Physics

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Physics

GRADE 9

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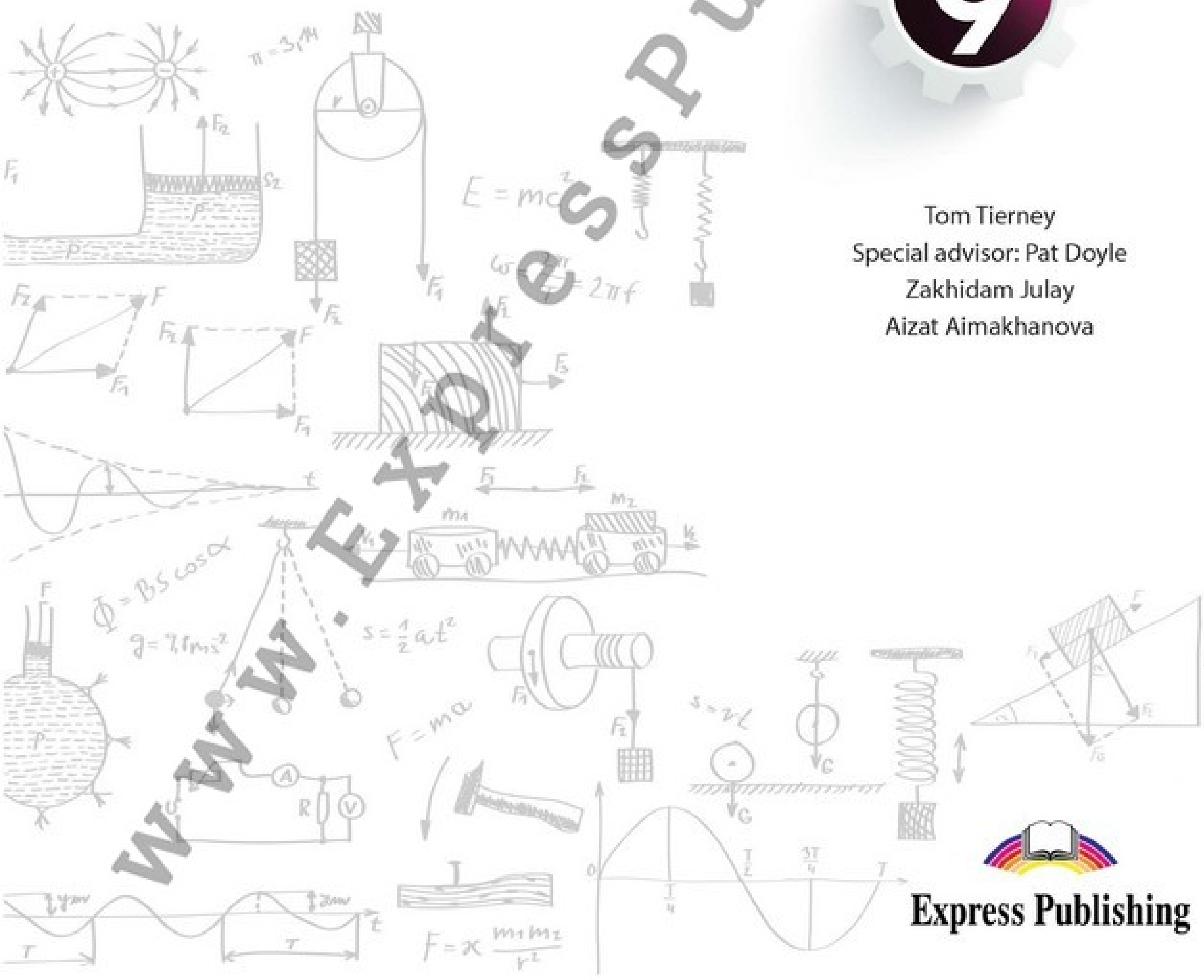

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Introduction

For the student

Welcome to your new Physics textbook, *Grade 9 Physics*. Your textbook comes with a **Grade 9 Physics Student's Portfolio** and a range of *digital resources*. This book will build on your previous learning of Physics by helping you to understand the world around you. It aims to develop your learning skills in science. You will develop these skills yourself while also learning from your teacher and your fellow students.

Glossary

A comprehensive Glossary for the Textbook and Student's Portfolio book is included at the back of this book.

For the teacher

Written for the new Grade 9 Physics subject programme in Kazakhstan, *Grade 9 Physics* aims to give students a sense of enjoyment and an interest in the learning of science. The book is based on the Grade 9 Learning Objectives in the Grade 7- 9 Physics subject programme document. It develops students' knowledge of and about science through the four content and skills strands described in the Physics subject programme and highlighted throughout the text, using four different logos (understanding science, researching and experimenting in science, communicating in science, and science and society).

- **Learning outcomes** are stated at the beginning of each module in student-friendly language.
- **Keywords** are listed at the start of each module to allow students to become familiar with important new terms.
- **Activities** allow students to build on their knowledge by completing research.
- **Diagrams** have been fully labelled and are drawn in a simple style so that students can replicate them easily.
- **Questions** are interspersed within the text to offer teachers the opportunity to use different teaching strategies. In particular, there are chances for group work and pair work.
- **Did you know?** boxes feature interesting facts to stimulate students' interest in science.

- The **language** used is clear and simple to allow for use by students of varying reading levels.
- Simple and helpful **logos** are used throughout to enhance student understanding.

Activity

Corresponding page in Student's Portfolio

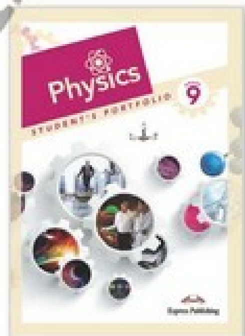
Key fact

Question

Group work

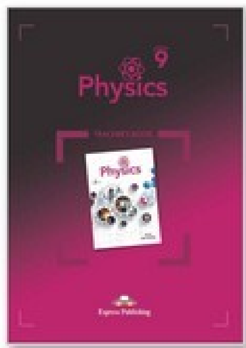
Research

Student's Portfolio



The Student's Portfolio provides additional material, activities and tasks. The portfolio book enables students to maintain a record of specific activities and reflect on their learning, as well as focusing on key words and key facts, through mind maps and comprehension and recall activities. It also contains templates for self-assessment and peer assessment. This book works in conjunction with the Textbook.

