressure on the ball below the surface of the sea is greater because seawater has a greater density.* [1]
- *c* *pressure = $\Delta h \rho g = 0.6 \times 1000 \times 9.8 = 5900$ Pa to 2 s.f.* [1]

Correct answers

- **a** The pressure increases because the ball is at a greater depth in the same liquid. [2]
- **b** The pressure on the ball below the surface of the sea is greater because seawater has a greater density and both balls are at the same depth. [2]
- **c** density of sea water = 1.025 × 1000 kg/m^3 = 1025 kg/m^3
  $\Delta p = \Delta h \rho g = 0.6 \times 1025 \times 9.8 = 6027$ Pa = 6000 Pa to 2 s.f. [2]

Teacher's comments

- **a** The statement is correct but there is no explanation.
- **b** The statement is correct and the reason is also correct, but not quite complete. The student should have mentioned that the comparison was at the same depth below each surface.
- **c** The pressure has been calculated in the correct way but at a depth of 60 cm below the surface of freshwater instead of seawater.

Exam-style questions

Answers available at: www.hoddereducation.co.uk/cambridgeextras

28 Describe how a drawing pin is designed so that it can be pushed into a notice board without hurting you. [2]

29 A block of marble weighing 4900 N has a base in contact with the ground of 0.80 m by 1.30 m. Calculate the pressure on the floor. [2]

30 Dams are built across rivers to trap water behind. They are built so that they are much thicker at the bottom than the top.

- **a** Explain why they are thicker at the bottom than the top. [2]
- **b** The depth of water behind a dam is 78.0 m. Calculate the pressure at the bottom of a dam. Density of water = 1000 kg/m^3. [1]

Revision activity

Create a mind map on pressure. Include any equations and some everyday examples of low- or high-pressure situations

2 Thermal physics

Key terms

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Term	Definition
Absolute zero	Lowest possible temperature: −273°C or 0 K
Condensation	Change of a gas to a liquid
Conduction	Flow of thermal energy transferred through matter from places of high temperature to places of low temperature without movement of matter as a whole
Convection	Flow of thermal energy through a fluid from places of high temperature to places of low temperature by movement of the fluid itself because of change of density
Degrees Celsius	°C; unit of temperature
Kelvin	K; SI unit of temperature; a kelvin has same size as a degree Celsius but 0°C = 273 K
Molecule	Combination of atoms
Particle	Any small piece of a substance; it could be one ion, electron, atom or molecule or billions of them
Radiation of thermal energy	Transfer of thermal energy from one place to another by infrared electromagnetic waves
Temperature	A measure of the average kinetic energy of the molecules of a body
Thermal energy	Energy of the molecules of a body
Vaporisation	Change of a liquid to a gas
Specific heat capacity	Energy needed per unit mass per unit temperature rise

2.1 Kinetic particle model of matter

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2.1.1 States of matter

Key objectives

By the end of this section, you should be able to:

- know the properties of solids, liquids and gases and the terms for the changes in state between them

Solids have a definite shape and size and are hard to compress.

Liquids have a definite volume but adopt the shape of their container. They are easier to compress than solids but still not easily compressed.

Gases have no definite size or shape but fill their container and adopt its shape.

Changes of state

Melting occurs when a solid becomes a liquid.

Solidification or freezing occurs when a liquid becomes a solid.

Evaporation or boiling occurs when a liquid becomes a gas.

Condensation occurs when a gas becomes a liquid.

2.1.2 Particle model

Key objectives

By the end of this section, you should be able to:

- explain how the kinetic particle model explains the nature of solids, liquids and gases
- know that the forces and distances between particles and the particle motion affect the properties of solids, liquids and gases
- describe the relationship between particle motion and temperature and understand the concept of absolute zero
- describe pressure and change in pressure in terms of particle motion and their collisions with a surface
- describe pressure and changes in pressure in terms of force per unit area
- distinguish between microscopic particles, atoms and molecules
- describe and explain Brownian motion

All matter is made up of **particles** (atoms, **molecules**, ions, electrons) in motion. The higher the temperature, the faster the motion of the particles. Almost always, matter expands with increases in temperature. Particles have their least kinetic energy at absolute zero, the lowest possible temperature.

Solids

Key features of solids:

- Particles are close together.
- Particles vibrate about fixed points in a regular array or lattice.
- The rigid structure of solids results from these fixed positions.
- As temperature increases, the particles vibrate further and faster. This pushes the fixed points further apart and the solid expands.

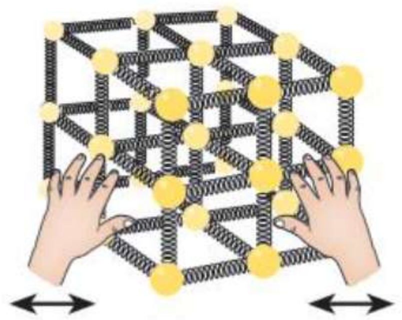
- There is only a very slight expansion of a solid with increases in temperature, e.g. the length of an iron rod increases by about 0.1% when it is heated from 20°C to 100°C.
- The positions of particles in a solid are fixed because the attractive and repulsive forces between neighbouring particles are balanced.
- The strong attractive forces between particles of a solid give them a rigid structure. The weaker attractive forces between particles of a liquid hold the liquid together but without a rigid structure. The lack of attractive forces between particles of a gas allow them to move freely within their container.

Skills

Drawing simple particle diagrams

Draw a diagram to show the arrangement and motion of particles of a solid. Use the model of Figure 2.1 to guide you.

- Draw the particles as rows of circles regularly arranged.
- Add two-way arrows to show vibration.
- Label the arrows 'vibration of the particles in the lattice'.



▲ **Figure 2.1 A model of the behaviour the particles of a solid**

Liquids

Key features of liquids:

- Particles are slightly further apart than in solids.
- Particles are still close enough to keep a definite volume.
- The main motion of the particles is vibration. The particles also move randomly in all directions, not being fixed to each other.
- As temperature increases, the particles move faster and further apart, so the liquid expands. One exception to this is that, when liquid water is heated from 0°C to 4°C, its structure changes, so it contracts instead of expands.

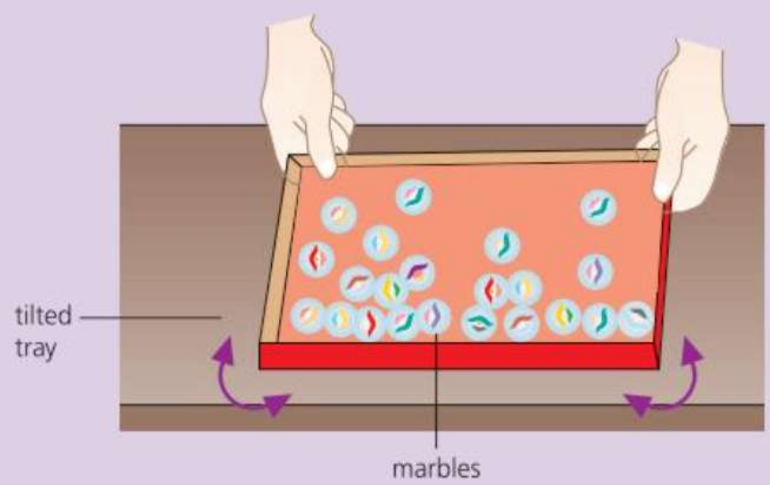
> - The forces between particles are too weak to keep them in a definite pattern but are enough to hold them to the bulk of the liquid.
> - There is a small expansion of a liquid with increases in temperature, e.g. the volume of many liquids increases by about 4% when heated from 20°C to 100°C.

Skills

Drawing simple particle diagrams

Draw a diagram to show the arrangement and motion of particles of a liquid. Use the model of Figure 2.2 to guide you.

- Draw some of the particles as rows of circles regularly arranged.
- Add other circles separated from the regular arrangement.
- Draw two-way arrows to show vibration of the particles regularly arranged.
- Label the arrows 'most particles vibrate'.
- Add labels to separated particles 'some particles are free to move through the liquid'.



▲ **Figure 2.2 A model of the behaviour of the particles of a liquid**

Gases

Key features of gases:

- Particles are much further apart than in solids or liquids.
- Particles move much faster than in solids or liquids.
- There is no definite volume. Particles move throughout the available space.
- Particles constantly collide with each other and the container walls.

> - There are no forces between particles except during a collision.

- There are no forces between particles except during a collision.
- Gases have low densities.
- The higher the temperature, the faster the speed of the particles. In fact, temperature is a measure of the average speed of the particles.
- The higher the temperature, the larger the volume of a gas at constant pressure.

> - There is a considerable expansion of a gas with increases in temperature at constant pressure, e.g. the volume of a gas increases by about 27% when it is heated from 20°C to 100°C.

Skills

Drawing simple particle diagrams

Draw a diagram to show the arrangement and motion of particles of a gas. Use the model of Figure 2.3 to guide you.

- Draw the particles as circles well spread out and arranged randomly through the container.
- Label the circles 'particles move at random colliding with the walls of the container and each other'.

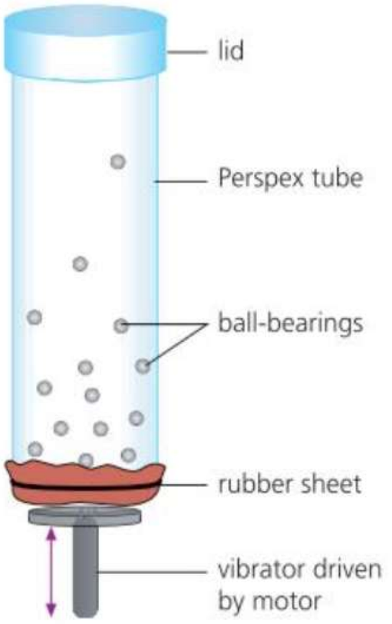


Figure 2.3 A model of the behaviour of the particles of a gas

Brownian motion

In the apparatus in Figure 2.4, smoke particles reflect the light, which is seen in the microscope as tiny bright dots. They move around randomly, and they also appear and disappear as they move vertically. This movement is caused by the irregular collisions between the microscopic smoke particles and fast-moving, **invisible** air particles. This is clear evidence for the particle model of matter.

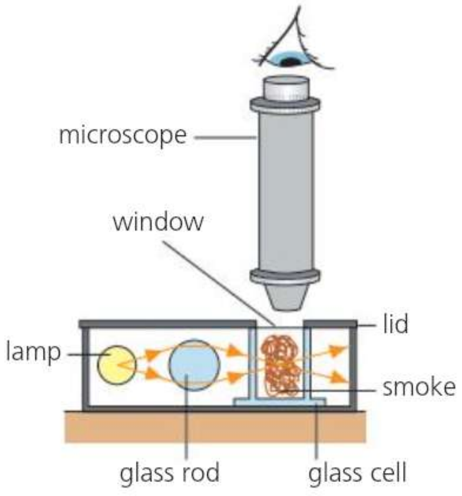


Figure 2.4 Observing Brownian motion of smoke particles

The particle model was first observed by Robert Brown, who observed in a microscope pollen particles suspended in water moving haphazardly due to bombardment by fast-moving, invisible water molecules.

Smoke/pollen particles are visible in a microscope and relatively massive.

Air/water particles are invisible and are fast-moving molecules.

Sample questions

1 Compare:

- **a** the separation of particles of a liquid and a gas [2]
- **b** the nature of the motion of particles of a solid and a liquid [2]
- **c** the forces between the particles of a solid and a gas [3]

Student's answers

- **a** *it is greater* [0]
- **b** *they vibrate* [1]
- **c** *there are strong attractive forces between particles of a solid but no forces between the particles of a gas* [2]

Teacher's comments

- **a** This is a vague statement that gives no information.
- **b** The student's statement is still too vague as it is not stated which state of matter it refers to. One mark is scored as the particles of both states do vibrate.
- **c** This statement is correct for a solid and most of the time for a gas.

Correct answers

- **a** The particles of a gas are much further apart. [2]
- **b** The particles of both states vibrate but some particles of a liquid also move randomly through the liquid. [2]
- **c** There are strong attractive forces between particles of a solid. There are no forces between the particles of a gas except when they collide and there are strong repulsive forces. [3]

2 A student looks in a microscope at a cell containing illuminated smoke particles. Explain:

- **a** what is seen [1]
- **b** the movement observed [1]
- **c** what causes this movement [2]

Student's answers

- **a** *Smoke particles* [0]
- **b** *Moving around* [0]
- **c** *The smoke molecules are bombarded by air.* [1]

Teacher's comments

- **a** It is reflected light, not smoke particles, that is seen.
- **b** Moving around is too vague.
- **c** The word 'molecule' is incorrect and the whole answer is incomplete.

Correct answers

- **a** Bright specks of light. [1]
- **b** Moving around haphazardly in *all* directions. [1]
- **c** The bright specks are light reflected off the smoke particles, which are bombarded by air particles. [2]

2.1.3 Gases and the absolute scale of temperature

Key objectives

By the end of this section, you should be able to:

- describe and explain in terms of particles the changes of gas pressure with changes of temperature and volume
- recall and use the equation pV = constant, including a graphical representation of this relationship
- recall and use the equation to convert temperature between kelvin and degrees Celsius

Gas pressure

There is a force when fast-moving particles collide with the walls of the container they are in. Gas pressure is caused by the total force of collisions per unit area. The higher the temperature, the faster the particles move. If the volume is kept constant, the pressure increases because:

- there are more frequent collisions with the container walls
- the collisions are harder, so exert more force

Note: The gas particles do collide with each other but this is not relevant to the cause of gas pressure.

Gas pressure and volume at constant temperature

At a **constant temperature**, gas molecules move at a constant average speed, so the average force from each collision is the same. If the gas is compressed into a smaller volume, there are more frequent collisions on each unit of area of the surface. So, the total force per unit area increases and the pressure increases.

Similarly, if the gas expands to a greater volume at a constant temperature, the pressure decreases.

You should know and be able to use the equation for a fixed mass of gas at constant temperature:

$$pV = \text{constant} \qquad \text{or} \qquad p_1V_1 = p_2V_2$$

The relationship between the varying pressure and volume of a fixed mass of gas at constant temperature is shown by Figure 2.5.

Skills

Rearranging the equation to make any variable the subject

You need to be able to rearrange the equation $p_1V_1 = p_2V_2$ to make any of the variables the subject.

To make p_1 the subject:

$$p_1V_1 = p_2V_2$$

$$p_1 = \frac{p_2V_2}{V_1}$$

To make p_2 the subject:

$$p_1V_1 = p_2V_2$$

$$p_2V_2 = p_1V_1$$

$$p_2 = \frac{p_1V_1}{V_2}$$

To make V_1 the subject:

$$p_1V_1 = p_2V_2$$

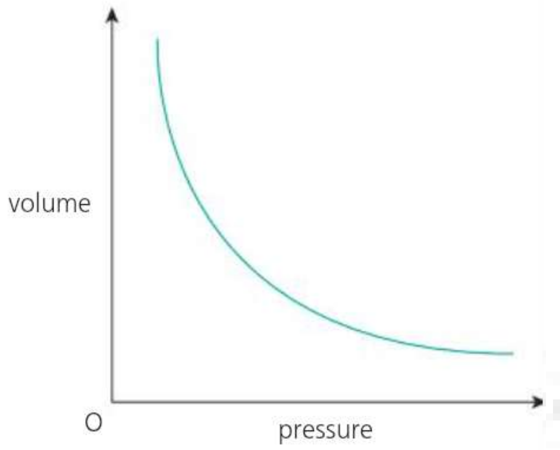
$$V_1 = \frac{p_2V_2}{p_1}$$

To make V_2 the subject:

$$p_1V_1 = p_2V_2$$

$$p_2V_2 = p_1V_1$$

$$V_2 = \frac{p_1V_1}{p_2}$$



▲ **Figure 2.5 Pressure and volume of a fixed mass of gas at constant temperature**

Celsius and Kelvin temperature scales

Absolute zero is the lowest possible temperature. On the Celsius scale absolute zero is −273°C. On the Kelvin scale it is 0 K. The two scales have units of the same size and are related by the equation:

$$\text{temperature in K} = \text{temperature in °C} + 273$$

Skills

Converting between kelvin and degrees Celsius

You need to be able to convert between **kelvin** and **degrees Celsius**. To do this you need to rearrange the equation temperature in K = temperature in °C + 273 to make temperature in °C the subject.

$$\text{temperature in °C} + 273 = \text{temperature in K}$$

$$\text{temperature in °C} = \text{temperature in K} - 273$$

Sample questions

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3 A piston slowly compresses a gas from 540 cm³ to 30 cm³, so that the temperature remains constant. The initial pressure was 100 kPa. Find the final pressure. [3]

Student's answer

Vol = 30 cm P = 100

100 × 30 = 3000 N [0]

Teacher's comments

The student has not approached the question at all systematically or used the right equation. Two numbers have been combined to give a value but this is meaningless and the unit is also incorrect for pressure.

Correct answer

Note: If you set out your working logically, as shown below, you are much more likely to get the answer right.

$p_1 = 100\,\text{kPa}, p_2 = \text{unknown}$

$V_1 = 540\,\text{cm}^3, V_2 = 30\,\text{cm}^3$

$p_1V_1 = p_2V_2$

$100 \times 540 = p_2 \times 30$

$p_2 = \frac{100 \times 540}{30} = \frac{54000}{30} = 1800\,\text{kPa}$ [3]

4 A gas cylinder is heated in a fire. State what happens to the pressure of the gas and explain your answer in terms of the gas particles. [4]

Student's answer

The pressure increases because the particles move around more, hitting each other and the walls. [1]

Teacher's comments

The student's answer is vague, mentioning the particles colliding with each other, which is irrelevant.

Correct answer

The pressure increases because the particles move faster [2], hitting the walls more frequently and harder, thus increasing the total force on the walls per unit area. [2]

5 Describe in terms of the particles of a gas the effect on the pressure of a gas of an increase of volume at constant temperature. [4]

Student's answer

The pressure gets less because the particles are further apart. [1]

Teacher's comments

The comment about pressure is correct. The rest of the statement is vague and does not explain anything.

Correct answer

The pressure decreases. The particles move with the same velocity but there are fewer collisions with the walls with the larger volume. So, there is less force on the walls per unit area. [4]

6 The temperature in a cold store is –24°C. Calculate the temperature in kelvin. [2]

Student's answer

temperature = 24 + 273 = 297 K [1]

Teacher's comments

The student knew 273 should be added but used the wrong Celsius temperature.

Correct answer

temperature in K = temperature in °C + 273 = −24 + 273 = 249 K [2]

Revision activities

1 Draw sketches to show models of the particles of solids, liquids and gases.
2 Draw a sketch of the path of smoke particles showing Brownian motion as would be seen in a microscope.

3 Make a revision poster for the equation showing the pressure and volume of a fixed mass gas which change at constant temperature. State the variables. Rearrange the equation four times so each variable is on its own on the left of the equals sign.

Exam-style questions

Answers available at: www.hoddereducation.co.uk/cambridgeextras

1 A gas particle strikes the wall of a container and bounces back. Explain:
   a in terms of momentum, how this causes a force on the walls of the container [2]
   b how all the particles of the gas cause a pressure on the walls of the container [2]

2 The volume of a gas increases at constant temperature. The particles of the gas are moving.
   For parts **a** to **d**, choose **one** of *increases*, *decreases* or *stays the same* to describe the new state of each quantity.
   a pressure
   b kinetic energy of the particles
   c rate of collisions of particles per unit area of walls
   d total force per unit area [4]

3 Which description compares the properties of the particles of solids to the properties of particles of gases?

	Solids	Gases
A	closest	move slowest
B	closest	move fastest
C	furthest apart	move fastest
D	furthest apart	move slowest

[1]

4 An experiment is carried out on some gas contained in a cylinder by a piston, which can move.
   In stage 1, the gas is heated with the piston fixed in position. State and explain whether the following will increase, decrease or stay the same during stage 1:
   a the speed of the gas particles [2]
   b the number of collisions per second between particles and the walls [2]
   c gas pressure [2]

5 A sample of gas stays at a fixed temperature while its volume increases.
Which describes the new state of the gas?

	Speed of the particles of the gas	Number of collisions per second between particles and walls
A	increases	stays the same
B	stays the same	decreases
C	stays the same	increases
D	decreases	stays the same

[1]

6 Describe an experiment using pollen particles to demonstrate Brownian motion. You should:
- a draw a labelled diagram of the apparatus [2]
- b state what is seen [2]
- c explain how what is seen illustrates Brownian motion [2]

7 The volume of the container holding a fixed mass of gas is reduced from 800 cm^3 to 300 cm^3. The final pressure of the gas is 600 kPa above the atmospheric pressure of 100 kPa.
Calculate the initial pressure of the gas compared with atmospheric pressure. [4]

2.2 Thermal properties and temperature

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Thermal energy flows from a hot body to a cold body.

Temperature measures the amount of thermal or internal energy in a body. In everyday terms, it measures how hot a body is.

2.2.1 Thermal expansion of solids, liquids and gases

Key objectives

By the end of this section, you should be able to:
- describe the consequences of the thermal expansion of solids, liquids and gases in a wide range of practical situations from everyday life
- describe the expansion of solids, liquids and gases as their temperatures rise

Relative amount of expansion of solids, liquids and gases

Solids when heated expand the least:
- Particles are close together and vibrate about fixed points in a regular array or lattice.
- As temperature increases, the particles vibrate further and faster. This pushes the fixed points a little further apart and the solid expands.

Liquids when heated expand more than solids but less than gases:
- Particles are slightly further apart than in solids but still close enough to keep a definite volume.
- The main motion of the particles is vibration. The particles also move randomly in all directions, not being fixed to each other.

- As temperature increases, the particles move faster and further apart, so there is a small expansion of a liquid.

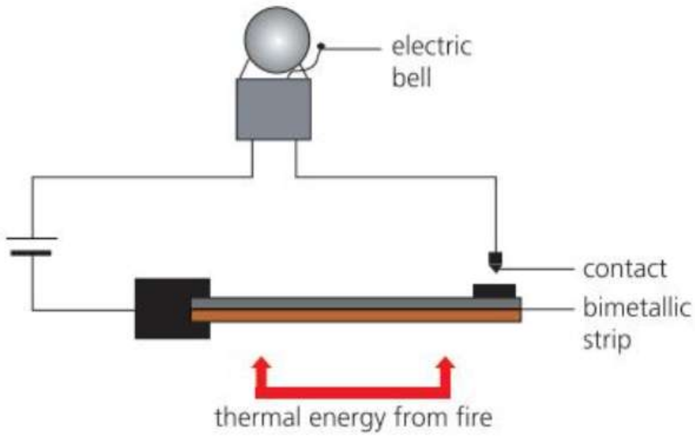
Gases when heated expand the most:

- Particles are much further apart than in solids or liquids. They move much faster than in solids or liquids and move throughout the available space.
- The higher the temperature, the faster the speed of the particles.
- The higher the temperature, the larger the volume of a gas to keep the pressure constant.
- There is a considerable expansion of a gas with increases in temperature at constant pressure.

▼ **Table 2.1 Uses and disadvantages of thermal expansion**

	Uses	Disadvantages
Thermal expansion of solids	Shrink-fitting, curling of a bimetallic strip in a fire alarm	Gaps need to be left between lengths of railway line to allow for expansion in hot weather.
Thermal expansion of liquids	Liquid-in-glass thermometers	The water in a car's cooling system expands when the engine gets hot. A separate water tank is needed for the hot water to expand into.
Thermal expansion of gases	Internal combustion engines	Gas cylinders can explode if overheated.

In the fire alarm circuit in Figure 2.6, thermal energy from the fire causes the lower metal in the bimetallic strip to expand more than the upper metal. This causes the strip to curl up, which completes the circuit and the alarm bell rings.



▲ **Figure 2.6 A fire alarm**

Sample question

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7 The lid is stuck on a glass jar. How could you use hot water to release it? Explain in terms of the particles how this works. [4]

Student's answer

Put the glass jar in hot water and the lid will come off [1] because the molecules expand. *[0]*

Teacher's comments

The student did not specify where exactly the hot water should be used and gave a vague, incorrect explanation of the role of the molecules. It is quite acceptable to use the terms molecules or particles.

Correct answer

The correct answer should include:

Put the lid in hot water so that it expands and can be released. [2] The particles in the lid will move faster; their mean positions move further apart, so the lid expands. [2]

2.2.2 Specific heat capacity

Key objectives

By the end of this section, you should be able to:

- understand that a rise in an object's temperature increases its internal energy
- describe temperature rise of an object in terms of an increase in average kinetic energy of its particles
- define specific heat capacity, and recall and use the equation for it
- describe experiments to measure the specific heat capacity of a solid and a liquid

When thermal energy flows into a body, its molecules move faster, increasing its internal energy, the kinetic energy of its particles and its temperature.

Specific heat capacity is a property of a material.

Specific heat capacity is defined as the thermal energy needed *per kilogram* (unit mass) to increase the temperature of a material by 1°C.

You should know and be able to use the following equation:

$$c = \frac{\Delta E}{m\Delta\theta}$$

You should know the following symbols: c = specific heat capacity, ΔE = energy change, m = mass, $\Delta\theta$ = temperature change.

Skills

Rearranging the equation for specific heat capacity

You need to be able to rearrange the specific heat capacity equation $c = \Delta E/m\Delta\theta$ to make any of the variables the subject.

Write down the equation when ΔE is the subject:

$$c = \frac{\Delta E}{m\Delta\theta}$$

$$\frac{\Delta E}{m\Delta\theta} = c$$

$$\Delta E = cm\Delta\theta$$

Write down the equation when m is the subject:

$$c = \frac{\Delta E}{m\Delta\theta}$$

$$cm\Delta\theta = \Delta E$$

$$m = \frac{\Delta E}{c\Delta\theta}$$

Write down the equation when $\Delta\theta$ is the subject:

$$c = \frac{\Delta E}{m\Delta\theta}$$

$$cm\Delta\theta = \Delta E$$

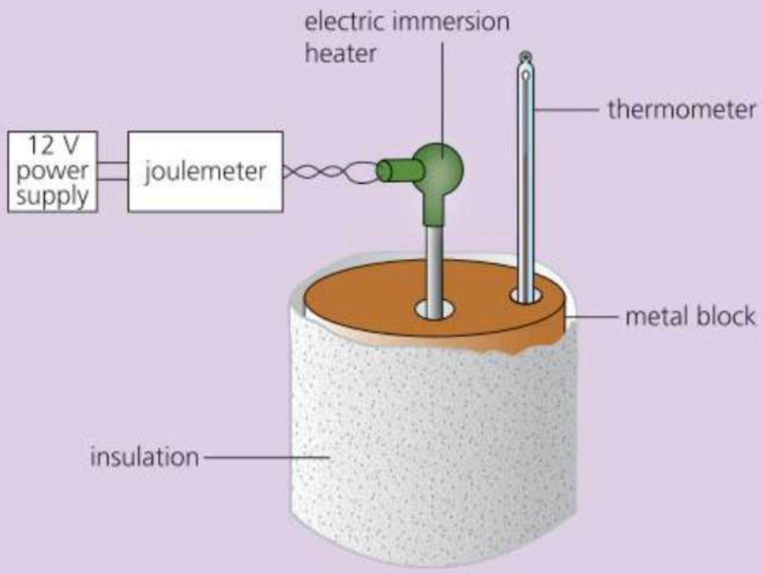
$$\Delta\theta = \frac{\Delta E}{cm}$$

Write down the units of specific heat capacity:

J/(kg °C)

Skills

Measuring the specific heat capacity of a solid



▲ **Figure 2.7 The insulation reduces thermal energy transfer to the surroundings**

Measure the mass of the metal block and the temperature before and after heating, and record the joulemeter reading of the energy supplied (Figure 2.7). Use these results to calculate the specific heat capacity of the block.

Here is an example of working out from another experiment:

mass of metal block = 1.6 kg

temperature before heating = 21°C

temperature after heating = 66°C

increase of temperature = 45°C

joulemeter reading = 46 800 J

specific heat capacity

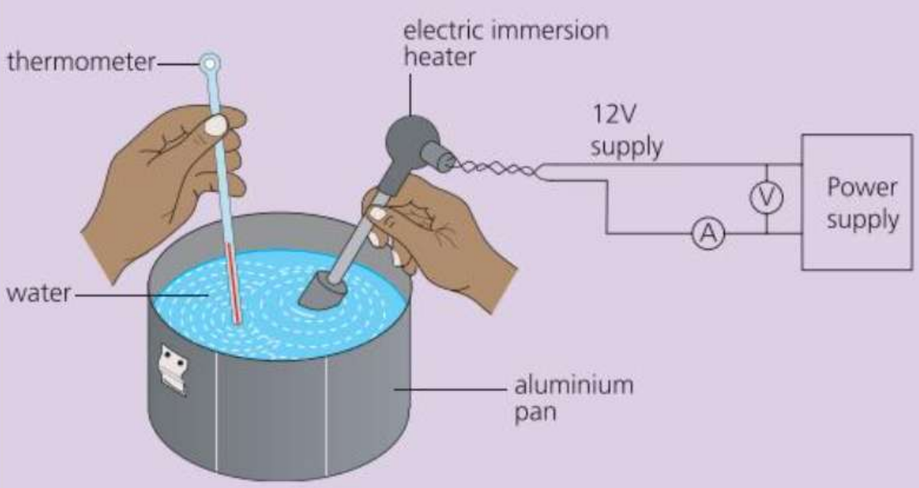
$$= \frac{\text{energy supplied by immersion heater}}{\text{mass} \times \text{temperature increase}}$$

$$= \frac{46800}{1.6 \times 45}$$

$= 650\ \text{J/(kg °C)}$ to 2 s.f.

Skills

Measuring the specific heat capacity of a liquid



▲ **Figure 2.8 Experiment to find the specific heat capacity of a liquid**

Measure the mass of the water and the temperature before and after heating. Record the voltmeter (V) and ammeter (I) readings and the heating time in seconds (t). Use these results to calculate the specific heat capacity of the water.

energy received by water = VIt

specific heat capacity =

$$\frac{\text{energy received by water}}{\text{mass} \times (\text{temperature after heating} - \text{temperature before heating})}$$

Sample question

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8 A heater of power 120 W heats a block of metal of mass 3.5 kg for 6 minutes. The specific heat capacity of the metal is 900 J/(kg°C) and its initial temperature 300 K. Calculate the final temperature of the metal block. [4]

Student's answer

$$c = \frac{\Delta E}{m\Delta\theta}$$

energy supplied = ΔE = 120 × 6 = 720 J

$$\Delta\theta = \frac{m\Delta E}{mc} = \frac{3.5 \times 720}{900} = 2.8°C = 2.8 K$$

final temperature = 273 + 2.8 = 276 K [1]

Teacher's comments

The student started with the correct equation but made mistakes in applying it.

As watts are joules/second, the power should have been multiplied by the time in seconds.

The specific heat capacity equation was incorrectly rearranged for $\Delta\theta$.

The temperature rise was added to the Kelvin temperature of freezing water not to the initial temperature.

Correct answer

$$c = \frac{\Delta E}{m\Delta\theta}$$

energy supplied = ΔE = 120 × 6 × 60 = 43 000 J

$$\Delta\theta = \frac{m\Delta E}{mc} = \frac{43000}{3.5 \times 900} = 14°C = 14 K$$

final temperature = 300 + 14 = 314 K [4]

2.2.3 Melting, boiling and evaporation

Key objectives

By the end of this section, you should be able to:

- describe melting, boiling, condensation, solidification and evaporation and use these terms
- know the melting and boiling temperatures of water at standard atmospheric pressure
- know that evaporation causes cooling of a liquid
- describe the differences between boiling and evaporation
- describe how temperature, surface area and air movement affect evaporation, and explain the cooling effect of an evaporating liquid on an object

During **vaporisation** (**evaporation** and **boiling**) thermal energy is supplied to break the bonds between particles without a change of temperature. The boiling temperature of water at standard atmospheric pressure is 100°C.

Evaporation causes the particles in the remaining liquid to cool down because energy is needed to break the bonds between molecules, and the more energetic particles escape from the surface.

The rate of evaporation increases with:

- higher temperatures, as more particles at the surface are moving faster
- increased surface area, as more particles are at the surface
- a wind or air movement, as the gas particles are blown away so cannot re-enter the liquid

An object is cooled when in contact with an evaporating liquid because the liquid has cooled down.

Condensation occurs when gas or vapour particles return to the liquid state. Thermal energy is given out as the bonds between particles in the liquid re-form.

Melting, or fusion, takes place at a definite temperature called the melting point. Ice is solid water. The melting temperature of ice at standard atmospheric pressure is 0°C. Thermal energy must be provided to break the bonds between particles for them to leave the well-ordered structure of the solid.

Solidification, or freezing, occurs when particles of a liquid return to the solid state. This takes place at a definite temperature called the freezing point, which has the same value as the melting point. Thermal energy is given out as the bonds between particles of the solid re-form.

Differences between boiling and evaporation

Evaporation takes place from the surface of the liquid at all liquid temperatures.

Boiling occurs at a definite temperature called the boiling point. Bubbles of vapour form within the liquid and rise freely to the surface. Energy must be supplied continuously to maintain boiling.

Sample question

REVISED

9 A student is playing football on a cool, windy day, wearing a T-shirt and shorts. He feels comfortably warm because he is moving around vigorously. His kit then gets wet in a rain shower. Explain why he now feels cold. [2]

Student's answer

The wet T-shirt makes him feel cold. [0]

Teacher's comments

The student's answer is far too vague and does not mention the cooling caused by evaporation.

Correct answer

The water in his wet kit is evaporated by the wind. [1] The thermal energy needed for this evaporation is taken from the water in his T-shirt and shorts, as well as from his body, so he feels cold. [1]

Revision activity

Work in pairs to revise the equation connecting temperature in kelvin and °C and how to rearrange it. On your own, complete each of the following questions. Then swap answers and check each other's work.

1. Write down the equation connecting temperature in kelvin and °C with temperature in kelvin on its own on the left of the equals sign.
2. Write down the equation connecting temperature in kelvin and °C with temperature in °C on its own on the left of the equals sign.

Exam-style questions

Answers available at: www.hoddereducation.co.uk/cambridgeextras

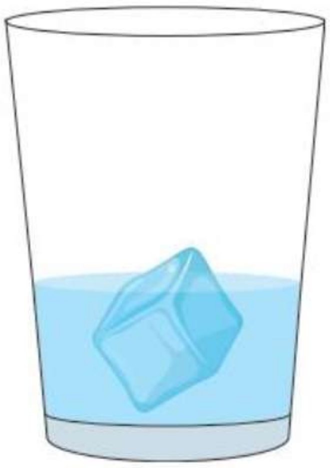
8 An ice cube with a temperature of 0°C is placed in a glass of water (Figure 2.9) with a temperature of 20°C.
After a few minutes, some of the ice has melted. State and for (a) and (b) explain whether the following increase, decrease or stay the same:
  a the temperature of the remaining ice [2]
  b the temperature of the water [2]
  c the mass of water in the glass [1]
  d the total mass of the ice and water [1]

9 Write down three differences and two similarities between boiling and evaporation. [5]

10 Write down the boiling temperature in kelvin and degrees Celsius of water at standard atmospheric pressure. [2]

11 Two straight strips of metal alloys (invar and bronze) are bonded together at room temperature. Bronze expands appreciably when heated, but invar expands very little. Describe the shape of the strips when heated in an oven. Explain your answer. [2]

12 An experiment is carried out to find the specific heat capacity of a metal. A 2 kg block of the metal is heated by a 200 W heater for 5 min, and the temperature of the block rises from 20°C to 51°C. Work out:
  a the energy supplied to the block by the heater [2]
  b the specific heat capacity of the metal [3]
When used in an engine, a component made from this metal receives 35 kJ of thermal energy and its temperature rises from 30°C to 290°C.
  c Work out the mass of the component. [2]



▲ Figure 2.9

2.3 Transfer of thermal energy

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Thermal energy is always transferred from a place of high temperature to a place of low temperature.

2.3.1 Conduction

Key objectives

By the end of this section, you should be able to:

- describe experiments to demonstrate the properties of good thermal conductors and bad thermal conductors
- describe thermal conduction in terms of lattice vibrations and in terms of the movement of free electrons
- describe why thermal conduction is bad in gases and most liquids, and know that many solids conduct thermal energy well

In **conduction**, thermal energy is transferred through a material without movement of the material.

Metals are generally good conductors, but most other solids are poor conductors. Liquids are generally much worse thermal energy conductors than metals.

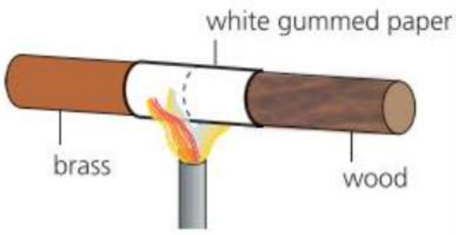
Gases are all very poor conductors of thermal energy. For example, if you put your hands in very cold water, they will feel cold almost at once. If your hands are in air of the same temperature, they will cool down but at a much slower rate because air is a bad conductor.