Teacher's Book



The Teacher's Book works in conjunction with the Textbook and the Student's Portfolio book by providing:

- An outline of the Grade 9 content and skills priorities in the subject programme
- Learning outcomes for each module with explanations of how they are incorporated into lessons
- Information on topics, questions and research ideas that can be used to enhance the students' learning
- Answers to all student questions in the Textbook and Student's Portfolio book
- Outlines of digital resources for each module and suggestions for integrating them into classroom work
- Suggestions of ways to assess student activities with assessment templates
- A range of other information and suggestions to support teachers in the delivery of the new course
- Key skills, literacy and numeracy linked to relevant modules
- Guidance for the teacher throughout the module
- Additional activities and research activities

Digital resources

The *Grade 9 Physics* **digital resources** will further enhance classroom learning. These resources have been designed to integrate with the Textbook and to complement lessons suggested in the Teacher's Book. Following the principles of the new national Physics subject programme, material is provided to suit a range of learner types and to encourage participation and engagement on the part of the student.

A series of **videos** allows students to observe science in action across all modules. These videos reinforce the topic at hand and allow for other perspectives, which may be discussed in class. Similarly, a series of **videos** about **scientist biographies** presents a lively gateway to develop students' interest in science and initiate student-led research.

Further classroom discussion and participation is opened up through **PowerPoint presentations**, including a thematic presentation of information from the Textbook. **Experiment videos** allow for a visual review of activities carried out in the classroom. **Extra assessment material** is provided to support teachers in carrying out a range of oral and written formative and summative assessments.

Guidance for integration of digital resources in the classroom is provided by the **digital resource symbol** used throughout the Textbook, as well as the provision of detailed notes and suggestions in the Teacher's Book.

Laboratory equipment

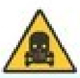
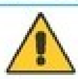
Laboratory safety rules for pupils

The following rules are enforced to keep you and your classmates safe while in a school laboratory.

1. Do not enter the laboratory without permission.
2. Do not use any equipment unless permitted to do so by your teacher.
3. Make sure you know exactly what you are supposed to do. If in doubt, ask your teacher.
4. Make sure you know the position of all safety equipment in the laboratory, e.g. the fire extinguishers, first aid equipment etc.
5. Always wear eye protection or gloves when instructed to do so.
6. Long hair must be tied back during practical classes.
7. Place your bag and other personal items safely out of the way.
8. Never handle any chemicals with bare hands.
9. Nothing must be eaten, tasted or drunk in the laboratory.
10. Any cut, burn or other accident must be reported at once to your teacher.
11. Always check that the label on the bottle is exactly the same as the material you require. If in doubt, ask your teacher.
12. Any chemical spilled on the skin or clothing must be washed at once with plenty of water and reported to your teacher.
13. Test tubes should never be overfilled. When heating a test tube ensure that the mouth of the test tube is pointed away from you and everyone else.
14. All equipment should be cleaned and put back in its correct place after use.
15. Always wash your hands after practical work.
16. Students should behave in a responsible manner at all times in the laboratory.

Safety labels

The following labels appear on bottles in the laboratory. They also appear on many everyday chemicals such as cleaning products and solvents. These labels indicate chemicals that could be dangerous if not used or handled properly. We use these warning symbols on activities in this book.

Toxic		Substances which can cause death if they are swallowed, breathed in or absorbed through the skin. Example: weedkiller.
Harmful or irritant		Substances which should not be eaten, breathed in or handled without gloves. Though not as dangerous as toxic substances they may cause a rash, sickness or an allergic reaction.
Oxidising		Substances which provide oxygen, allowing other materials to burn more intensely. Example: hair bleach.
Highly flammable		Substances which easily catch fire. Example: petrol.
Corrosive		Substances which attack and destroy living tissue, including skin and eyes. Example: oven cleaner.
Warning sign		This sign is used to draw attention to a warning of danger, hazards and the unexpected.
Safety glasses		Wear safety glasses to protect your eyes.

MODULE 1

Motion and Vectors

Learning outcomes

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

- Explain meaning of concepts: material point, reference system, the relativity of mechanical motion and apply theorems of addition velocities and displacements 9.2.1.1
- Conduct addition, subtraction of vectors and multiply vectors on scalar 9.2.1.2
- Find vector's projection on coordinate axe and distribute a vector for components 9.2.1.3
- Find displacement, velocity and acceleration from graphs of dependence of these values on time 9.2.1.4
- Apply formulas of velocity and acceleration at uniform straight motion in solving problems 9.2.1.5
- Apply kinematic equations of coordinate and displacement at uniform straight motion in solving problems 9.2.1.6
- Experimentally define acceleration of a body at uniformly accelerated motion 9.2.1.7
- Analyse factors influencing the experiment result and suggest ways to improve the experiment 9.1.3.2
- Plot and explain graphs of displacement and velocity dependency on time for straight uniformly accelerated motion 9.2.1.8

Keywords

✔ speed ✔ velocity ✔ acceleration ✔ reference frame ✔ coordinates
✔ scalar ✔ vector ✔ deceleration ✔ distance ✔ displacement
✔ components ✔ protractor ruler ✔ parallel ✔ perpendicular

Frames of reference

The study of Physics involves the observation and mathematical description of physical phenomena and to do this we need reference frames which provide points of reference relative to bodies that we wish to study. You will be familiar with some frames of reference from other subjects, for example, locating a position on a map through degrees of longitude and latitude. The frames of reference used in the study of motion are referred to as co-ordinate systems. These frames use coordinates relating to axes from a given point of origin to determine the positions and velocities of objects in that frame.

Vectors and Scalars

In dealing with concepts of mechanical motion and forces we need to distinguish between two types of measurement: vectors and scalars.

Scalars are measurements which have only magnitude e.g. time.
Vectors are measurements which have both magnitude and direction e.g. force.