The atoms or molecules in a hot part of a solid vibrate faster and further than those in a cold part.

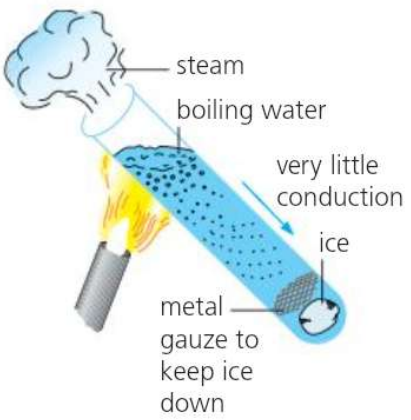
In metals, thermal energy is transferred by fast-moving free electrons, which pass through the solid, causing atoms in colder parts to vibrate more.

There is a secondary mechanism that is much slower. The vibrating atoms or molecules in the lattice cause their neighbours to vibrate more, thus passing on thermal energy. Non-metals do not have free electrons so can use only this mechanism, which is why non-metals are poor conductors. Some substances, e.g. semiconductors, have a limited number of free electrons so conduct thermal energy better than thermal insulators but less well than good thermal conductors.

These mechanisms explain why liquids are generally poor conductors and gases even worse. There are no free electrons and the secondary mechanism works poorly. There is very little contact between vibrating atoms or molecules in liquids and almost none in gases.



▲ **Figure 2.10 The paper over the brass does not burn because brass is a good conductor**



▲ **Figure 2.11 Water is a poor conductor of thermal energy**

Skills

Demonstrating the properties of good and bad thermal conductors

The practicals shown in Figure 2.10 and Figure 2.11 can be done to show the properties of good thermal conductors and poor thermal conductors.

2.3.2 Convection

Key objectives

By the end of this section, you should be able to:

- explain convection in liquids and gases and describe experiments to illustrate convection

In **convection**, thermal energy is transferred owing to movement of the liquid or gas itself. Convection cannot take place in a solid.

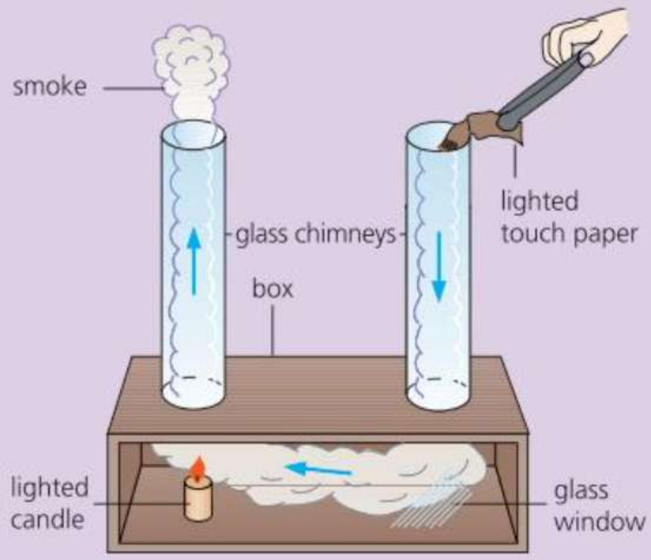
The liquid or gas expands on heating, so its density falls. The warmer and lighter liquid or gas rises to the cooler region, transferring thermal energy in the process.

Skills

Demonstrating convection

Figure 2.12 demonstrates a convection current. The heated air above the candle rises up the left-hand chimney and draws smoke from the lighted paper down the right-hand chimney and into the box.

Convection currents in water can be seen by dropping a potassium permanganate crystal into a beaker of water. The coloured traces indicate the flow of the convection currents.



▲ **Figure 2.12 Demonstrating convection in air**

2.3.3 Radiation

Key objectives

By the end of this section, you should be able to:

- know that thermal radiation is infrared radiation, which does not require a medium
- describe the effect of surface colour and texture on the emission, absorption and reflection of infrared radiation
- know the effect on the temperature of an object of the rates at which it receives and transfers energy away
- know how the Earth's temperature is affected by the balance between incoming radiation and radiation emitted from the Earth's surface
- describe experiments to distinguish between good and bad emitters and absorbers of infrared radiation
- describe how temperature and surface area affect rate of emission of radiation

In **radiation**, thermal energy is transferred by infrared radiation, which is part of the electromagnetic spectrum (see Topic 3). All objects emit this radiation.

Surfaces that are good absorbers of thermal energy radiation are also good emitters. Surface colour and texture can affect emission, absorption and reflection of infrared radiation. Black surfaces are better emitters and absorbers than white surfaces. Dull or matt surfaces are better emitters and absorbers than polished surfaces.

There need not be any matter between the hot and cold bodies (no medium is required).

Most solids and liquids absorb infrared radiation, including water, which is transparent to light.

Core students do not have to describe the two experiments below, but if you understand them it will help you to answer questions on the Core syllabus.

The rate of radiation emitted increases with the surface area and surface temperature.

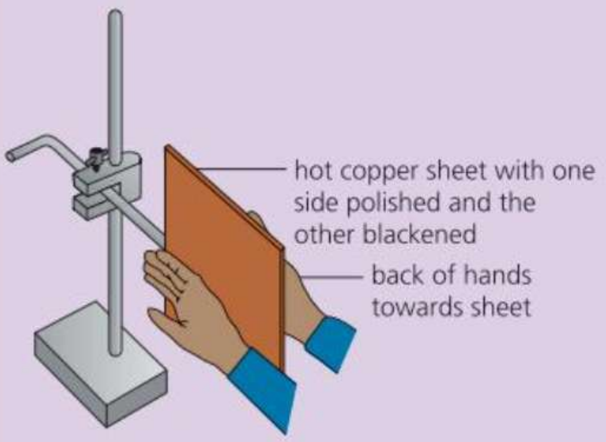
Skills

Good and bad emitters and absorbers of infrared radiation

Good and bad emitters

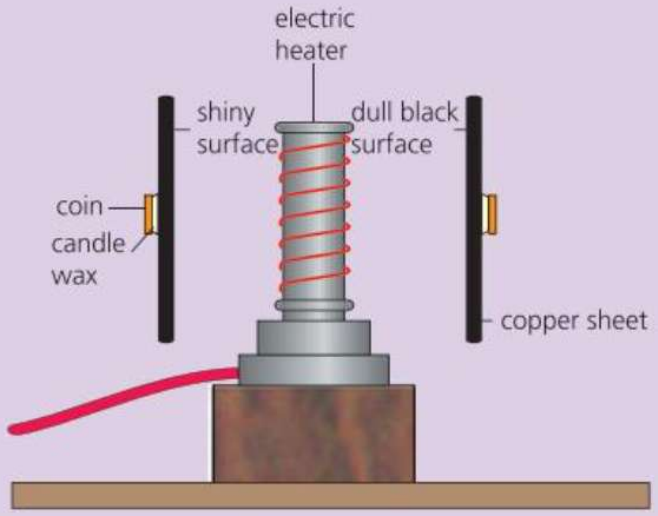
The copper sheet in Figure 2.13 has previously been heated strongly with a Bunsen burner. The hand next to the black surface feels much hotter than the hand next to the polished surface. This is because black surfaces emit thermal energy radiation more than polished surfaces.

Health and safety note: if you do this experiment, the copper plate needs to be very hot. If touched, it could cause a serious burn.



▲ **Figure 2.13 Comparing emitters of radiation**

Good and bad absorbers



▲ **Figure 2.14 Comparing absorbers of radiation**

The heater is the same distance away from each copper sheet in Figure 2.14, so each receives the same amount of radiation. The dull black surface absorbs much more radiation than the shiny surface, so after a few minutes the wax on the black sheet melts and the coin falls off. The shiny surface reflects a lot of the radiation, so it stays cool and the wax does not melt.

Health and safety note: for clarity, the essential protective guard round the heater has not been shown. This safety feature is essential to protect users from a hot object at high electrical voltage.

If an object receives energy at a higher rate than it transfers it away, its temperature increases. If it receives energy at a lower rate than it transfers it away, its temperature decreases. If the two rates are the same, the object remains at constant temperature. The temperature of the Earth is determined by the balance between incoming radiation and radiation emitted.

2.3.4 Consequences of thermal energy transfer

Key objectives

By the end of this section, you should be able to:

- explain basic everyday applications of conduction, convection and radiation
- explain more complex applications of conduction, convection and radiation where more than one type of thermal energy transfer is significant

Saucepans and other solids through which thermal energy must travel are made of metals such as aluminium or copper, which are **good conductors.**

Blocks of expanded polystyrene are used for house insulation because they contain trapped air, which is a **bad conductor.**

A domestic radiator heats the air next to it which then rises and transfers thermal energy to the rest of the room. Despite its name, a radiator works mainly by **convection**.

Double glazing reduces the transfer of thermal energy by trapping a narrow layer of air between the window panes and **reducing convection**.

The Sun heats the Earth by infrared **radiation** through space.

Refrigerators have cooling pipes at the back. These have fins to give a larger surface area to increase loss of thermal energy by convection and radiation. The fins are also painted black to increase thermal energy loss by radiation because black surfaces are **good emitters**.

Many buildings in hot countries are painted white because white surfaces are **bad absorbers** of radiation from the Sun.

The colour of the surface influences radiation only. Black surfaces do not increase thermal energy transfer by conduction and convection.

> In more complex situations, more than one type of thermal energy transfer can be significant.
>
> A fire burning wood or coal warms a room by convection and radiation.
>
> The radiator of a car dissipates thermal energy by convection and radiation.

Sample questions

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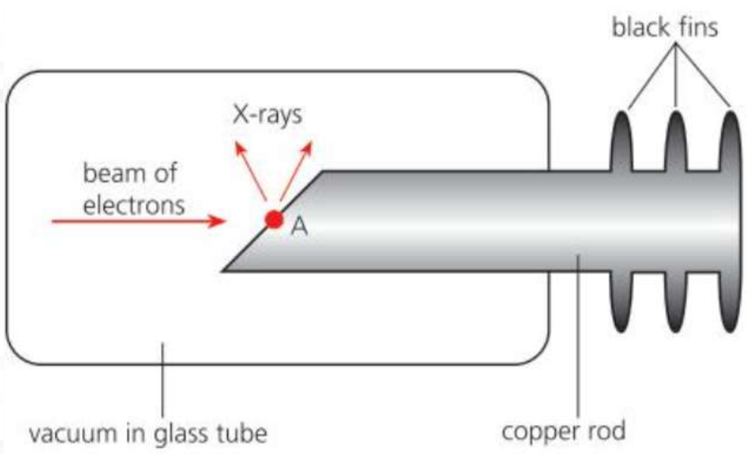


▲ **Figure 2.15**

10 Figure 2.15 shows an X-ray tube. Only a small proportion of energy from the electrons that strike point A goes into the X-rays that are emitted from that point. Most of the energy is transferred to thermal energy at point A; this energy is removed by the copper rod. Explain how conduction, convection and radiation play a role in the removal of this thermal energy. [6]

Student's answer

The thermal energy goes down the rod and is conducted out by the fins [1] through convection and radiation. [1]

Teacher's comments

The student's answer shows an incorrect understanding of conduction.

Correct answer

Thermal energy is conducted along the rod to the fins [2] and is then emitted from the fins to the air by convection and radiation. [2] The black colour of the fins increases the rate of radiation. [2]

11 A metal spoon rests in a hot drink in a cup.

a State the type of thermal energy transfer which makes the end of the spoon out of the drink become hot. [1]

b Explain in terms of electrons and lattice vibrations why the end of a wooden spoon would not become so hot. [4]

Student's answer

a *The electrons are conducted along the spoon.* [1]

b *Lattice vibrations occur in solids. The electrons in the metal are free to move and transfer energy to the end of the metal spoon.* [2]

Teacher's comments

a Although it is an incorrect statement and electrons are not conducted, the mark is scored for the mention of conduction.

b The student has scored some marks for correct mentions of lattice vibration and free electrons. However, this was not applied to the situation and did not relate to how the ends of the spoons became hot.

Correct answer

a conduction [1]

b Lattice vibrations transfer thermal energy in all solids but this is a poor energy transfer mechanism. So the end of the wooden spoon receives little thermal energy and does not become hot. The free electrons in the metal move readily and transfer much more thermal energy so the end of the metal spoon becomes much hotter. [4]

12 Heat is applied to the bottom of a pan containing water. State and explain any types of thermal energy transfer which are significant in heating the water. [4]

Student's answer

Conduction and radiation. [1]

Teacher's comments

Conduction does occur which scores a mark. Radiation is not significant so is an incorrect answer. There is no explanation about where the types of energy transfer take place.

Correct answer

Thermal energy is conducted through the pan. This heats the water at the bottom, which transfers thermal energy to the rest of the water by convection. [4]

Revision activity

Write down how the change of density causes convection in a liquid or gas.

Revision activity

Make flash cards for the following questions to revise the mechanisms for conduction of thermal energy in solid metals and thermal radiation. Write the question on one side of each card and the answer on the other.

1 Explain how thermal energy is conducted by electrons in metals.
2 Explain the secondary mechanism of conduction used by non-metals.
3 Write down what is meant by thermal radiation.
4 State and explain whether thermal radiation can occur in space.

Exam-style questions

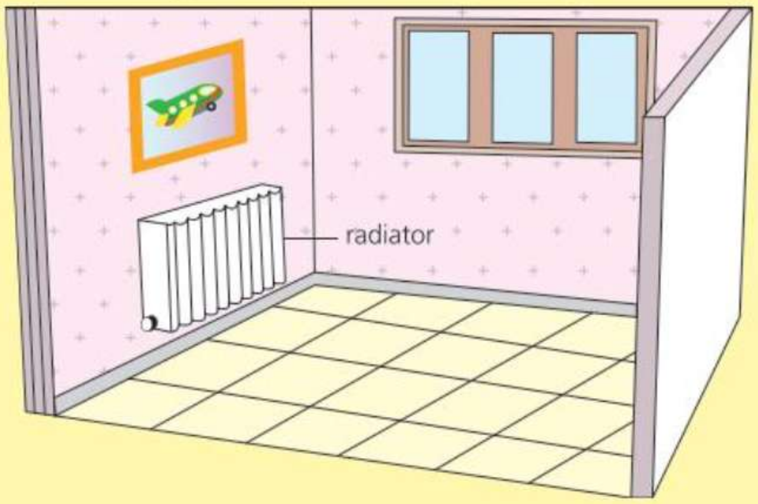
Answers available at: www.hoddereducation.co.uk/cambridgeextras

13 Explain in terms of particles why metals are much better thermal conductors than gases and most liquids. [3]

14 A child goes for a walk in winter in a cold country.
 a They open a metal gate which makes their hands cold. State and explain which type of thermal energy transfer cools their hands. [2]
 b They then wash their hands in a stream. State and explain which type of thermal energy transfer cools their hands. [2]
 c When they go home, they find a fire has been lit in the fireplace, and so hold out their hands near the fire. State and explain which type of thermal energy transfer warms their hands. [2]

15 Two space probes X and Y are identical in size and shape are in orbit around the Sun.
 a State the type of thermal energy transfer from the Sun to the probes. [2]
 b Probe X has a dull black surface and probe Y a shiny black surface. Which probe absorbs thermal energy from the Sun at a higher rate? [1]
 c Probe X is moved to an orbit further from the Sun. State and explain what happens to the steady temperature of probe X in its new orbit. [3]

16 In cold countries, houses are often heated by metal objects filled with hot water, often referred to as 'radiators'.
State and explain the types of thermal energy transfer involved in the energy transfer from the hot water to the air in a house. [4]



▲ Figure 2.16

3 Waves

Key terms

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Term	Definition
Amplitude	The maximum displacement of a wave from the undisturbed position, or maximum change of value from zero
Converging lens	A lens which refracts parallel rays of light such that they converge to meet at a point
Crest of a wave	A wavefront where all the points have their highest displacement
Diverging lens	A lens which refracts parallel rays of light such that they diverge away from a point
Electromagnetic spectrum	Waves of the same nature with a wide range of wavelengths made up of oscillating electric and magnetic fields
Focal length	The distance between the optical centre and the principal focus of a lens
Frequency	The number of complete oscillations per second
Longitudinal wave	Direction of vibration of particles of the transmitting medium is parallel to the direction of travel of the wave
Principal focus (focal point)	Point on the principal axis to which light rays parallel to the principal axis converge, or appear to diverge from
Real image	An image which can be formed on a screen
Transverse wave	Direction of vibration or change of value is perpendicular to the direction of travel of the wave
Trough of wave	A wavefront where all the points have their lowest displacement
Virtual image	An image which cannot be formed on a screen
Wave speed	The distance moved by a point on a wave in 1 s
Wavefront	A line on which the particles or values of the wave are in phase
Wavelength	The distance between corresponding points in successive cycles of a wave
Analogue signal	A signal that can take any value within a range
Compression	Regions where particles of the transmitting medium are closer together
Digital signal	A signal that can only take one of two definite values: high (maximum value) or low (close to 0)
Rarefaction	Regions where particles of the transmitting medium material are further apart
Refractive index	The ratio of the speeds of a wave in two different regions

3.1 General properties of waves

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Key objectives

By the end of this section, you should be able to:

- know that waves transfer energy without transferring matter
- describe what is meant by wave motion as illustrated by simple experiments
- understand the terms wavefront, wavelength, frequency, crest (peak), trough, amplitude and wave speed
- recall and use the wave equation: $v = f\lambda$
- distinguish between transverse and longitudinal waves and know different types of each wave
- describe how water waves can be used to illustrate reflection, refraction and diffraction

- describe how wavelength and gap size affect diffraction through a gap
- describe compressions and rarefactions
- describe how, with increasing wavelength, there is less diffraction at an edge

Waves transfer energy from one point to another without transferring matter. Some waves (e.g. water waves and sound waves) are transmitted by particles of a material vibrating about fixed points. They cannot travel through a vacuum.

Electromagnetic waves (e.g. light waves and X-rays) are a combination of travelling electric and magnetic fields. They *can* travel through a vacuum.

Types of wave motion

In **transverse waves**, the oscillation of the material or field is at right angles to the direction of travel of the wave. Figure 3.1 shows a transverse wave travelling in a horizontal rope. Each piece of rope oscillates vertically about a fixed point, but the pieces do not oscillate in time with each other.