A typical measurement for a force, for example, is 20 N west, where the direction is given in terms of the points of the compass. Think, for example, of a football that is slowly rolling towards a goal line on a windy day. The direction of the force matters. If a force is applied behind the football, it will reach and cross the line. If a force is applied in the opposite direction, there may be time for the defending team to prevent a goal.

Q Understanding U_2

1.1 Look at the following types of measurements and decide whether they are scalars (s) or vectors (v). Think about whether direction is a factor in these measurements.

mass	**time**	**velocity**	**temperature**
speed	**length**	**momentum**	**volume**
force	**distance**	**displacement**	**energy**
acceleration			

Objects moving in a straight line

While there are many types of motion, in this module we examine one type: objects moving in a straight line. We use certain words to describe motion, such as:

- speed
- velocity
- acceleration

We will look at what these mean in the following sections.

Speed

Speed is calculated by dividing the distance travelled by a person by the time to travel this distance. In the language of mathematics we say:

$$\text{speed} = \frac{\text{distance}}{\text{time}}$$

Units for speed

Since speed $= \frac{\text{distance}}{\text{time}}$, units are $\frac{\text{unit of distance}}{\text{unit of time}} = \frac{\text{metre}}{\text{second}} = \frac{\text{m}}{\text{s}}$

Instead of writing $\frac{\text{m}}{\text{s}}$ we usually use m/s or ms^{-1}

Note: When you are answering a mathematical question about speed you might be given the distance in centimetres (cm) or in kilometres (km). You must always **change the distance value to metres.**

Remember:

100 cm	is the same as	1 m
70 cm	is the same as	0.7 m
16 cm	is the same as	0.16 m
1 km	is the same as	1000 m
4 km	is the same as	4000 m
7.5 km	is the same as	7500 m

In mathematical questions in physics, we always use seconds for values of time. If the value for time is in minutes or hours, then **change the time value to seconds.**

Remember:

1 minute	is the same as	60 s
5 minutes	is the same as	60 x 5 = 300 s
1 hour	is the same as	60 x 60 = 3600 s

Did you know?

- In science we measure speed in metres per second (ms^{-1}).
- Most countries measure the speed of cars in kilometres per hour (kph).
- Scientist Albert Einstein said that nothing can travel faster than the speed of light.

Q Understanding U2

1.2 What is the meaning of speed?

1.3 What units are used for speed?

1.4 Convert the following to metres:

(a) 17 cm (b) 9 cm (c) 4 km (d) 7.2 km

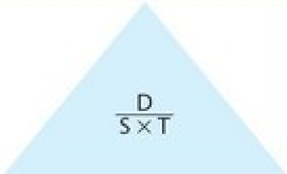
1.5 Convert the following to seconds:

(a) 6 minutes (b) 4 hours (c) 1 day

Calculating speed

Helpful hint: look at the triangle:

Where D = distance
S = speed
T = time



Place your finger over the quantity you are measuring in the triangle above and the instruction for your calculation is right in front of you.

- To calculate speed: $\text{speed} = \frac{\text{distance}}{\text{time}}$
- To calculate time: $\text{time} = \frac{\text{distance}}{\text{speed}}$
- To calculate distance: $\text{distance} = \text{speed} \times \text{time}$

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Sample question 1

Calculate the speed of a car that travels 400 m in a time of 10 s.

Answer:

$$\text{speed} = \frac{\text{distance}}{\text{time}} = \frac{400\text{ m}}{10\text{ s}} = 40\text{ ms}^{-1}$$

Sample question 2

Calculate the speed of a train that travels a distance of 1.8 km in a time of 1 minute.

Answer:

$$\text{speed} = \frac{\text{distance}}{\text{time}} = \frac{1.8\text{ km}}{1\text{min}} = \frac{1800\text{ m}}{60\text{ s}} = 30\text{ ms}^{-1}$$

Sample question 3

How long does it take a car travelling at a speed of 40 ms^{-1} to travel a distance of 720 m?

Answer:

Be careful with a question that starts with the words 'how long' because the word 'long' can refer to both distance and time. In this question you are being asked about time.

$$\text{time} = \frac{\text{distance}}{\text{speed}} = \frac{720\text{ m}}{40\text{ ms}^{-1}} = \frac{720\text{ m}}{40\text{ ms}^{-1}} = 18\text{ s}$$

Sample question 4

Calculate the distance travelled by a person running at a speed of 5 ms^{-1} for 2 hours.

Answer:

$$\begin{aligned}\text{distance} &= \text{speed} \times \text{time}\\ &= 5 \times 2 \times 60 \times 60\\ &= 36000\text{ m}\end{aligned}$$

Q Understanding U2

1.6 Calculate the speed of a car that travels a distance of 450 m in a time of 90 s.

1.7 Calculate the speed of a car that travels a distance of 2.4 km in 2 minutes.

1.8 Calculate the time taken for a car to travel 50 m if the speed of the car is 20 ms^{-1}.

1.9 Calculate the distance travelled by a train in 50 s if it has a speed of 70 ms^{-1}.

Did you know?

Words do not always mean the same in science as they do in general conversation. When talking normally with friends we often use words that can have more than one meaning. For example, the word 'cool' does not always refer to the fact that something is cold. But in science we need to be very precise with the meaning of words.

Velocity

The words **speed and velocity** have similar meanings but there is a very important difference between them.

The velocity of an object tells you **the speed** at which it is travelling *and* the **direction** in which it is travelling.

The **direction** of a moving object is usually given using points of the compass, for example: north, south, east or west.

Figure 1.1 *Skydivers – after falling for a short time skydivers reach a 'terminal velocity'*

Communicating C1 Communicating C2

1.10 Using the Internet, research the term 'terminal velocity' as it applies to:

(a) rain drops

(b) hailstones

Present your findings to the class as a brief PowerPoint presentation.

Unit for velocity

The unit we use for velocity is the same as the unit we use for speed: **m/s** or **ms^{-1}**.

Acceleration

In normal conversation many people would use the word acceleration to refer to an object that is increasing its speed, i.e. going faster. In science this is not fully correct.