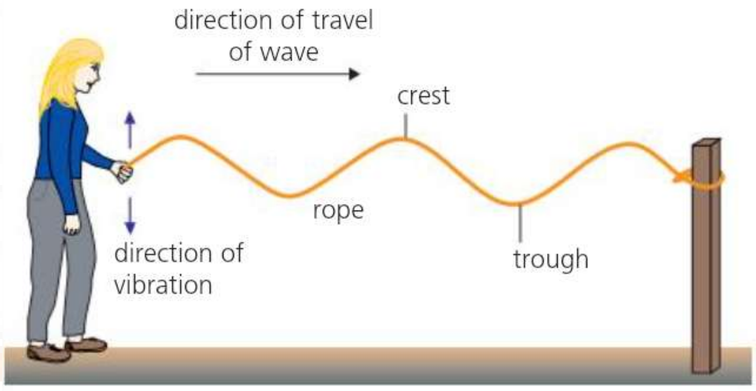


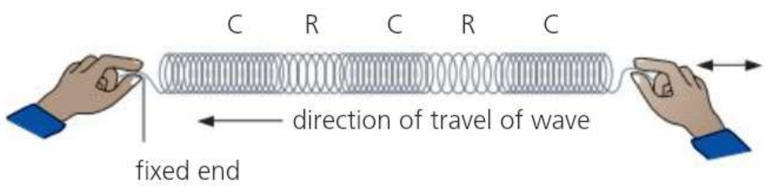
Figure 3.1 Transverse waves in a rope

Transverse waves only oscillate vertically when the wave travels horizontally. Transverse waves oscillate horizontally when the wave travels vertically because the oscillation is always at right angles to the direction of travel.

In **longitudinal waves**, the oscillation of the material is parallel to the direction of travel of the wave.

Figure 3.2 represents a longitudinal wave travelling in a horizontal spring. Each coil of the spring oscillates horizontally about a fixed point, but the coils do not oscillate in time with each other.

The points marked 'C' are where the coils are most tightly packed (**compressions**) and 'R' marks the points where the coils are furthest apart (**rarefactions**).



▲ **Figure 3.2 Longitudinal waves in a spring**

Longitudinal waves only oscillate horizontally when the wave travels horizontally. Longitudinal waves oscillate vertically when the wave travels vertically, because the oscillation is always parallel to the direction of travel.

Electromagnetic radiation, water waves and seismic S-waves (secondary) are transverse waves.

Sound waves and seismic P-waves (primary) are longitudinal waves.

Describing waves

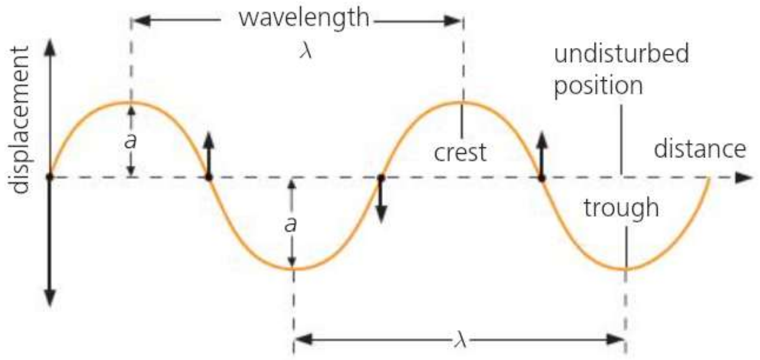
The **wave speed** (v) is the distance moved by a point on the wave in 1 s.

The **frequency** (f) of a wave is the number of complete cycles per second and is measured in hertz (Hz).

The **wavelength** (λ) of a wave is the distance between two corresponding points (e.g. crests) in successive cycles.

The **amplitude** of a wave is the maximum displacement of the wave from the undisturbed position (marked *a* in Figure 3.3) or maximum change of value from zero.

Amplitude is not the height difference between the top of a crest and the bottom of a trough. Amplitude is the height difference between the top of a crest and the mean position, or between the bottom of a trough and the mean position.



▲ **Figure 3.3 Displacement–distance graph for a wave at a particular instant**

Speed, frequency and wavelength are related by the equation:

$$v = f\lambda$$

Table 3.1 summarises some types of waves.

▼ **Table 3.1 Types of waves**

Type of wave	Longitudinal/transverse	Travel through a material
Wave on a rope	Transverse	Material needed
Wave on a spring	Either	Material needed
Water	Transverse	Material needed
Earthquake wave	Both	Material needed
Sound	Longitudinal	Material needed
Electromagnetic, e.g. light, X-rays, radio waves	Transverse	No material needed, but some electromagnetic waves can travel through certain materials

You need to be able to use the term **wavefront** as a line showing the position of a wave. A wavefront shows similar points of an extended travelling wave, such as a wave in water. The **crest** of a wave is a wavefront where all the points have their highest displacement. The **trough** of a wave is a wavefront where all the points have their lowest displacement.

Water waves

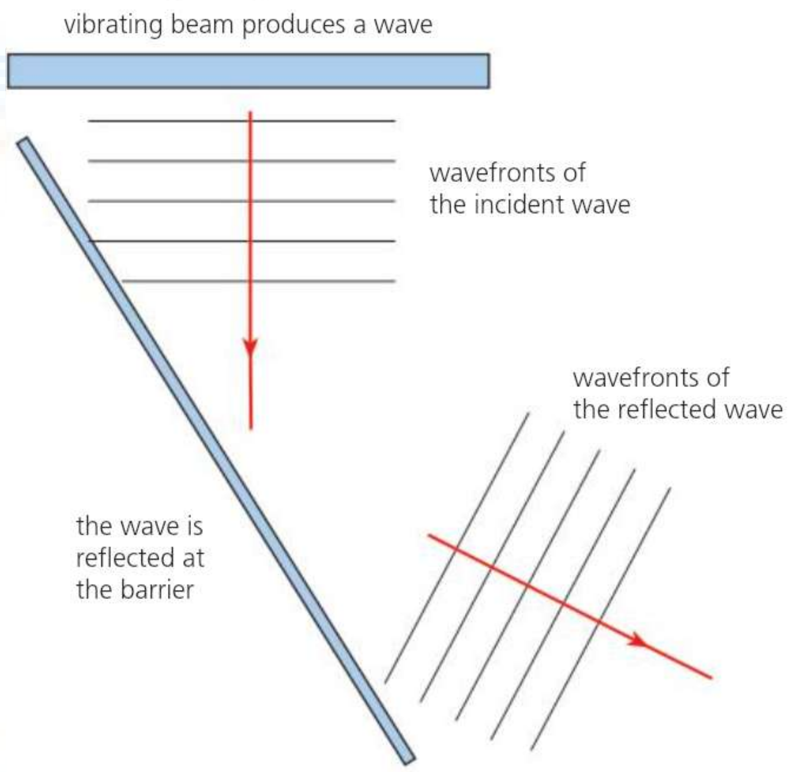
We can observe a wave travelling on the water surface of a ripple tank to illustrate how waves behave.

Key features of a ripple tank:

- A beam just touching the surface vibrates vertically to produce a wave.
- A light source shines through the water and shows the wave pattern on a screen above or below the ripple tank.

Reflection

In Figure 3.4, the wave produced by the vibrating beam is reflected from the flat metal barrier. The reflected wave is at the same angle to the reflecting surface as the incident wave. Speed, wavelength and frequency are unchanged by reflection.



▲ **Figure 3.4 Reflection of a wave in a ripple tank**

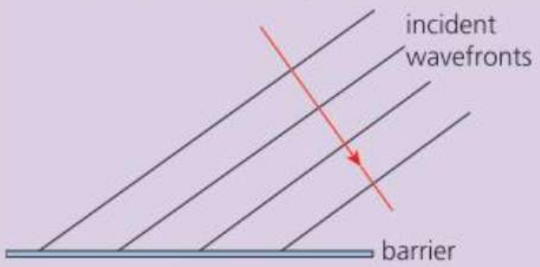
Skills

Drawing wavefronts to show reflection at a plane surface

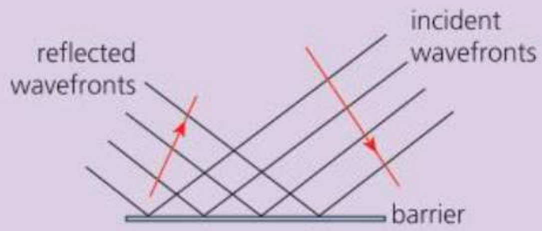
You must be able to describe how water waves can be used to show reflection at a plane surface (barrier).

- Draw a straight line across the page to represent the barrier.
- Draw four wavefronts separated by 10 mm at an angle of 35° from the barrier striking the middle section of the barrier. They show the incident wave.
- Add an arrow at right angles to the wavefronts to show the direction of travel.
- Your diagram should look like Figure 3.5.
- Where each incident wavefront strikes the barrier draw a reflected wavefront at 35° the other way from the barrier.
- Add an arrow at right angles to the reflected wavefronts to show the direction of travel.

- Your finished diagram should look like Figure 3.6.



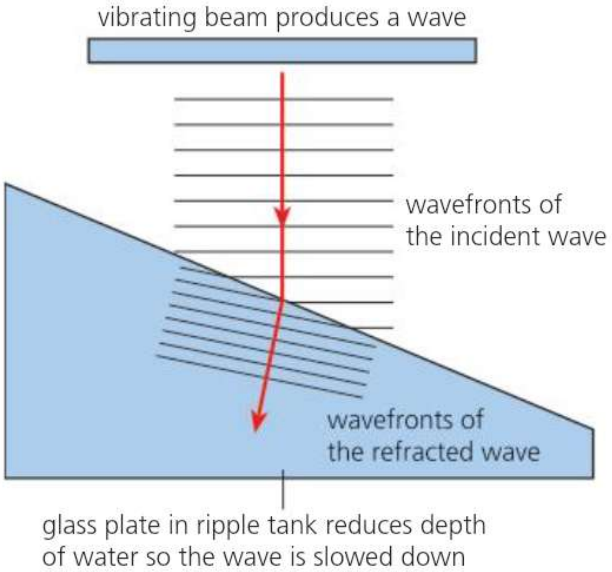
▲ **Figure 3.5**



▲ **Figure 3.6**

Refraction

Figure 3.7 shows a wave entering the shallow water above the glass where its speed is reduced. The frequency stays the same, so the wavelength is also reduced. The refracted wave changes direction.



▲ **Figure 3.7 Refraction of a wave in a ripple tank**

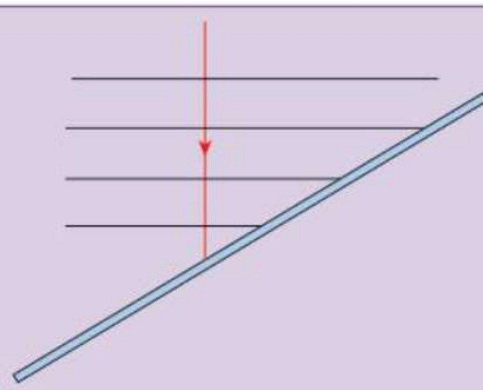
Skills

Drawing wavefronts to show refraction due to change of speed

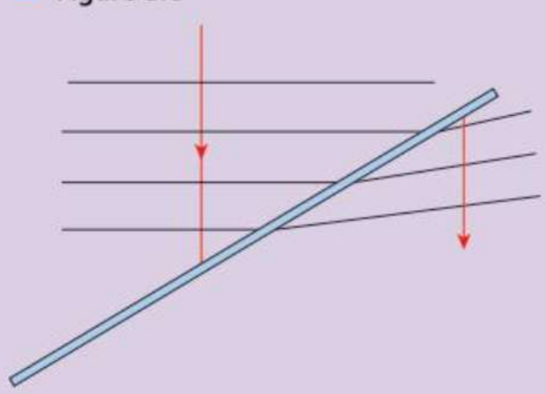
You must be able to describe how water waves can be used to show refraction.

In this exercise, you will draw a wave that is refracted as it travels into a region where its speed is changed due to a change in depth.

- Draw a line across the page at 30° to show the interface between the two regions where the wave has different speeds.
- Draw wavefronts horizontally at 30° to the interface separated by 10 mm and continue them down so three strike the interface.
- Add an arrow at right angles to the wavefronts to show the direction of travel.
- Your diagram should look like Figure 3.8.
- Draw the refracted wavefronts sloping up away from the barrier at 22° and joining onto the incident wavefronts where they strike the interface.
- Add an arrow at right angles to the refracted wavefronts to show the direction of travel.
- Your diagram should look like Figure 3.9.



▲ **Figure 3.8**



▲ **Figure 3.9**

- Check the accuracy of your working. The refracted wavefronts should be between 8 mm and 9 mm apart measured at right angles to the wavefronts.

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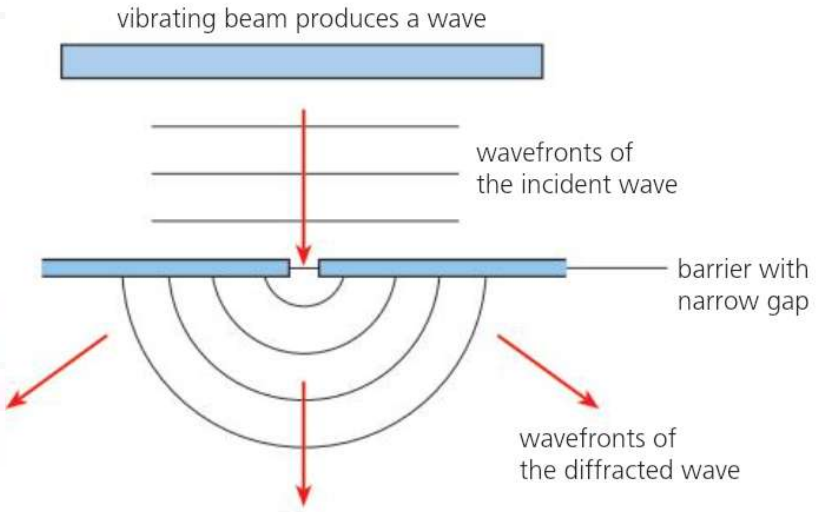
Diffraction through a narrow gap

Speed, wavelength and frequency are unchanged by diffraction, as shown in Figure 3.10.



▲ **Figure 3.10 Diffraction of waves in a ripple tank by a gap that is narrower than the wavelength**

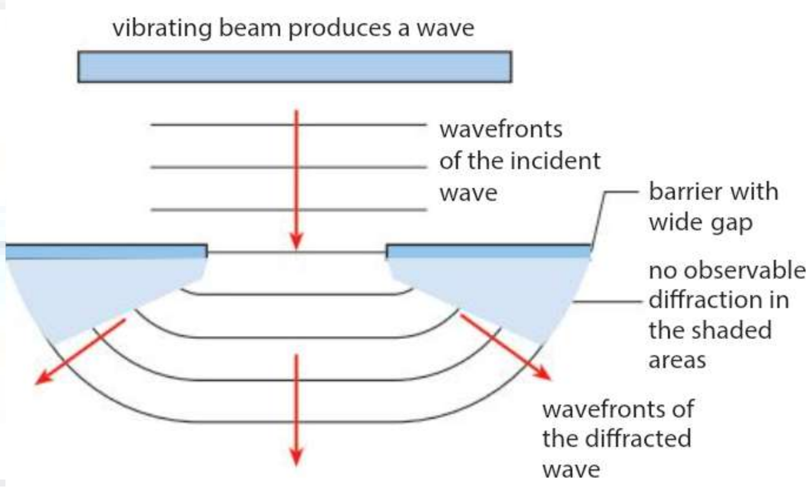
Notes for drawing wave diagrams

Points to note when drawing wave diagrams to show reflection, refraction and diffraction:

- Careful, accurate measuring and drawing are *essential* to produce good diagrams.
- The initial wavefronts must be parallel and have constant wavelength.
- Measure the wavelength of the incident waves.
- Reflected wavefronts must be parallel and have the same constant wavelength as the incident waves.
- Refracted wavefronts must be parallel and have a constant wavelength. Depending on the situation, the wavelength will be more or less than the incident wavelength.
- Diffracted wavefronts have straight and/or circular portions. The wavelengths between diffracted wavefronts must be carefully measured to be the same as the incident wavelength. The change of radius of the circular portions is the wavelength.

Diffraction at a gap or at an edge

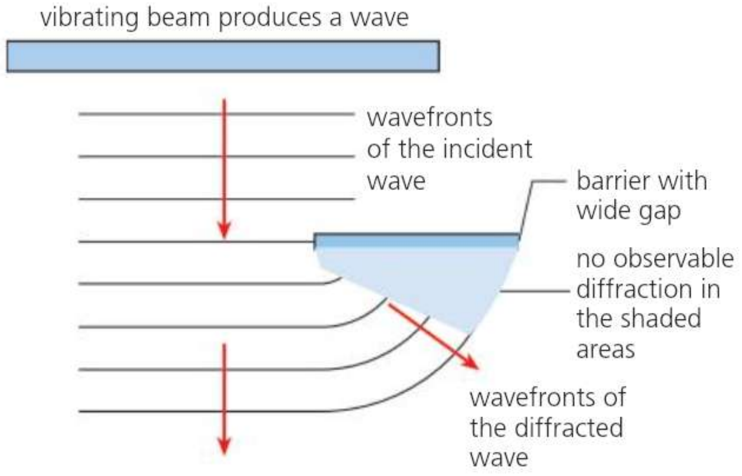
Diffraction from a gap is shown in Figure 3.11.



▲ **Figure 3.11 Diffraction of waves in a ripple tank by a gap**

Note: the centres of the part-circles are at the edges of the wide gap.

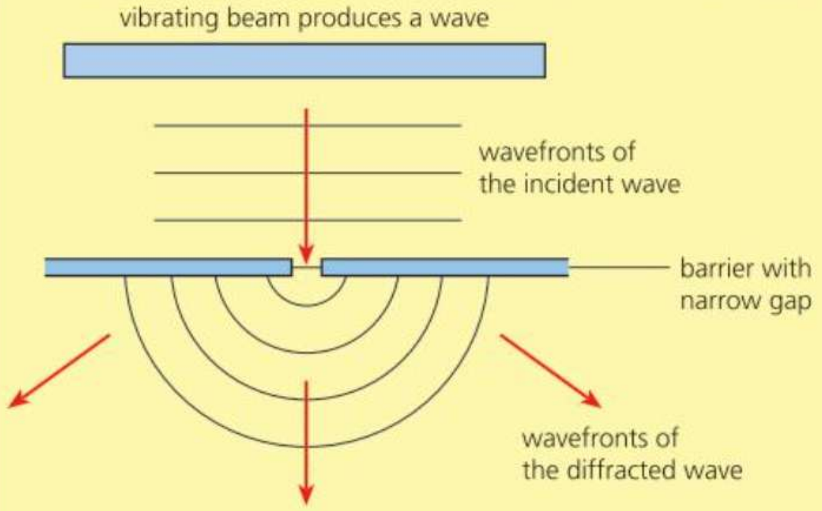
Diffraction at an edge is shown in Figure 3.12.