Acceleration is about the rate of **change in velocity**. Remember that a change can be an increase or a decrease. Acceleration could refer to a car slowing down. In this case we would have a negative acceleration or a deceleration.

Research R2 Research R3 Research R4 Portfolio 8

Activity 1.1

Question

How can you identify acceleration?

Equipment needed

Laptop with data logging software installed
Printer
Speed sensor
Trolley
Motion track
Protractor
Set of books

Safety

- The laptop and printer are electrical devices that may be plugged into a socket. Take care when working with electrical appliances.
- Take care not to drop heavy equipment such as the trolley and the track.

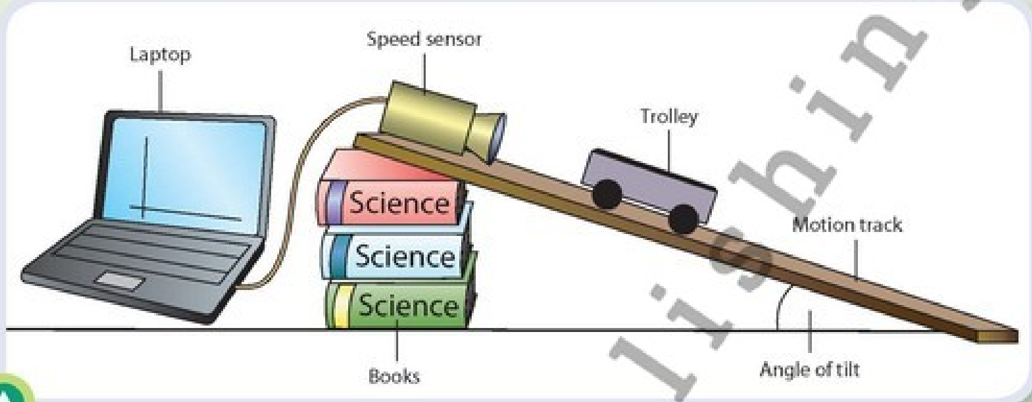

Figure 1.2

Conducting the activity

1. Arrange the motion track so it is tilted at an angle of 10° above the horizontal. Books can be used to tilt the track.
2. Release the trolley from rest at the top of the track.
3. Using the speed sensor connected to the laptop, record the speed of the trolley as it rolls down the tilted track.
4. On the laptop display a graph of speed on the y-axis and time on the x-axis.
5. Print a copy of this graph. Write on it what angle of tilt was used.
6. Repeat the above steps for different angles of tilt, 20°, 30° and 40°.

Q Research R4 Research R5

1.11 Compare the four graphs. Have they the same shape. How do they differ?

1.12 From doing the activity, which angle of tilt caused the greatest acceleration?

You will need to know this formula for acceleration:

$$\text{acceleration} = \frac{\text{final speed} - \text{first speed}}{\text{time taken for the change in speed}}$$

Unit for acceleration

The unit we use for acceleration is ms^{-1} divided by the second.

This can be written two ways: m/s^2 or ms^{-2}.

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Sample question 5

A car is moving at a speed of 4 ms^{-1}. After 12 s it is moving at a speed of 28 ms^{-1}. Calculate the acceleration of the car.

Answer:

$$\text{acceleration} = \frac{\text{final speed} - \text{first speed}}{\text{time taken for the change in speed}}$$
$$= \frac{28 - 4}{12}$$
$$= \frac{24}{12}$$
$$= 2\ ms^{-2}$$

Figure 1.3

Sample question 6

A train starts from rest in a station and after 2 minutes it is moving at a speed of 90 ms^{-1}. Calculate the acceleration of this train.

Answer:

The words 'from rest' mean that the first speed of the train was zero.

Remember to change the minutes to seconds.

$$\text{acceleration} = \frac{\text{final speed} - \text{first speed}}{\text{time taken for the change in speed}}$$
$$= \frac{90 - 0}{2 \times 60}$$
$$= \frac{90}{120}$$
$$= 0.75\ ms^{-2}$$

Sample question 7

A car was travelling at a speed of 50 ms^{-1}. After a time of 14 seconds the speed of the car had changed to 8 ms^{-1}. Calculate the acceleration.

Answer:

$$\text{acceleration} = \frac{\text{final speed} - \text{first speed}}{\text{time taken for the change in speed}}$$
$$= \frac{8 - 50}{14}$$
$$= \frac{-42}{14}$$
$$= -3\ ms^{-2}$$

This could be considered as a deceleration.

Q U2 Understanding

1.13 When a car is first observed it has a speed of 20 ms^{-1}. After a time of 10 s it is observed that the speed is 50 ms^{-1}. Calculate the acceleration of this car.

1.14 A car starts from rest and after a time of 20 s it has a speed of 40 ms^{-1}. Calculate the acceleration of this car.

1.15 When a car is first observed it has a speed of 30 ms^{-1}. After a time of 6 s the speed has been reduced to 12 ms^{-1}. Calculate the value of the deceleration.

In **Activity 1.1** you plotted your results using a graph. We will now look at different types of graph and work out the different kinds of calculation that can be made from them.

Displacement – Time graphs

Displacement is plotted on the vertical axis and time on the horizontal axis. Look at the five graphs below and match one of the labels below to what they show.

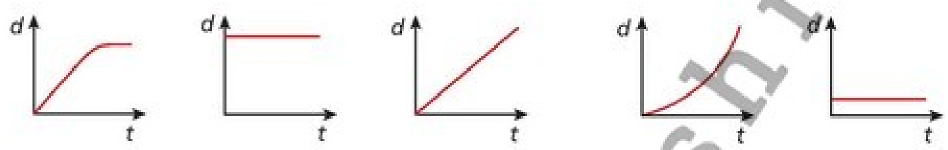


Figure 1.4 *Time graphs*

(a) constant velocity
(b) accelerating
(c) zero velocity
(d) decelerating

From a graph such as the one in **Figure 1.5** which shows the motion of a car travelling along a road at constant velocity, several calculations can be made.

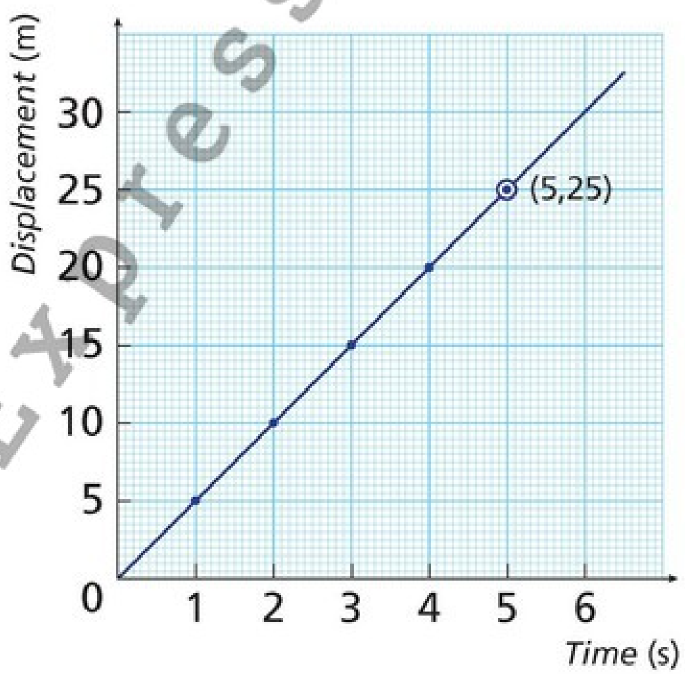


Figure 1.5 *Displacement-time graph*

Understanding U2

1.16 Calculate the time taken for the car to travel a distance of 8 m.

1.17 Calculate the distance travelled by the car after 4.5 s.

1.18 Calculate the velocity of the car.

The graphs below in contrast to Figure 1.5 show the displacement of a car starting at rest and moving at a constant acceleration. The average for velocity of the car for any part of this journey can still be calculated from the graphs, using the formula shown in Figure 1.7, but the calculation will give an average velocity for that section of the journey.

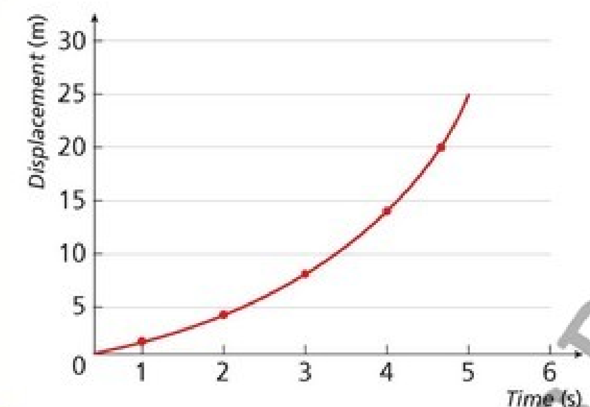


Figure 1.6 *Constant acceleration*

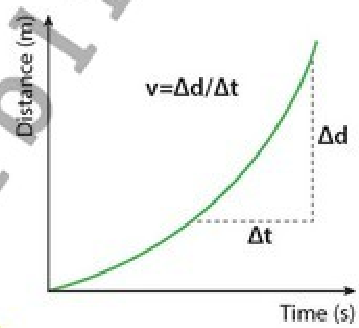


Figure 1.7 *Constant acceleration – formula*

Understanding U2

1.19 Calculate the average velocity of the car in Figure 1.6 between seconds 3 and 4 of the journey.

1.20 Calculate the average velocity of the car across the entire journey shown in Figure 1.6.

Velocity – Time Graphs

In a velocity – time graph, velocity is plotted on the vertical axis and time on the horizontal axis. In Figure 1.8, the graph represents the velocity of a train starting at rest and then moving at constant acceleration. It is important to remember that the graph does not represent the direction of the journey but the velocity of the train.

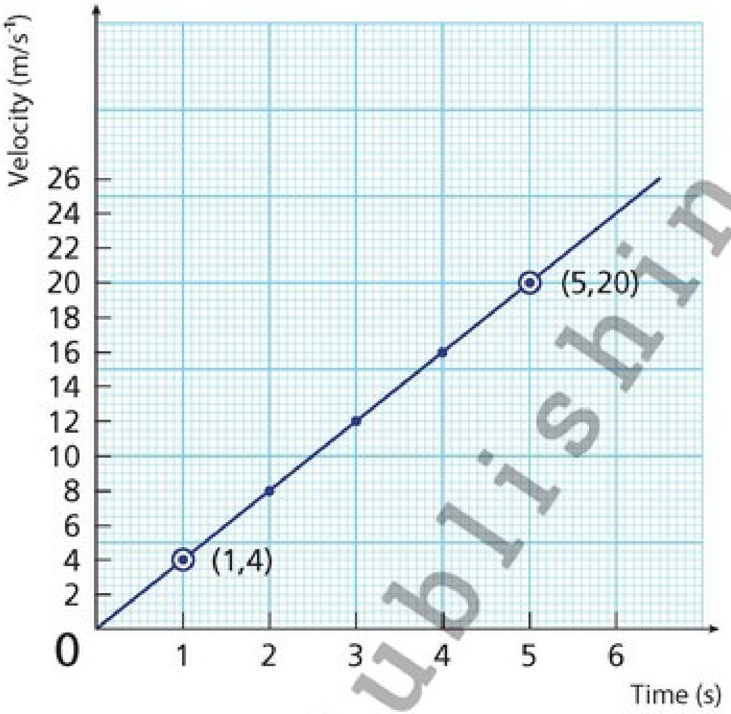


Figure 1.8 *Velocity-time graph*

Q U2 Understanding

1.21 Calculate the velocity of the train after 4.5 seconds.

1.22 Calculate how long it takes to reach a velocity 10 ms^{-1}.

1.23 Calculate the acceleration between points (1,4) and (5,20) on the graph.

1.24 If the shape of the slope on diagram A in Figure 1.9, represents constant acceleration, what do the slopes in diagrams B and C represent?