▲ **Figure 3.12 Diffraction of waves in a ripple tank by an edge**

Wavelength and gap size affect diffraction

Diffraction from a narrow gap is shown in Figure 3.13.



▲ **Figure 3.13 Diffraction of waves in a ripple tank by a gap that is narrower than the wavelength**

Reducing the wavelength with the same gap reduces diffraction.

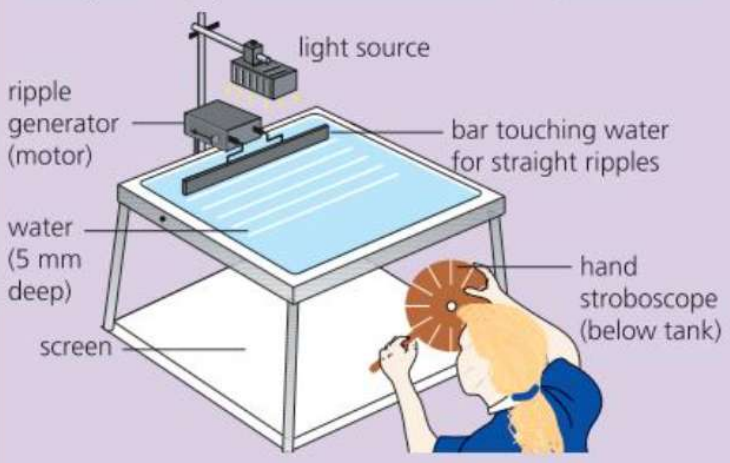
Increasing the wavelength with the same gap increases diffraction.

Diffraction past an edge increases if the wavelength increases.

Skills

Describing diffraction due to an edge

Set up the ripple tank as shown in Figure 3.14.



▲ **Figure 3.14 A ripple tank**

Observe the wave produced and the wavelength.

Place a barrier across half the length of the wavefronts, parallel to the wavefronts.

Observe and sketch the pattern of the diffracted wavefronts past the edge of the barrier.

Change the motor speed so the wavelength increases. Using $v = f\lambda$, decide whether to speed up or slow down the motor to change the wave frequency and hence the wave velocity. Observe the wavelength before the barrier to see if you have done that correctly.

Observe and sketch the pattern of the diffracted wavefronts past the edge of the barrier.

You should see less diffraction at the edge of the barrier with greater wavelength.

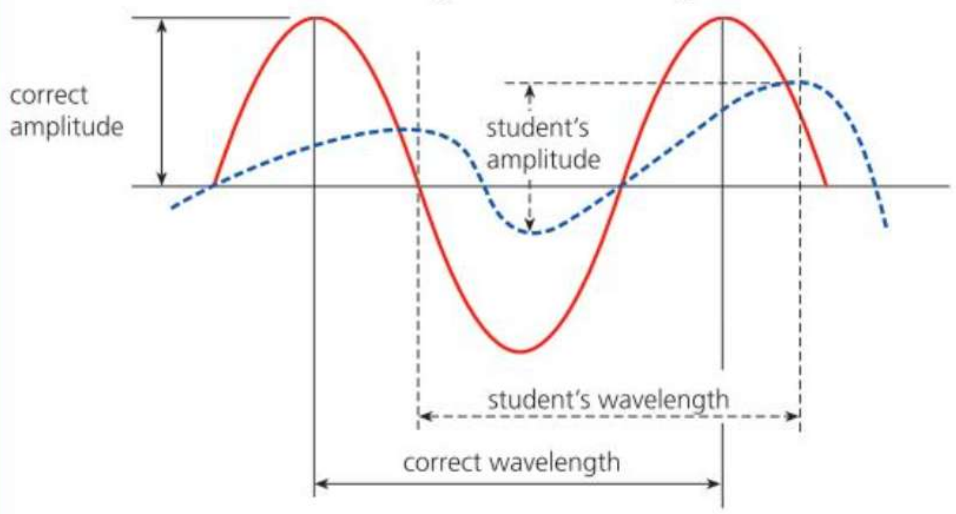
Sample questions

REVISED

1 Sketch one and a half cycles of a transverse wave and mark on your sketch the amplitude and wavelength. [4]

Student's answer

The student's answer is shown by dashed lines in Figure 3.15. [1]



▲ **Figure 3.15**

Teacher's comments

With this type of question, it is essential to work carefully and accurately or few marks will be gained. Even for a sketch, the student's diagram is too casual. For minimum acceptable accuracy, the student must indicate that each half wavelength is the same length, and the distance from the axis to each crest and trough is the same. The student's amplitude is incorrectly measured from crest top to trough bottom. Given the irregular wave, the student has correctly labelled one wavelength.

Correct answer

The correct answer is shown by the solid red line in Figure 3.15. [4]

2 A sensor detects that 1560 cycles of a wave pass in 30 s. Work out the frequency of the wave. [3]

Student's answer

frequency = 52 cycles in 1 s [2]

Teacher's comments

The student's answer is correct, but the unit of frequency is hertz (Hz).

Note that, although it is a fairly easy calculation, there is no working. If the student had made a slight slip, no credit could have been given for using the correct method.

Correct answer

$$\text{frequency} = \frac{\text{number of cycles}}{\text{time}} = \frac{1560}{30} = 52\ \text{Hz}$$ [3]

3 Find the frequency of a radio wave with a wavelength of 1500 m. [3]

Please note, extended candidates are expected to know the speed of electromagnetic waves.

Student's answer

$v = f\lambda$ [1]

So

$$f = \frac{v}{\lambda} = \frac{3 \times 10^8}{\lambda} = 200\,000\ \text{kHz}$$ [1]

Teacher's comments

The student has done everything correctly, but the unit is wrong. It should be Hz not kHz. Perhaps the student assumed that, as radio frequencies are often expressed in kHz, this was the correct unit.

Correct answer

$v = f\lambda$ [1]

So

$$f = \frac{v}{\lambda} = \frac{3 \times 10^8}{\lambda} = 200\,000\ \text{Hz} = 200\ \text{kHz}$$ [2]

4 An earthquake wave is travelling vertically down into the Earth; the oscillations are also vertical. State, with a reason, whether the wave is longitudinal or transverse. [2]

Student's answer

The wave is transverse because it is vibrating up and down. [0]

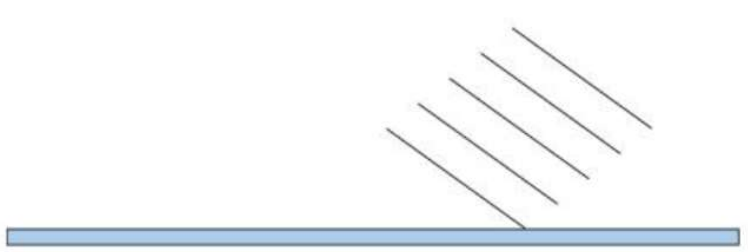
Teacher's comments

It is the direction of oscillation relative to the direction of travel that matters – the student does not mention this.

Correct answer

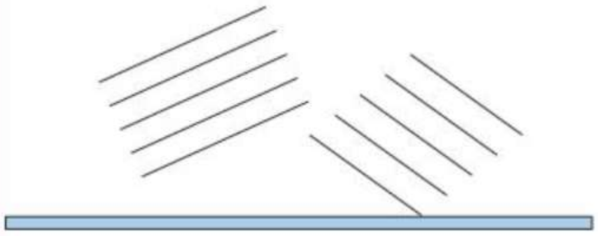
The wave is longitudinal because the oscillations are parallel to the direction of travel. [2]

5 Complete the diagram to show the wave reflected at the barrier. [3]



▲ **Figure 3.16**

Student's answer

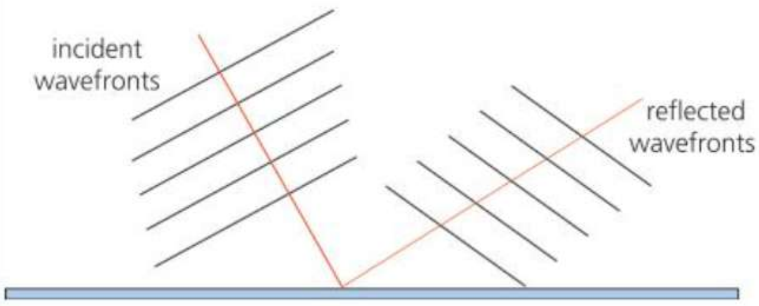


▲ **Figure 3.17** [2]

Teacher's comments

The reflected wavefronts drawn by the student are all parallel and at the correct angle, which is good work. However, the wavelength between wavefronts is not constant. The wavelength must be the same as the incident wave.

Correct answer



▲ **Figure 3.18** [3]

6 Waves in a ripple tank have a wavelength of 16 mm and approach an interface parallel to the wavefronts. The waves slow down after the interface to 0.75 of their original speed.

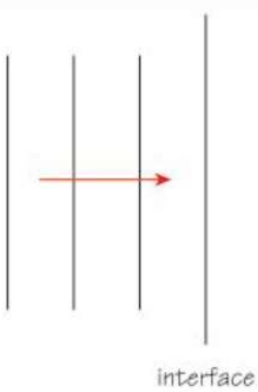
a Draw four wavefronts and the interface. [2]

b Calculate the new wavelength after passing the interface. [2]

c Add four wavefronts after passing the interface to your diagram drawn for part **a**. [2]

Student's answer

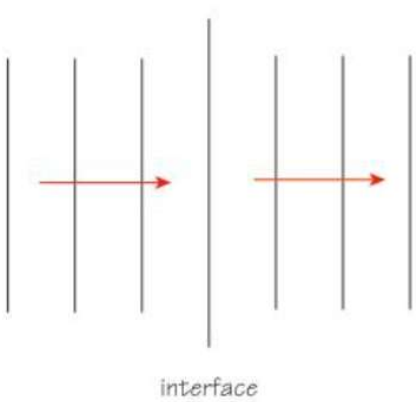
a



▲ **Figure 3.19** [2]

b new wavelength $= \frac{16}{0.75} = 21.3$ mm [0]

c



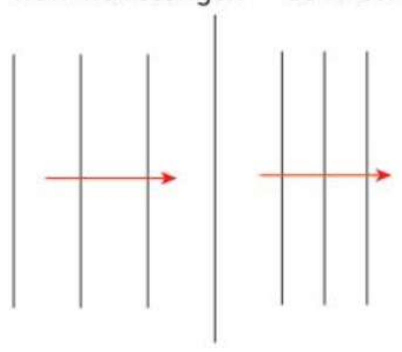
▲ **Figure 3.20** [2]

Teacher's comments

a The student's answer is correct and carefully drawn.
b The student has used inverse proportionality between wavelength and speed instead of direct proportionality.
c Based on the incorrect wavelength in part b, the student has correctly drawn the new wavefronts.

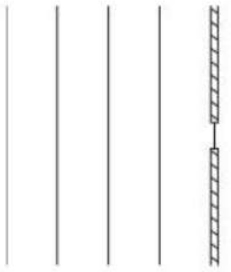
Correct answers

a As student's answer. [2]
b As frequency is constant, wavelength is proportional to speed.
new wavelength = $16 \times 0.75 = 12\,\text{mm}$ [2]
c



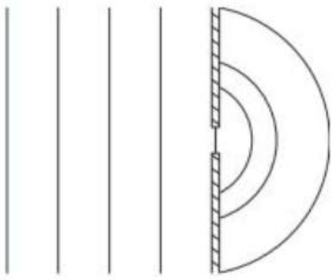
▲ **Figure 3.21** [2]

7 Figure 3.22 shows wavefronts 12 mm apart approaching a barrier with a gap of 8 mm.
Draw carefully three wavefronts to show the pattern of the waves after passing through the barrier.



▲ **Figure 3.22** [3]

Student's answer



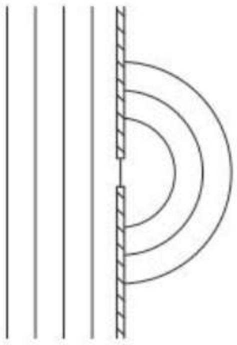
▲ **Figure 3.23** [1]

Teacher's comments

The student has carefully drawn three semicircles which score 1 mark.

The semicircles should be centred on the middle of the gap. The wavelength should be constant and the same as the wavelength of the incident wavefronts.

Correct answer



▲ **Figure 3.24** [3]

Revision activity

Draw two careful sketches to show how wavefronts of different wavelength are diffracted differently as they pass the edge of a barrier.

Exam-style questions

Answers available at: www.hoddereducation.co.uk/cambridgeextras

1 A woman swimming in the sea estimates that when she is in the trough between two crests of a wave, the crests are 1.5 m above her.

a Work out the amplitude of the wave. [1]

b An observer counts that the swimmer moves up and down 12 times in 1 min. Work out the frequency of the wave. [2]

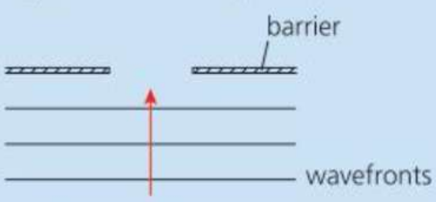
2 A child throws a ball into a pond, hears the sound of the splash and observes water waves travelling towards him.

a As the sound waves travel towards him, in which direction are the air particles oscillating? [1]

b As the water waves travel towards him, in which direction are the water particles oscillating? [1]

3 A wave in water with a wavelength of 15 mm approaches a straight interface. The wavefronts are at an angle of 50° to the interface. After the interface, the speed of the wave increases. Draw three wavefronts before and three wavefronts after the interface to show any change of direction of the wave. [4]

4 Figure 3.25 shows wavefronts of a wave approaching a barrier with a gap much larger than the wavelength.



▲ **Figure 3.25**

a Complete the diagram drawing three wavefronts which show the pattern of the waves after passing through the gap. [3]

b State the name of the process the wave undergoes. [1]

c Describe how the pattern of the wave after the gap would appear if the size of the gap was doubled. [2]

Revision activity

Draw careful sketches to show the diffraction of water waves through a gap that is smaller than the wavelength. Then do the same for a gap that is much larger than the wavelength.

3.2 Light

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Light moves as waves of very small wavelength, but it is often convenient to use light rays to work out and explain the behaviour of light.

A light ray is the direction in which light is travelling and is shown as a line in a diagram.

An object is what is originally observed.

An optical image is a likeness of the object, which may not be an exact copy.

A real image is formed where the rays cross and can be shown on a screen.

A virtual image is observed where rays appear to come from and cannot be formed on a screen.

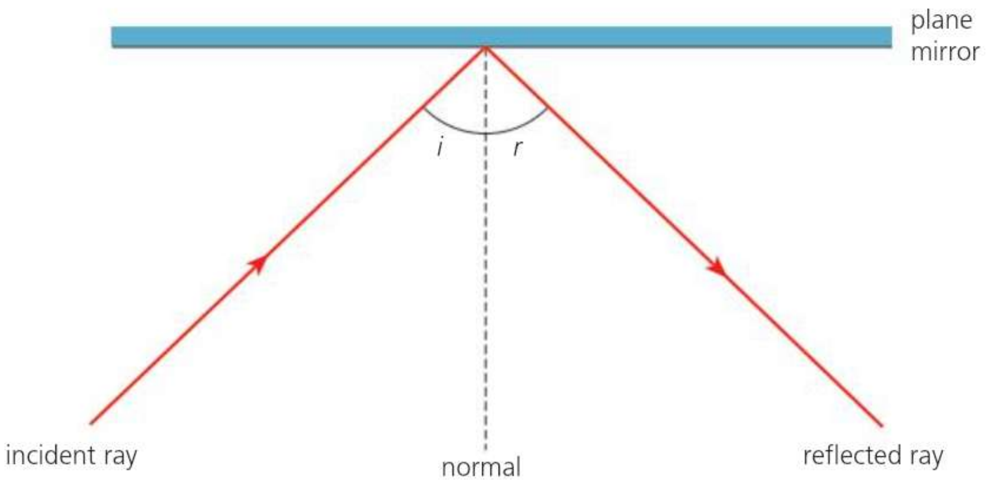
3.2.1 Reflection of light

Key objectives

By the end of this section, you should be able to:

- know and use the terms normal, angle of incidence, angle of reflection
- know what is meant by real and virtual images
- describe the formation of an optical image by a plane mirror
- state and use the relationship 'angle of reflection equals angle of incidence'
- perform simple constructions, measurements and calculations for plane mirrors

When light rays strike a mirror or similar surface, they return at the same angle from the normal as the incident ray. This is called **reflection**.



▲ **Figure 3.26 Reflection of light by a plane mirror**

i = angle of incidence = angle between **normal** and incident ray

r = angle of reflection = angle between **normal** and reflected ray

angle of incidence = angle of reflection or $i = r$

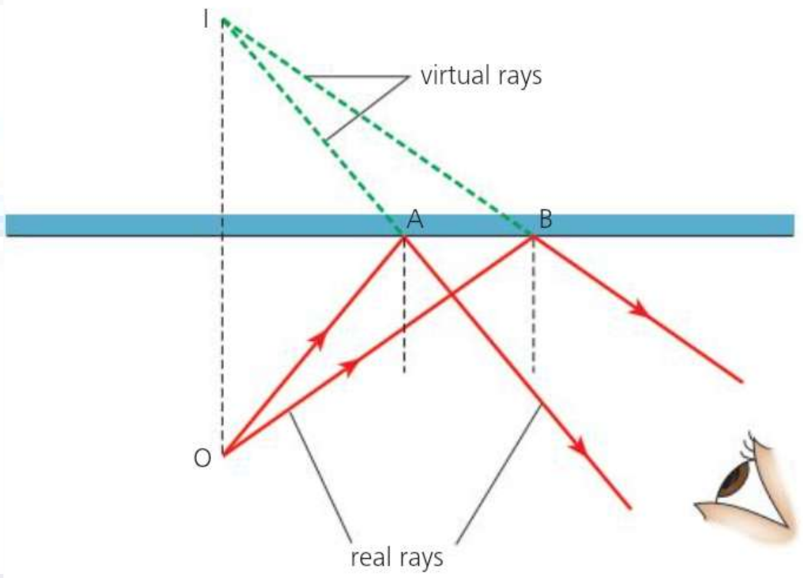
Real and virtual images

A **real image** is formed where light rays actually converge. It can be formed on a screen.

A **virtual image** can be seen as a point from which light rays diverge. It cannot be formed on a screen.