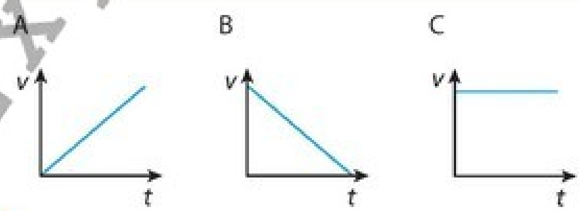


Figure 1.9

It is possible to calculate displacement from velocity-time graphs, as the area under the line is equal to displacement of the object up to that point. So from the Figure 1.10, we need to calculate the area of the purple triangle (which represents the section of the journey where the train is accelerating) and the orange rectangle (which represents the section of the journey where the train is moving at constant velocity).

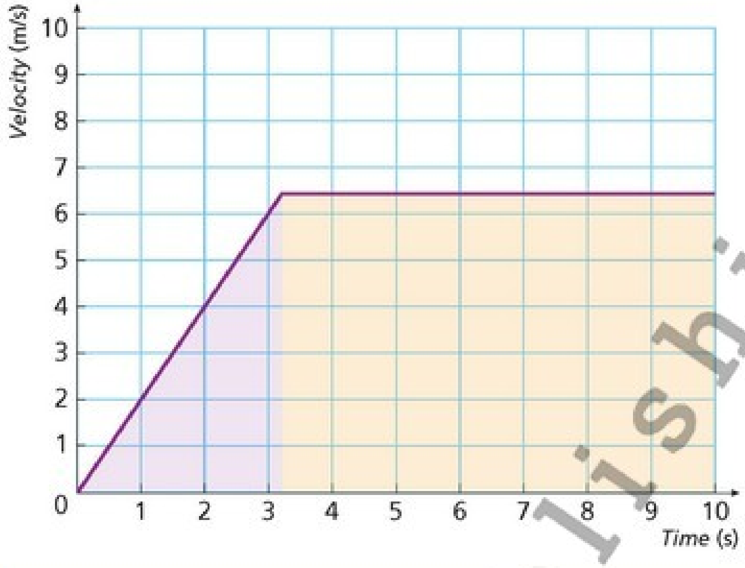


Figure 1.10 *Calculating displacement in velocity-time graphs*

area of triangle = base × height
= ½ × 3 × 6 = 9 m
area of rectangle = base × height
= 6 × 7 = 42 m
Total displacement = 51 m

Understanding U2

1.25 Calculate the displacement of the vehicle represented in the graph for the first 8 seconds of the journey.

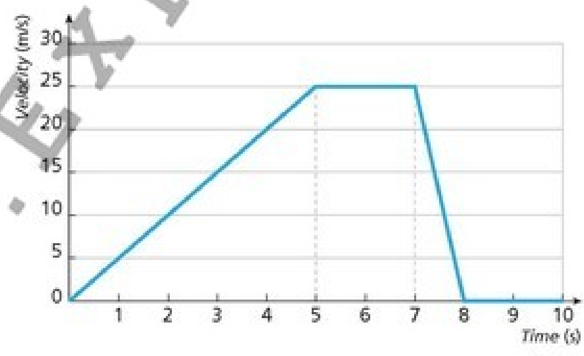


Figure 1.11

1.26 A speedboat starts from rest and reaches a velocity of 25 m s^{-1} in 10 s. It continues at this velocity for a further 4 s. It then comes to a stop in the next 4 s.

(a) Draw a velocity–time graph to describe the motion of the boat during its journey.

(b) Use your graph to estimate the velocity of the speedboat after 6 s.

(c) Calculate the acceleration of the boat during the first 10 s.

(d) What was the distance travelled by the boat when it was moving at a constant velocity?

(e) What was the total distance travelled by the boat?

Figure 1.12

Vector addition

So far in this module, we have looked at the vector quantities of velocity, displacement and acceleration so we will only take examples of mathematical operations with these measurements and consider forces in the next module.

Adding scalars is simpler than adding vectors because you simply add numbers e.g. 4 seconds + 12 seconds = 16 seconds. Adding vectors is more complicated because direction has to be taken into account. When adding vectors together we are essentially looking to see how two or more vectors could be replaced with a single vector. We want to know how large that single vector would be, and in what direction it would point.

The single vector that is found as the result of adding two vectors is called the resultant vector. This can be found either graphically by drawing and measuring scale diagrams or mathematically.

Scale diagram

Take the example of a man walking in a forest who initially walks 6 km east and then 4km north. We could represent this on a scale diagram as follows:

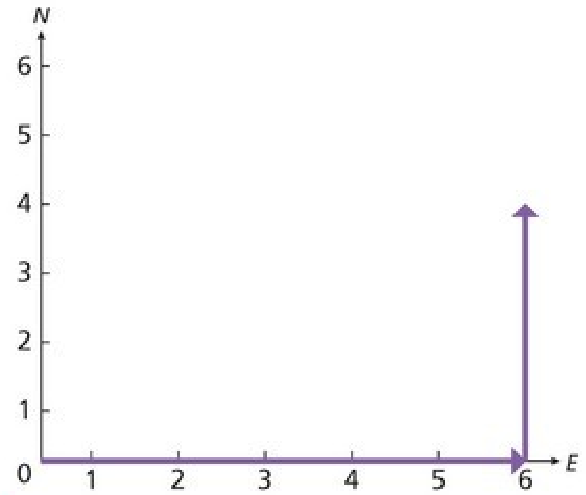


Figure 1.13 *Scale diagram*

Q U2 Understanding

1.27 By drawing a line from the tail of the first vector to the head of the second vector, you will be able to measure the resultant displacement with a ruler and the resultant direction with a protractor.