Formation of a virtual optical image by a plane mirror

Figure 3.27 shows the formation of a virtual image by a plane mirror.



▲ **Figure 3.27 Construction to find the image in a plane mirror**

The image of the object O is not formed on a screen. It is at point I where the rays appear to come from. The properties of an image in a plane mirror are:

- It is the same size as the object.
- The line joining the object and the image is perpendicular to the mirror.
- It is the same distance behind the mirror as the object is in front of the mirror.
- It is laterally inverted.
- It is virtual.

Simple construction for reflection by a plane mirror

You must be able to draw simple constructions. Hints for drawing a construction to show the position of the image of a point object in a plane mirror:

- Carefully measure the distance of the object from the mirror.
- Mark the image the same distance behind the mirror as the object is in front of the mirror. The object and image should be on a line at right angles to the mirror line (OI in Figure 3.27).
- Draw two lines from the image towards the eye; draw dotted lines behind the mirror where they represent virtual rays.
- Join up the two lines from the object to where the previous two lines cut the mirror line (A and B in Figure 3.27).
- Mark arrows on the real rays and label the diagram as necessary.

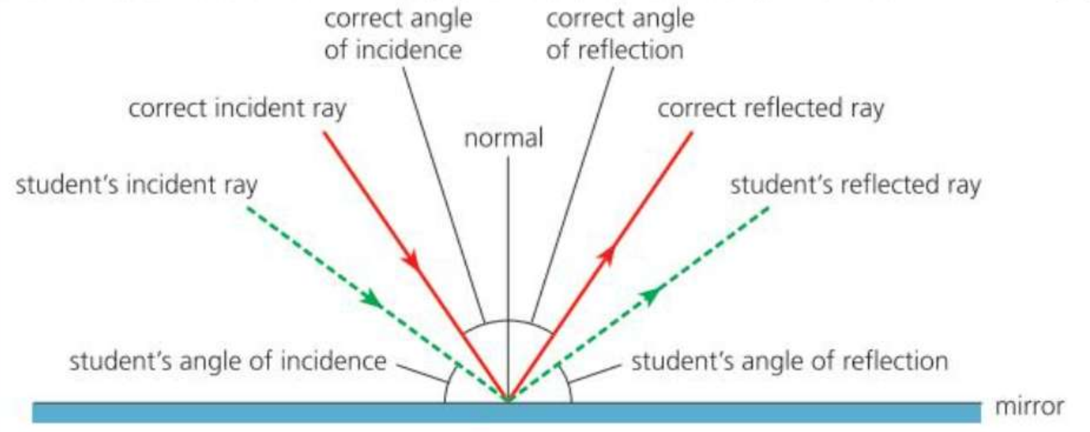
Sample question

REVISED

8 Draw a diagram to show the path of a ray striking a plane mirror with an angle of incidence of 35°. Mark and label the incident ray, normal, reflected ray and angles of incidence and reflection. [4]

Student's answer

The student's answer is shown by green dashed lines in Figure 3.28. [2]



▲ **Figure 3.28**

Teacher's comments

The student has measured the angle of incidence away from the mirror line, not away from the normal. The normal is correct, as is the reflected ray for the incident ray drawn. The angle of reflection is also incorrectly measured away from the mirror line.

Correct answer

The correct answer is shown by the red solid lines in Figure 3.28. [4]

3.2.2 Refraction of light

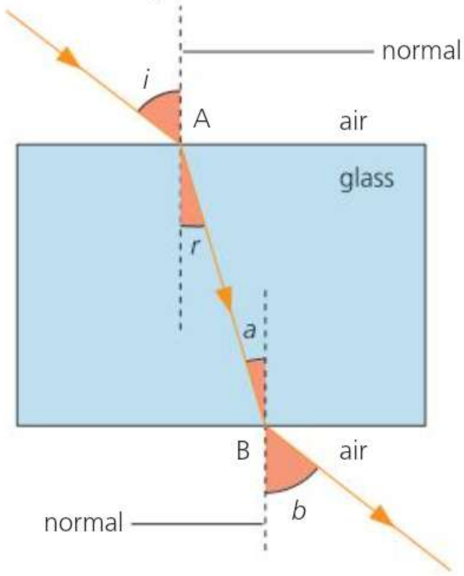
Key objectives

By the end of this section, you should be able to:

- know and use the term angle of refraction
- describe an experiment to show the refraction of light by transparent blocks of different shapes, showing the passage of light through transparent material
- know that refractive index n = the ratio of the speeds of a wave in two different regions
- know and use the equation $n = \frac{\sin i}{\sin r}$
- state the meaning of critical angle
- know and use the equation $n = \frac{1}{\sin c}$
- describe internal reflection and total internal reflection with examples
- describe the use of optical fibres in telecommunication.

When a ray is travelling at an angle to a surface and enters a material where it travels slower, it changes direction *towards* the normal (Figure 3.29). This is called **refraction**.

When a ray leaves this material, it is refracted *away from* the normal.



▲ **Figure 3.29 Refraction of a ray through a glass block**

For refraction at point A, where the ray enters the glass:

- i = angle of incidence = angle between **normal** and incident ray
- r = angle of refraction = angle between **normal** and refracted ray
- The ray is refracted towards the normal, so the angle of refraction is less than the angle of incidence.

For refraction at point B, where the ray leaves the glass:

- a = angle of incidence = angle between **normal** and incident ray
- b = angle of refraction = angle between **normal** and refracted ray
- Passing from glass to air, the ray is refracted away from the normal, so the angle of refraction is greater than the angle of incidence. When the block is parallel sided, the ray leaving is parallel to the ray entering.

Skills

Demonstrating refraction of light

You will need to be able to describe an experiment to demonstrate the refraction of light.

You should do this experiment in a darkened room. Direct a narrow beam of light at an angle to the side of a glass block placed on a large piece of paper. Mark on the paper the paths of the beams entering and leaving the block. By joining up the lines after removing the block, you can draw the path of the light as it travelled through the block. Figure 3.29 shows the paths of the rays in this experiment.

Measure the angles of incidence and refraction. Be careful to measure them from the normal not the interface.

This can be done with blocks of different shapes.

Refractive index

The amount of refraction is determined by the **refractive index** n – the ratio of the speed of light in air to the speed of light in the material.

For example, to find the refractive index of glass,

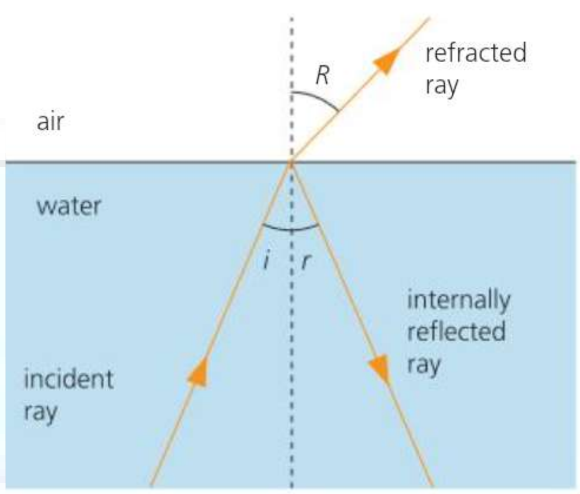
$$n = \frac{\text{speed of light in air}}{\text{speed of light in glass}}$$

The refractive index is related to the angles of incidence and refraction by this equation:

$$n = \frac{\sin i}{\sin v}$$

Internal reflection and critical angle

Figure 3.30 shows a ray inside a tank of water passing out into the air; some light is reflected internally and some is refracted away from the normal.



▲ **Figure 3.30 Rays at a water–air boundary**

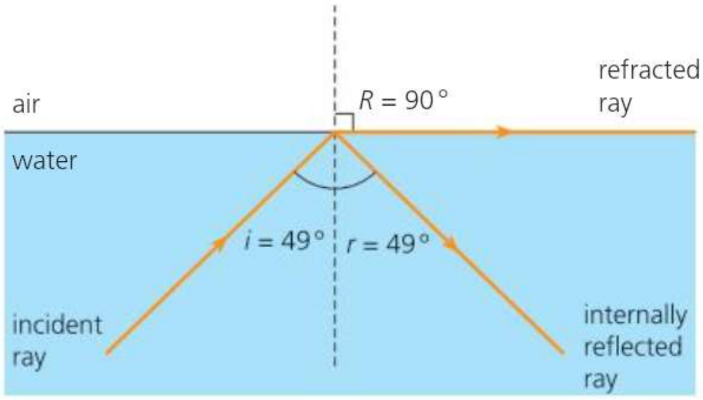
i = angle of incidence = angle between **normal** and incident ray

r = angle of internal reflection = angle between **normal** and internally reflected ray

R = angle of refraction = angle between **normal** and refracted ray

The law of reflection still applies, so $i = r$.

The greater the angle of incidence, the more energy goes into the internally reflected ray, which becomes brighter. The greatest angle of incidence when refraction can still occur is called the **critical angle** (c). In Figure 3.31, the angle of refraction is 90° and the refracted ray travels along the surface.

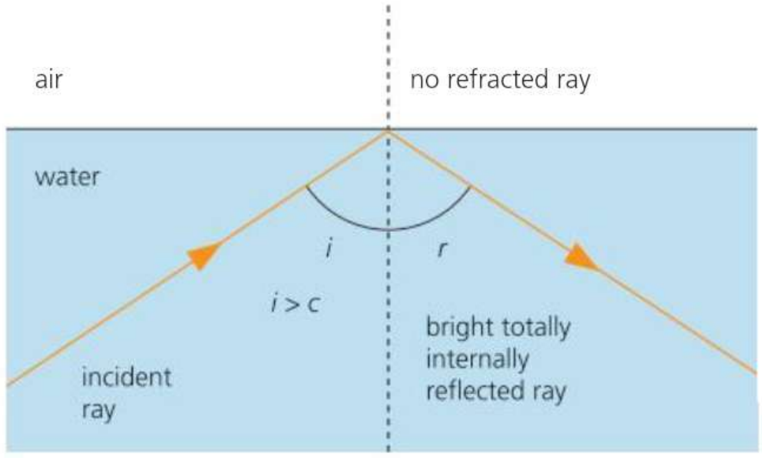


▲ **Figure 3.31 Angle of incidence is the same as the critical angle**

In this case, $\sin R = \sin 90 = 1$ and the refractive index is $1/n$ because the light is passing from water into light. The refraction equation becomes:

$$\frac{1}{n} = \frac{\sin c}{1} \text{ or } n = \frac{1}{\sin c}$$

If the angle of incidence is greater than the critical angle, there is no refracted ray and all of the energy is in the bright internally reflected ray. This is called **total internal reflection** (Figure 3.32).

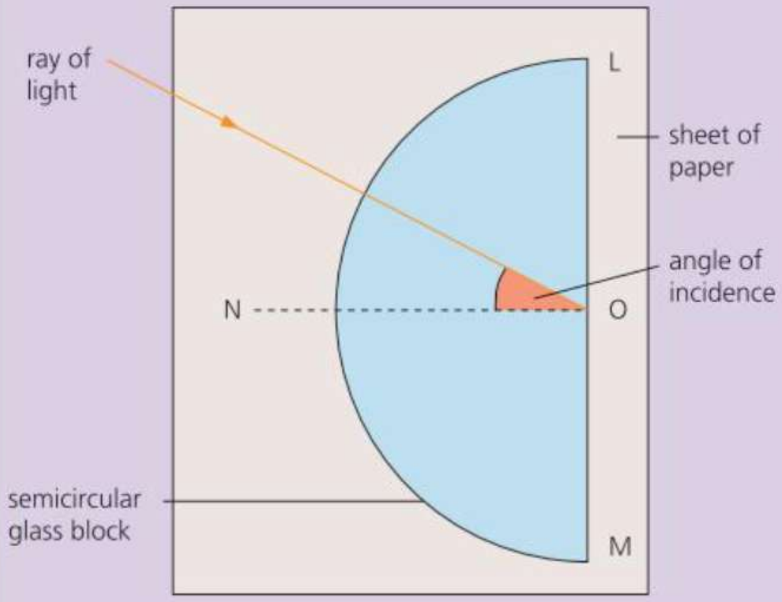


▲ **Figure 3.32 Total internal reflection**

Everyday uses of total internal reflection are binoculars and periscopes.

Skills

Internal reflection and total internal reflection in a semicircular glass block



▲ **Figure 3.33 Demonstrating total internal reflection**

- Direct the ray of light at an angle of incidence of about 20°.

  Observe the internally reflected ray emerging from the curved surface below the normal. Without measuring, notice that the angle of reflection is about equal to the angle of incidence.

  Observe the refracted ray emerging from the flat surface at O. Without measuring, notice that the angle of refraction is greater than the angle of incidence.
- Direct the ray of light at an angle of incidence of about 35°.

  Observe the internally reflected ray emerging from the curved surface below the normal. The angle of reflection will still be about equal to the angle of incidence.

  Observe the refracted ray emerging from the flat surface at O. Without measuring, notice that the angle of refraction is now much greater than the angle of incidence.
- Slowly increase the angle of incidence from 35°.

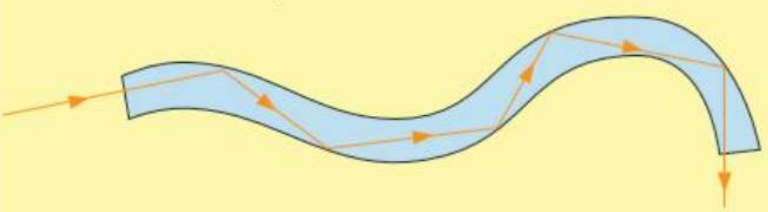
  Observe the internally reflected ray emerging from the curved surface below the normal. The angle of reflection remains about equal to the angle of incidence. If you observe carefully, the reflected ray becomes a little brighter.

  The refracted ray emerges closer and closer to the flat surface at O. At some point there is no refracted ray. Total internal reflection has occurred. The angle of incidence at this point is the critical angle.

Optical fibres

Optical fibres are used in telecommunication with visible light or infrared, e.g. for cable television or high-speed broadband. Glass fibres are used because they are transparent to light and some infrared.

Each time the light strikes the wall of the optical fibre, the angle of incidence is greater than the critical angle and so total internal reflection occurs. There is very little loss of energy. The light can be considered trapped in the optical fibre and can travel long distances, even if the fibre is bent, in order to carry information or illuminate and view inaccessible places.



▲ **Figure 3.34 Light travels through optical fibre by total internal reflection**

Sample questions

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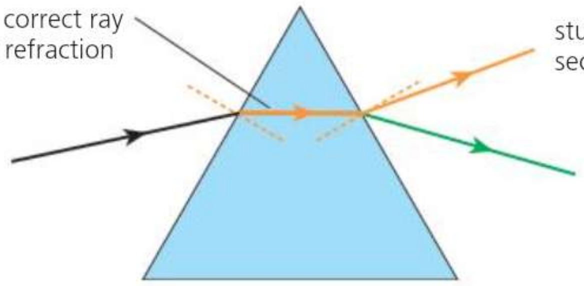
9 Copy and complete Figure 3.35 to show the path of the ray through the glass prism as it is refracted twice. Show *both* normals. [4]



▲ **Figure 3.35 The black line shows the question**

Student's answer

The student's answer is shown by the orange lines in Figure 3.35. [3]

Correct answer

The correct rays are shown by the green line in Figure 3.35. [4]

Teacher's comments

The student has correctly drawn the refracted ray within the prism and both normals. However, the student's second refraction, as the ray leaves the prism, is towards the normal. When a ray moves into a region where it travels faster, it is refracted away from the normal.

10 Light travels at 3×10^8 m/s in air and at 2.25×10^8 m/s in water. Calculate:

a the refractive index, n, of water [2]

b the angle of refraction for a ray approaching water with an angle of incidence of 55°. [2]

Student's answers

a $n = \dfrac{3 \times 10^8}{2.25 \times 10^8} = 1.33$ [2]

b $r = 34°$ [0]

Teacher's comments

a Correct answer with working.

b The answer is only slightly inaccurate, but there is no working, which means the examiner has no way of knowing whether the student has made a small mistake or was completely wrong and was simply close to the correct answer by chance. Examiners can only give credit for what they see.

Correct answers

a $n = \dfrac{3 \times 10^8}{2.25 \times 10^8} = 1.33$ [2]

b $\sin r = \dfrac{\sin i}{n} = \dfrac{\sin 55}{1.33} = \dfrac{0.8192}{1.33} = 0.616$

$r = 38°$ to 2 s.f. [2]

11 A ray of light is in water of refractive index 1.33. The ray approaches the interface with air at an angle of incidence of 52°. Carry out a suitable calculation and state what happens to the ray after striking the interface. [4]

Student's answer

$$n = \frac{\sin i}{\sin r}$$

$$\sin r = \frac{\sin 52^\circ}{1.33} = 0.592$$

$$r = 36^\circ$$ [1]

Teacher's comments

The student failed to make a final statement.

The student used the wrong value for refractive index.

Students should know and be able to use the equation $n = \frac{1}{\sin c}$.

Correct answers

For light passing from water to air, the correct value is $n = \frac{1}{1.33}$.

$$n = \frac{\sin i}{\sin r}$$

$$\frac{1}{1.33} = \frac{\sin i}{\sin r}$$

$$\sin r = 1.33 \times \sin 52^\circ = 1.05$$

It is impossible to have a sin value greater than 1, which indicates that the critical angle must have been exceeded and total internal reflection occurs. This would be a completely correct answer. [4]

If a student happens to recognise that this is possibly the case, there is an alternative approach.

Alternative approach:

The angle of incidence is close to the critical angle, so check that first.

$$\sin c = \frac{1}{1.33}$$

$$c = 48.75^\circ$$ [3]

The angle of incidence is confirmed as greater than the critical angle, so total internal reflection occurs and the ray is reflected back in the water with an angle of reflection of 52°. [1]

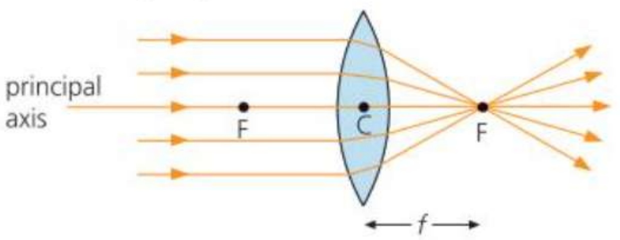
3.2.3 Thin lenses

Key objectives

By the end of this section, you should be able to:
- describe the action of thin converging and thin diverging lenses on parallel beams of light
- know and use the terms focal length, principal axis and principal focus
- draw diagrams of light rays undergoing refraction and passing through thin converging lenses to produce real images
- describe an image using the terms enlarged/same size/diminished, upright/inverted and real/virtual

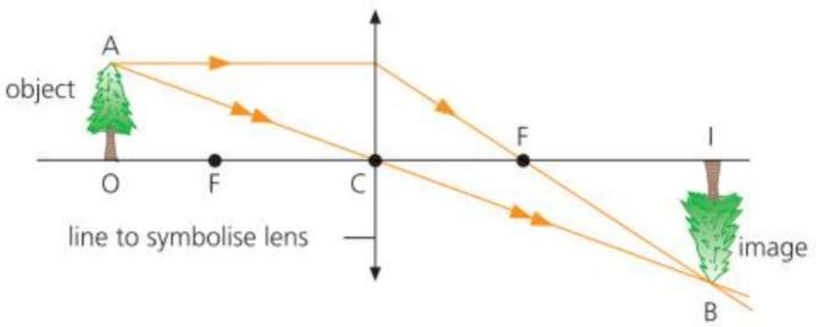
- draw diagrams of light rays passing through thin converging lenses to produce virtual images
- know how lenses are used to correct long-sightedness and short-sightedness

Converging lenses



▲ **Figure 3.36 Action of a converging lens on a parallel beam of light**

All rays of light parallel to the principal axis are refracted by the **converging lens** to pass through the **principal focus**, F (Figure 3.36). The distance between F and the optical centre, C, is called the **focal length**, *f*.



▲ **Figure 3.37 Ray diagram for a converging lens**

If the object is placed more than one focal length behind the lens, the image will always be real and inverted (Figure 3.37). Depending on where the object is placed, the image may be enlarged, the same size as the object or diminished.

Skills

Drawing ray diagrams

You must be able to draw ray diagrams to illustrate the formation of an image by a converging lens.

A lens has a focal length of 4.0 cm and an object of height 2.0 cm is placed 8.0 cm to the left of the lens.

Note: You must work **very carefully**. Small errors in drawing can lead to large errors in the result. Use a sharp pencil, draw points to within 0.5 mm of the correct position and draw lines **exactly** through points. Follow these steps to determine the position, size and nature of the image:

1. Preliminary – draw the principal axis, the object, a vertical line for the lens, mark the principal focus 'F' on both sides of the lens and mark the point where the principal axis crosses the lens as 'C'.
2. Ray 1 – draw a ray from the top of the object to the line of the lens, parallel to the principal axis, and continue this ray to pass through F and a few centimetres beyond. This is because all rays parallel to the principal axis pass through the principal focus.
3. Ray 2 – draw this ray from the top of the object through C to pass straight on until it cuts ray 1.

This is because the centre of the lens acts as a thin pane of glass, so rays pass through the centre undeviated.

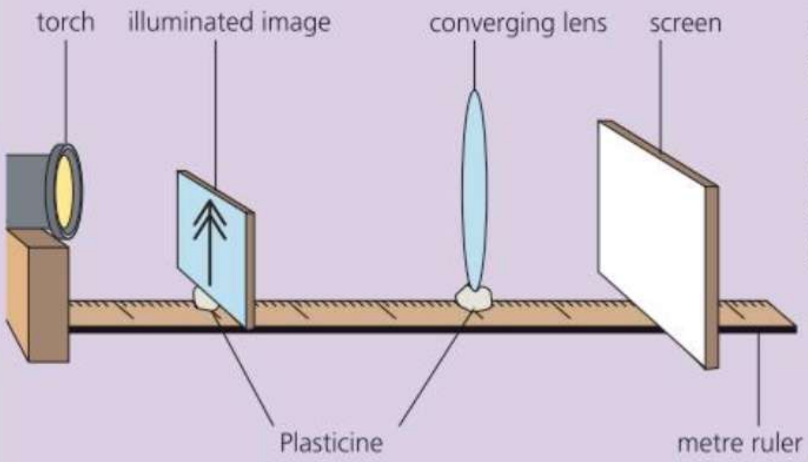
4 The rays should converge at a point 8.0 cm to the right of the lens, 2.0 cm below the principal axis. Expect a small error of a few mm but no more. The image is real, inverted and the same size as the object.

5 The diagram should look like Figure 3.37.

Skills

Forming a real image with a converging lens

In a darkened room, set up on a bench a converging lens of known focal length, an illuminated object and a small white screen in a straight line as in Figure 3.38.



▲ **Figure 3.38 Forming an image with a lens**

Place the object about three focal lengths away from the lens and write down this distance. Place the screen on the other side of the lens about two focal lengths away from the lens. Observe the image as you slowly move the screen towards the lens. At the position of sharpest focus, write down the distance from the image to the lens.

To check your result, draw a ray diagram using your results as in Skills: Drawing ray diagrams and see if you get the same image distance as in your practical.

If the object is placed closer to a converging lens than the principal focus, the rays leaving the lens do not converge to form a real image. A virtual image is formed where diverging rays meet when extrapolated backwards. These rays cannot form a visible projection on a screen.

Magnifying glass

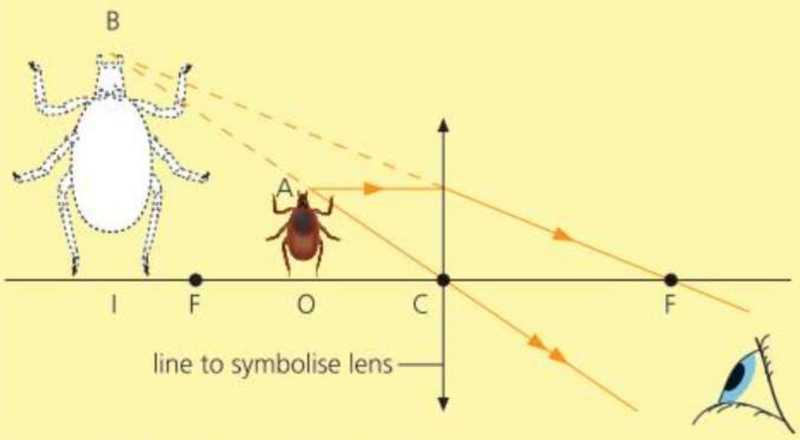


Image is behind object, virtual, upright, larger

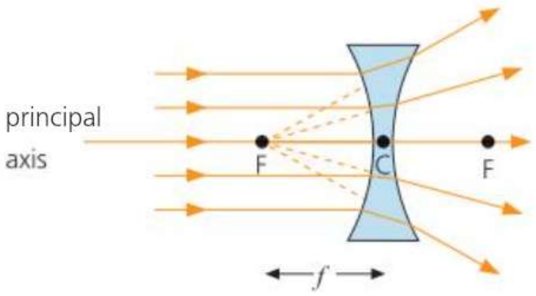
▲ **Figure 3.39 Ray diagram for a converging lens used as a magnifying glass**

Figure 3.39 shows how a converging lens can be used as a magnifying glass. The object is placed less than one focal length behind the lens. No real image is formed, but the eye sees the rays diverging from the magnified virtual image. O is the object and I the image.

The nature of an image

The characteristics of an image are described using the following terms for an image when it is compared with the object: enlarged/the same size/diminished, upright/inverted and real/virtual.

Diverging lenses

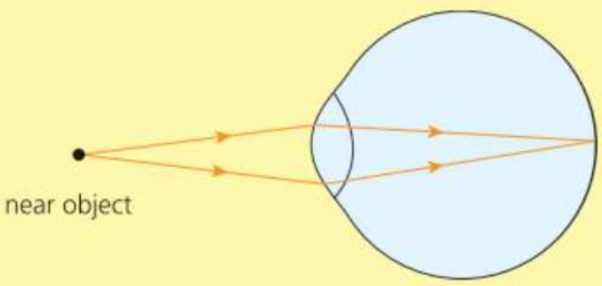


▲ **Figure 3.40 Action of a diverging lens on a parallel beam of light**

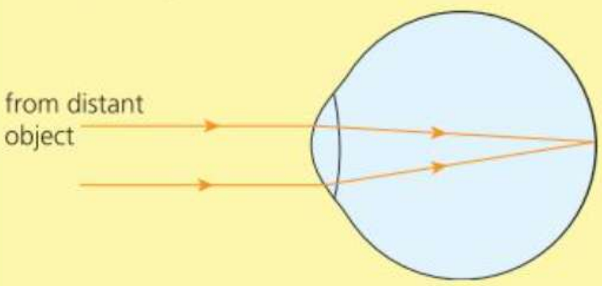
All rays of light parallel to the principal axis are refracted by the **diverging lens** to pass away from the principal focus, F. The distance between F and the optical centre, C, is called the focal length, *f*.

Lenses to correction vision

The human eye contains a converging lens which forms an image on the light-sensitive cells in the retina at the back of the eye. The muscles in the eye change the shape of the lens, which changes the focal length for objects at different distances. A healthy eye can focus objects from about 25 cm (Figure 3.41) to infinity (Figure 3.42).



▲ **Figure 3.41 Focusing an object at 25 cm, the eye lens is 'thicker' and has shorter focal length**

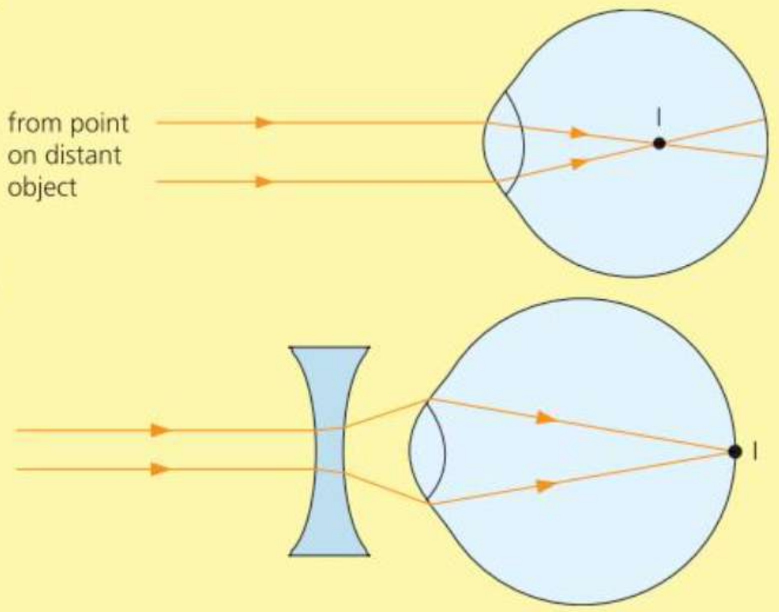


▲ **Figure 3.42 Focusing an object at infinity, the eye lens is 'thinner' and has longer focal length**

Short-sighted people have eye lenses that refract light from distant objects too much. They can see close objects clearly but distant objects are blurred. This is corrected by diverging lenses in spectacles or contact lenses (Figure 3.43).

a

b

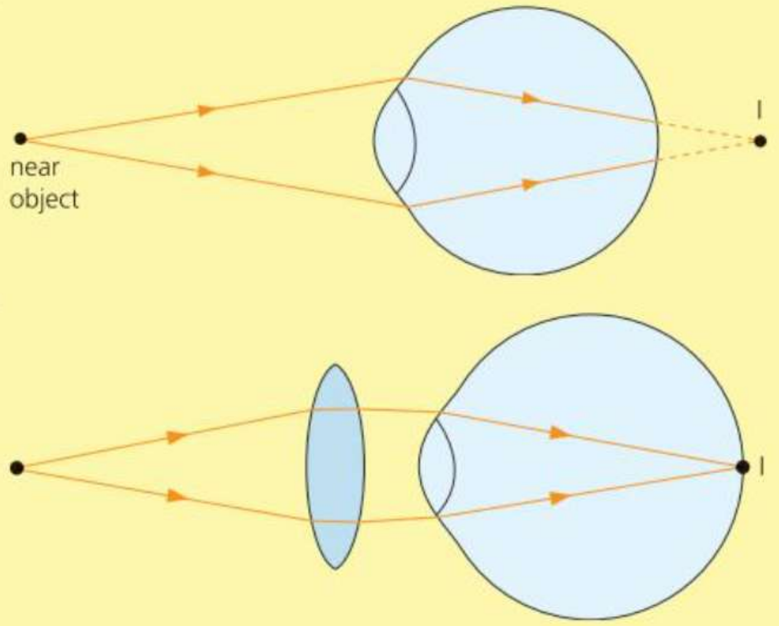


▲ **Figure 3.43 Short-sightedness and its correction by a diverging lens**

Long-sighted people have eye lenses that do not refract light from near objects enough. They can see distant objects clearly but close objects are blurred. This is corrected by converging lenses in spectacles or contact lenses (Figure 3.44).

a

b



▲ **Figure 3.44 Long-sightedness and its correction by a converging lens**

Sample question

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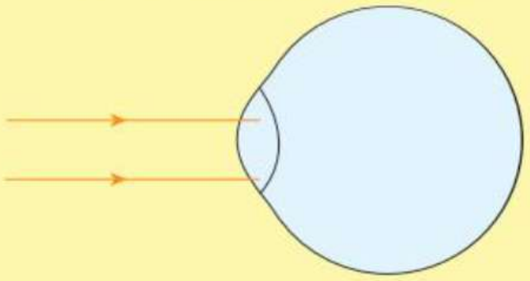
12 a Figure 3.45 shows parallel rays from a distant object approaching the eye of a short-sighted person.

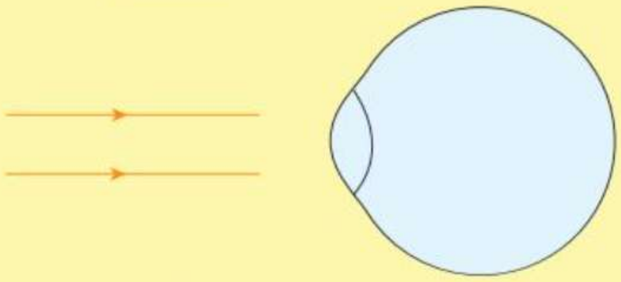


▲ **Figure 3.45**

Draw the rays continuing to show their paths to the back of the eyeball. [1]

b The person wears correcting lenses so distant objects can be seen in sharp focus.

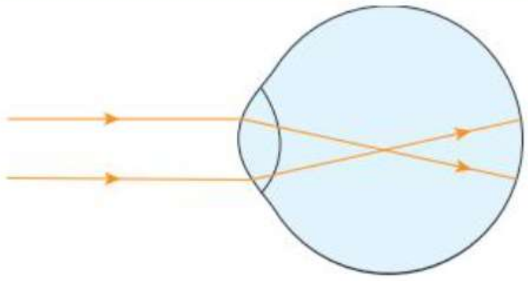
In Figure 3.46 draw the correcting lens and the paths of the rays through the correcting lens and the eye lens to the back of the eyeball. [2]



▲ Figure 3.46

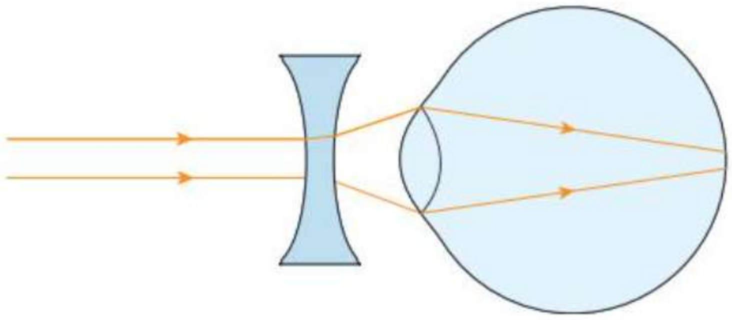
Student's answer

a



▲ Figure 3.47 [1]

b



▲ Figure 3.48 [1]

Teacher's comments

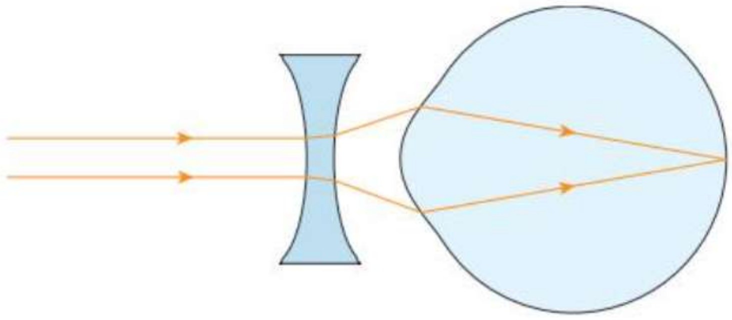
a The student's answer is correct.

b The student might have intended the correct answer but has not been careful when drawing. The rays should converge **exactly** at the back of the eyeball.

Correct answers

a The student's answer is correct. [1]

b



▲ Figure 3.49 [2]

3.2.4 Dispersion of light

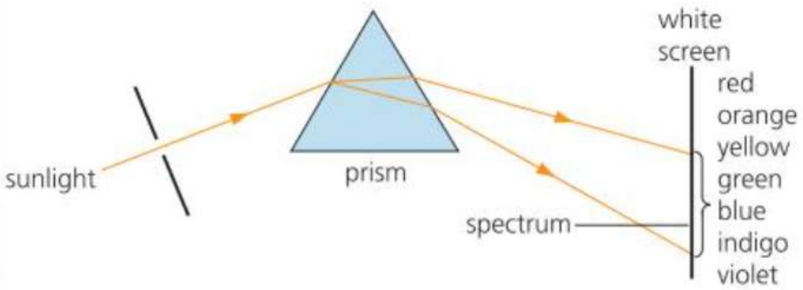
Key objectives

By the end of this section, you should be able to:

- describe the dispersion of white light by a glass prism
- know the traditional seven colours of the visible spectrum in order of frequency and wavelength
- know that visible light of a single frequency is described as monochromatic

White light is made up of seven colours. In order of increasing wavelength these are violet, indigo, blue, green, yellow, orange and red. In order of increasing frequency, the sequence is reversed.

Each colour is refracted by a different amount in glass. If a beam of white light falls on a glass prism, it is dispersed into a **spectrum** of the seven colours (Figure 3.50).



▲ **Figure 3.50 Forming a spectrum with a prism**

Monochromatic light
Light of a single frequency or wavelength is described as monochromatic, which means it is of a single colour.