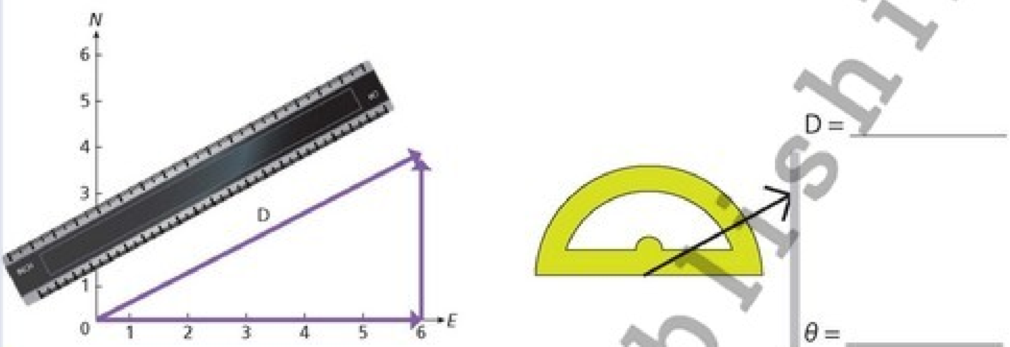
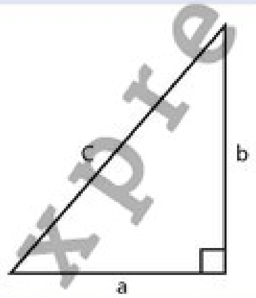


Figure 1.14 *Measuring resultant displacement*

Mathematical method

The Pythagorean Theorem can also be used to calculate the result of two vectors at a right angle to each other. The theorem which you need to remember can be stated as follows:



$$a^2 + b^2 = c^2$$

Figure 1.15 *Pythagorean Theorem*

It can be used to solve the type of problem in the example calculation.

Sample question 8

A person is walking along the deck of a ship so that their velocity is 2 m s^{-1} east. The ship is moving through the sea with a velocity of 5 m s^{-1} north. What is the overall velocity of the person?

Answer:

$v^2 = 5^2 + 2^2$

$v = 5.39\ ms^{-1}$

$\tan\theta = \frac{2}{5}$

$\theta = 21.8°$

$v = 5.39\ ms^{-1}$ (north 21.8° east)

(or 68.2° north east)

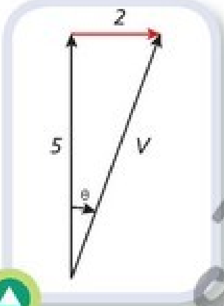


Figure 1.16

Understanding U2

1.28 A boat moves across a river as shown in the diagram, so that the forward velocity is 11 ms^{-1}. The river is flowing with a current of 4 ms^{-1}. In what direction, and with what velocity, would the boat cross the river?

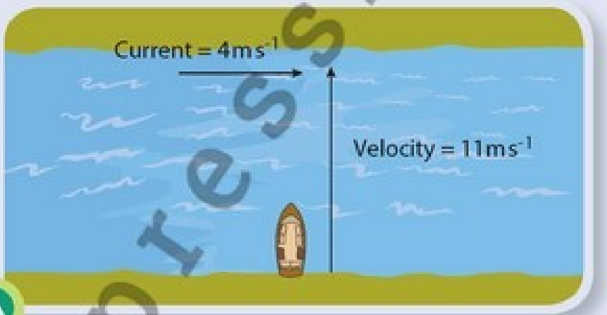


Figure 1.17

1.29 An aircraft takes off from an airport, A. It flies 6 km east, it then swings round to fly 8 km north to point B. What is its displacement from A?

Vector subtraction

The negative of a vector is defined as a vector with the same magnitude but the opposite direction. The diagram shows vector A is of the same length as –A, but indicates an opposite direction.

Let us take a situation and work through a problem.

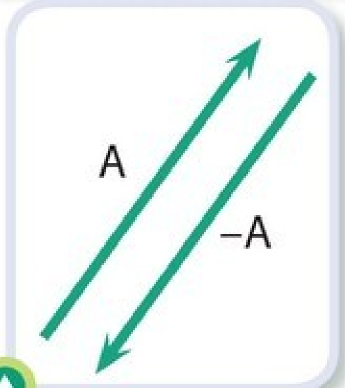


Figure 1.18 *Vector subtraction*

A group of orienteering students are given a challenge of finding their way to a base camp at night. They have been told to head 4.5 km 62 north of east of their starting point and then to head 110 north of east from that point for 4.8 km to reach the camp.

Their intended route represented diagrammatically should look like this.

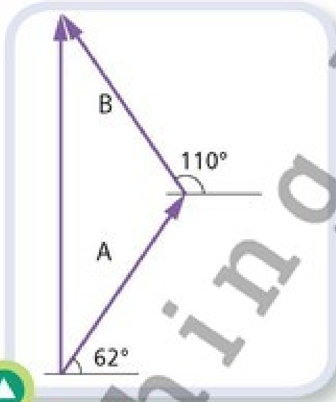


Figure 1.19

Q U2 Understanding

1.30 Using the vector tail and head (ruler and protractor) method we used earlier, draw this diagram to scale and calculate the resultant vector of the base camp by vector addition. Now imagine that at the head of point A, they make a mistake and travel in the opposite direction and travel 4.8 km in direction – B?

1.31 Draw vectors A and –B using the tail to head method. Use your ruler and protractor to measure the magnitude and direction of resultant vector from the group's starting point.

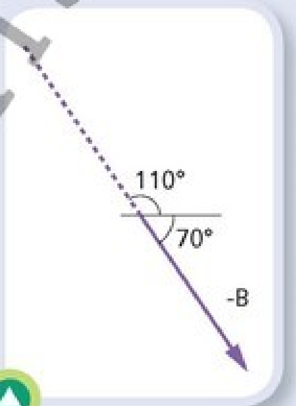


Figure 1.20

Did you know?

If you **add** two vectors in opposite directions, their magnitudes are *subtracted*, not added. For example, the resultant vector of adding 4 m N to 3 m S is 1 m N.

Q U2 Understanding

1.32 A man walks 51.5 m east, then 29 m west. Calculate his displacement from the point at which he started.

Vector multiplication by scalars

The result of the multiplication or division of a vector by a scalar is a vector. Take for example, the displacement vector of someone who walks 750 m due north: 750 m N. If we multiply this vector by 2 (a positive number) the magnitude is multiplied by the scalar quantity and the direction of the result is the same as for the original vector. The calculation tells us that the person has walked twice as far in the same direction: 1500 m N. If, however, the scalar is negative, then the direction of the result is the opposite of the original vector. 750 m N $\times -2$ gives 1500 m S. This tells us that the person walked twice as far in the opposite direction.