Sample question

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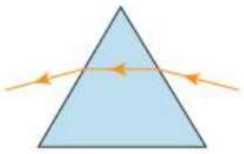
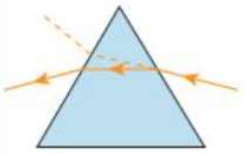
13 Figure 3.51 shows a ray of green light passing through a glass prism from right to left.
A ray of orange light enters the prism on the same path as the original ray of green light.
On the diagram draw with a dashed line the path of this ray through and out of the prism. [3]



▲ **Figure 3.51**

Student's answer



▲ **Figure 3.52** [1]

Teacher's comments

The student has drawn the correct path within the prism. However, on leaving the prism the ray should be refracted away from the normal not towards the normal.

9 A surveyor's telescope used to observe a measuring pole with a scale produces an upside-down image compared with the object.
  a Suggest and explain a helpful way to have the numbers of the scale on the measuring pole printed. [1]
  b The telescope's image can be seen only in the eyepiece and cannot be projected on a screen.
  Choose three items from the following list that describe the image:
  - enlarged
  - same size
  - diminished
  - upright
  - inverted
  - real
  - virtual [3]

10 a Draw a ray diagram to show the action of a diverging lens. [2]
  b Mark and label the principal axis and principal focus. [2]

11 Describe how a lens is used to correct long-sightedness. You should include a statement of the type of lens used and a ray diagram showing the action of the lens and the formation of a sharp image at the back of the eye. [4]

12 a Calculate the frequency of green light of wavelength 5.5×10^{-7} m. [3]
  b Use your knowledge of the electromagnetic spectrum to deduce and choose from the following list a possible wavelength for red light:
  - 5.5×10^{-10} m
  - 4.1×10^{-7} m
  - 7.1×10^{-7} m
  - 5.5×10^{-4} m [1]

3.3 Electromagnetic spectrum

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Key objectives

By the end of this section, you should be able to:

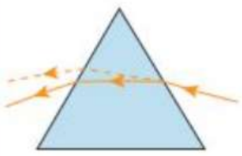
- know the main features of the electromagnetic spectrum
- know that the speed of all electromagnetic waves in a vacuum is 3.0×10^8 m/s and is approximately the same in air
- describe typical uses of different regions of the electromagnetic spectrum
- describe the harmful effects on people of excessive exposure to electromagnetic radiation
- know that communication with artificial satellites is mainly by microwaves
- know the important systems of communication using electromagnetic radiation
- know the difference between a digital and an analogue signal and that sound can be transmitted as either
- explain the benefits of digital signalling

Properties of electromagnetic waves

All types of waves that make up the **electromagnetic spectrum** have these properties in common:

- They can travel through a vacuum at the same high speed, which is much faster than other types of waves that travel through a material.
- They show the normal wave properties of reflection, refraction and diffraction.

Correct answer



▲ **Figure 3.53** [3]

Revision activity

Make flash cards to revise and rearrange the equation for refraction relating n, i and r with n on the left of the equals sign. Include what the symbols in the equation represent. Rearrange the equation with $\sin i$ on its own on the left of the equals sign. Then rearrange the equation with $\sin r$ on its own on the left.

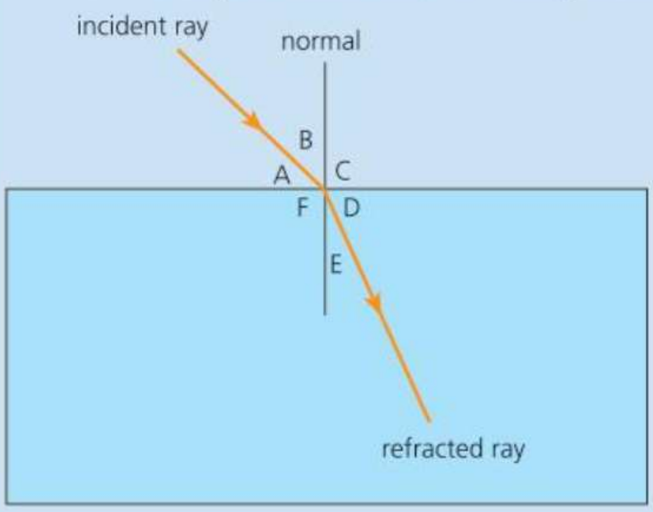
Revision activity

Write down the seven colours in order of their refraction in a glass prism. You may find it helpful to use the capital letters of this mnemonic: Richard Of York Gave Battle In Vain (or the name 'Roy G Biv') to stand for the first letters of the colours. To remember which end of the visible spectrum is refracted most remember 'Blue bends best'.

Exam-style questions

Answers available at: www.hoddereducation.co.uk/cambridgeextras

5 Figure 3.54 shows a light ray entering a glass block of refractive index 1.5. The angle of incidence is changed so that angle A is now 60°.



▲ **Figure 3.54**

- **a** Which of angles A–F is the angle of incidence? [1]
- **b** Which of angles A–F is the angle of refraction? [1]
- **c** Work out the values of angles B–F
  Do not measure from the diagram. [2]

6 **a** Describe the action of optical fibres in a medical application. [3]
- **b** Describe the action of optical fibres in a telecommunications application. [3]

7 An object of height 1.5 cm is placed 4.5 cm from a thin converging lens of focal length 3 cm. Draw a ray diagram to find:
- **a** the size and position of the image [4]
- **b** the nature of the image [3]

8 An object of height 1.5 cm is placed 2 cm from a thin converging lens of focal length 3 cm. Draw a ray diagram to show two parallel rays from the object passing through the lens.
- **a** What can you say about the two rays as they leave the lens? [1]
- **b** With dashed lines, draw your rays back behind the object. [2]
- **c** Find:
  - **i** the size and position of the image [1]
  - **ii** the nature of the image [1]

- They are transverse waves.
- They travel owing to moving electric and magnetic fields.

- The speed of electromagnetic waves in a vacuum is 3×10^8 m/s. The speed is approximately the same in air.

The wave equation $v = f\lambda$ applies, so the lower the wavelength, the higher the frequency.

The Sun and other stars give off a wide range of types of electromagnetic waves, which travel through space to Earth. Much of this radiation is stopped by Earth's atmosphere and can be detected only by satellites in orbit outside the atmosphere.

Types of electromagnetic waves

You need to know the types of electromagnetic waves, in order of decreasing wavelength and increasing frequency, as listed below.

Radio waves are used for:

- radio and television transmission
- radio astronomy detecting signals from stars and galaxies
- radio frequency identification (RFID) systems which track objects fitted with a small radio transmitter

- Bluetooth signals which have limitations because they are weakened when passing through walls

Microwaves are used for telecommunication, radar and microwave ovens. They are used for satellite and mobile phone (cell phone) telecommunication because microwaves can pass through some walls and only require a short aerial. Microwaves can damage living cells and, as they travel through matter, cause internal burns. Parts of the ears and eyes, in particular, are easily damaged by microwaves, so great care is needed to ensure that the doors of microwave ovens are always closed when in use and that excessive mobile phone use is avoided. Personnel servicing military aircraft in an operational situation wear protective suits to reflect the microwaves emitted by the high-powered radar in the aircraft.

Infrared radiation is produced by hot objects and transfers thermal energy to cooler objects. Hot objects below about 500°C produce infrared radiation only; above this temperature, visible light is also radiated. Used for thermal imaging (e.g. night-vision goggles which detect the infrared radiation given off by warm objects), remote controllers, intruder alarms, optical fibres as short wavelength infrared can carry high rates of data.

Excess infrared radiation can cause skin burns.

Visible light is a very narrow range of wavelengths that can be seen by the human eye as the colours of the visible spectrum from violet to red.

It is used in optical fibres as light can also carry high rates of data.

Ultraviolet radiation is produced by the Sun, special ultraviolet tubes and welding arcs. The radiation can cause sunburn and skin cancer and damage eyes. It also produces vitamins in the skin and causes certain substances to fluoresce. This fluorescence can reveal markings that are invisible in visible light so is useful for security marking, detecting fake bank notes. It is used for sterilising water.

Note: the commonly used expression ultraviolet light is incorrect. Ultraviolet radiation is not part of the visible spectrum, so must *not* be called light. This misconception might occur because often ultraviolet lamps give off blue and violet light as well as ultraviolet radiation.

X-rays are produced in high-voltage X-ray tubes. They are absorbed differently by different types of matter. They can produce shadow pictures of inside the human body, which are invaluable for medical diagnosis. X-rays can penetrate inaccessible solid structures. They are used by security machines at airports and other travel hubs to scan luggage for dangerous hidden objects. X-rays are dangerous to living matter as they can kill cells and cause cell mutations which lead to cancers. Lead shielding must be used to protect people from exposure, especially those who work regularly with X-rays.

Gamma rays are produced by radioactive substances. They are very dangerous to living matter. They are used to kill cancer cells and dangerous bacteria. They are used to sterilise food and medical equipment.

Communication with electromagnetic radiation

You should know the difference between an **analogue** and **digital signal**.

You should be able to explain the benefits of digital signalling, including the increased rate of data transmission and increased range due to accurate signal regeneration.

Sound can be transmitted as a digital or analogue signal.

Communication with artificial satellite is mainly by microwaves.

Some satellite phones use low-orbit artificial satellites.

Some satellite phones and television use geostationary satellites (see Topic 6 Space Physics).

Sample questions

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14 State the type of orbit of satellites used for satellite television. [1]

15 State two advantages of digital signalling. [2]

Student's answers

14 *Circular* [0]

15 *Faster and further* [1]

Teacher's comments

14 Incorrect answer.

15 Partially correct answer. The signal does not travel faster. Further is a vague description but would just be enough to score a mark.

Correct answers

14 Geostationary orbit. [1]

15 Increased rate of data transmission and increased range due to accurate signal regeneration. [2]

Revision activity

Make a flash card to revise the values of the speed of waves in the electromagnetic spectrum in a vacuum.

Revision activity

Make a revision poster to show all the types of radiation in the electromagnetic spectrum. Include the types of waves and directions of increasing wavelength and increasing frequency.

Exam-style questions

Answers available at: www.hoddereducation.co.uk/cambridgeextras

13 An observatory receives X-rays and gamma rays from a star.

a Which type of radiation has the higher wavelength? [1]

b Which type of radiation has the higher frequency? [1]

c Light from the star takes four years to reach the observatory. Do the X-rays take less, more or the same time to reach the observatory? [1]

d Work out the distance from the observatory to the star in metres. [3]

14 The solid line in Figure 3.55 shows the path of a ray of blue light through a prism. A different type of radiation is directed towards the prism on the same path as the ray of blue light. The dashed line shows the path of this radiation through the prism.

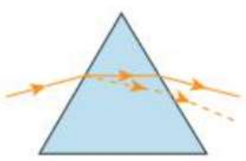

Figure 3.55

a Which type is this radiation?

A microwaves
B orange light
C ultrasound
D violet light [1]

b Explain your answer [2]

15 Which are the correct statements in the table about ultraviolet radiation?

	Its wavelength is shorter than…	A harmful effect on people of excessive exposure is…
A	visible light	skin cancer
B	visible light	burning of internal organs
C	X-rays	skin cancer
D	X-rays	burning of internal organs

[1]

16 a Which type of electromagnetic radiation is Bluetooth? [1]

b Write down how there could be a problem in the transmission of Bluetooth signals within a building. [2]

17 a i What is the nature of infrared radiation? [1]

ii State two uses of infrared radiation. [2]

b Microwaves are similar to infrared waves.

i State one similarity and one difference between them. [2]

ii State a danger when people are close to a strong source of microwaves. [1]

3.4 Sound

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Key objectives

By the end of this section, you should be able to:

- know that sound waves are longitudinal waves with compressions and rarefactions produced by vibrating sources which require a medium for transmission
- be able to describe compressions and rarefactions (see 3.1 General properties of waves)
- know that the approximate range of audible frequencies to humans is 20 Hz to 20 000 Hz and that the speed of sound in air is approximately 330–350 m/s
- know that in general sound travels faster in solids than in liquids and faster in liquids than gases
- describe a method to determine the speed of sound in air involving the measurement of distance and time
- describe how changes of amplitude affect the loudness of sound waves and changes of frequency the pitch
- describe an echo as the reflection of sound waves
- describe typical uses of ultrasound

Sound waves are **longitudinal** waves that are produced by a vibrating source, which causes a material to vibrate. A material or medium is required to transmit sound waves.

The speed of sound in air at normal temperatures is 330–350 m/s.

Sound travels faster in solids than in liquids and faster in liquids than in gases.

Sound can be transmitted as a digital or analogue signal.

Although normally observed in air, sound waves can travel through liquids and solids, e.g. sea creatures communicate by sound waves travelling through water.

The healthy human ear can hear sound in air in the frequency range of 20 Hz to 20 000 Hz (20 kHz). This is called the **audible range**. In practice, only people with very good hearing can hear throughout this range. With ageing, this range is reduced and hearing tests usually only check frequencies between 250 Hz and 8 kHz.

Sound of a higher frequency than 20 kHz (the audible range) is called **ultrasound**.

Typical uses of ultrasound:

- medical scanning of soft tissue
- non-destructive testing of materials
- using sonar to determine the depth of underwater objects

The greater the amplitude of sound waves, the louder the sound.

The greater the frequency of sound waves, the higher the pitch.

Sound waves can be reflected, especially from large, hard, flat surfaces. The reflected sound is called an **echo**.

As sound travels through a material, compressions and rarefactions occur (see Figure 3.2 on p. 58). Compressions are regions where particles of material are closer together. Regions of material are rarefied where the particles move further apart (at rarefactions).

Sonar measures the time taken for ultrasound waves to be reflected from underwater objects in order to determine the depth of the object.

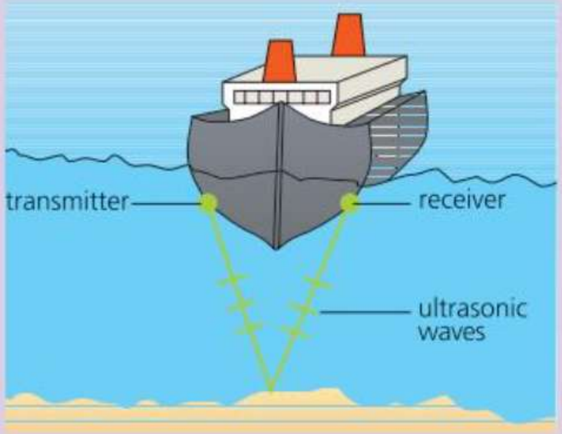
Skills

Determining depth from time and wave speed

An ultrasound signal transmitted to the seabed is measured to take 0.25 s to return to the ship. The speed of sound in water is 1400 m/s. Calculate the depth of the seabed.

Distance travelled by wave = speed × time = 1400 × 0.25 = 350 m

depth of seabed = $\frac{350}{2}$ = 175 m



▲ **Figure 3.56 A ship using sonar**

Sample questions

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16 A student stands across a field from a large building and claps their hands regularly. They hear each clap coinciding exactly with the echo from the clap before. They measure their distance from the building as 100 m and the time taken for 16 claps as 10 s. Work out the speed of sound in air. [4]

Student's answer

time between claps = $\frac{16}{10}$ = 1.6 s [0]

distance travelled = 2 × 100 = 200 m [1]

speed = $\frac{200}{1.6}$ = 125 m/s [1]

Teacher's comments

The student calculated the number of claps per second instead of the time from one clap to the next. No further error was made in calculating the speed, so the student gained the last two marks.

As the source and observer are at the same place, the student correctly realised that sound travels twice the distance between the observer and the reflecting surface. Be careful in problems involving echoes not to take the distance from the observer to the reflecting surface as the distance travelled by the sound.

Unfortunately, in problems when no echo or reflection is involved, students often wrongly double the distance travelled by the sound.

Correct answer

time between claps $= \frac{10}{16} = 0.625\,s$ [2]

distance travelled $= 2 \times 100 = 200\,m$ [1]

speed $= \frac{200}{0.625} = 320\,m/s$ [1]

You must be able to describe an experiment involving the measurement of distance and time to find the speed of sound in air. (Such as this sample question.)

17 A railway worker gives a length of rail a test blow with a hammer, striking the end of the rail in the direction of its length. A sound of frequency 10 kHz travels along the rail. The speed of sound in the rail is 5000 m/s.
Calculate the wavelength of the wave. [2]

Student's answer

wavelength, $\lambda = \frac{v}{f} = \frac{3000}{10000} = 0.3\,m$ [1]

Teacher's comments

The student has used the correct equation but has substituted the wrong speed of sound.

Correct answer

wavelength, $\lambda = \frac{v}{f} = \frac{5000}{10000} = 0.5\,m$ [2]

18 A machine uses sound waves of frequency 3 MHz to form images within the human body.
Choose one of the following as the best description of these waves:

- long wavelength
- hypersound
- polarised sound
- supersonic
- ultrasound [1]

Student's answer

polarised sound [0]

Teacher's comments

Incorrect response

Correct answer

ultrasound [1]

19 Dolphins emit sound waves of 95 kHz. State and explain if these waves are ultrasound. [2]

Student's answer

Sound waves of 95 kHz are ultrasound because they travel faster than normal sound waves. [1]

Teacher's comments

Ultrasound is correct but the reason is incorrect.

Correct answer

Ultrasound, because the frequency is higher than the audible range. [2]

20 At a concert attended by people of all ages, including children and old people, a sound of frequency 19 kHz is produced. Comment on how this would be heard by the audience. [1]

Student's answer

Everyone would hear it because it is in the audible range. [1]

Correct answer

People with healthy hearing would hear the sound of 19 kHz. It is right at the top of the audible range, so people with any loss of high-frequency hearing would not hear it. [1]

Teacher's comments

The answer is on the right lines but is incomplete because in such an audience it is unlikely that everyone would have completely healthy ears.

21 Is sound always transmitted as an analogue signal? [1]

Student's answer

Yes [0]

Correct answer

Sound can be transmitted as an analogue signal or a digital signal. [1]

Teacher's comments

Incorrect answer; sound is sometimes transmitted as an analogue signal but not always.

Revision activity

Sketch a sound wave by drawing vertical lines of length 1 cm to show wavefronts. Show and label compressions and rarefactions and label one wavelength.

Revision activity

Make flash cards to revise some values about sound waves. Include the speed of sound waves in air, the range of frequencies audible to humans and the frequency of ultrasound.

Exam-style questions

Answers available at: www.hoddereducation.co.uk/cambridgeextras

18 A research ship uses sonar to locate a shoal of fish. The speed of sound in water is 1500 m/s.

a The frequency of this sound is 750 Hz.
Calculate the wavelength of the sound waves. [2]

b The ship receives back an echo 37 ms after a sound is transmitted.
Work out the depth of the shoal below the ship. [3]

c Some sound of this frequency is emitted into the air.

i Is it audible to members of the crew of the ship?
Explain your answer. [2]

ii What is the wavelength of this sound in air? [2]