Q Understanding U_2

1.33 A man walks 340 m on a straight road. The vector for the journey is 340 m 41.0° north of east. His friend follows exactly the same path but only covers half the distance. What is the vector for the friend's journey.

1.34 What is the vector 217 m W $\times -3$?

Vector components

In the above section on vector addition, it was shown that two vectors can be represented by a single vector [the resultant vector] that has the same effect. The reverse process involves calculating the component vectors that have the same effect as the single vector. Imagine a plane flying from Almaty to Nur Sultan. Under normal circumstances, taking a reasonably direct route the plane would fly northwest as indicated by the displacement vector below.

Figure 1.21

There are two components in this displacement vector: a north component and west component as shown in the diagram.

Figure 1.22

The pair of vertical and horizontal vector components would have the same overall effect as the original single displacement vector.

Calculating vector components

Let us take an example involving a velocity vector. We take the original velocity vector and identify its components on x and y axes as shown in the diagram.

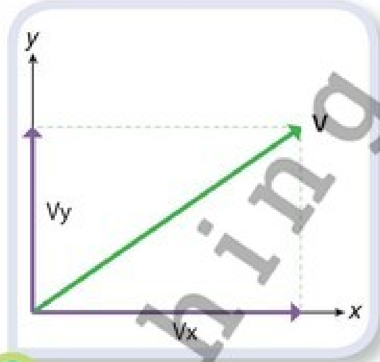


Figure 1.23 *Calculating vector components*

Parallelogram Method

Draw a parallelogram around the two vectors and measure the length of the sides of the parallelogram. Using a scale you will be able to work out the magnitude of the components in real units by measuring them accurately.

Q U2 Understanding

1.35 The velocity of the original single vector is 50 m/s. Using the parallelogram method draw and calculate the magnitude of the two component vectors: V_y and V_x.

Trigonometry method

We can resolve the component vectors of a single vector of known magnitude and known angle to the x and y axes by using simple right angle trigonometry.

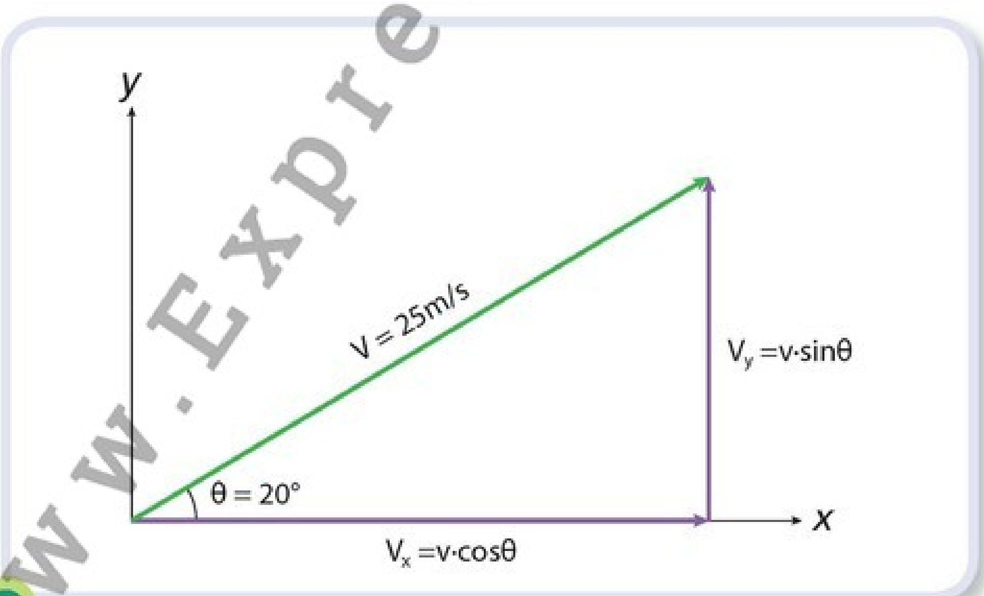


Figure 1.24

Sample question 9

Calculate the values V_x and V_y in the above vector diagram.

Answer:

$$v_x = v \cdot \cos(\theta) = 25 \cos 20^\circ = 23.49 \text{ m s}^{-1}$$

$$v_y = v \cdot \sin(\theta) = 25 \sin 20^\circ = 8.55 \text{ m s}^{-1}$$

Q Understanding U2

1.36 Resolve this vector into its horizontal and vertical components.

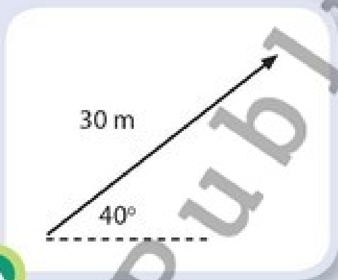


Figure 1.25

1.37 A plane taking off has a velocity of 215 m/s at an angle of 21° to the ground. Calculate the horizontal and vertical components of its velocity.

1.38 A woman crosses a road walking at 5 m s^{-1}. She crosses a road of width 25 m, at an angle of 45° to the side of the road. What is the component of her velocity **(a)** parallel to **(b)** perpendicular to the side of the road?

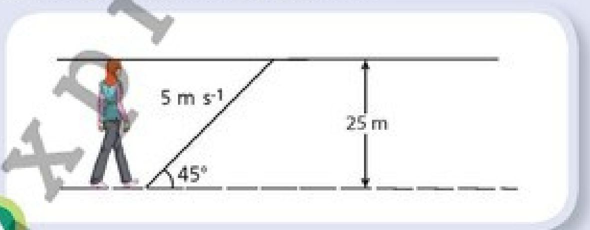


Figure 1.26

How long will it take her to cross the road?

1.39 A car travels 3120 m at an angle of 35°. How far did it travel north and east?

MODULE 2

Circular motion

Learning outcomes

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

- Describe uniform motion of a body in a circle using values for linear and angular velocity 9.2.1.13
- Apply formulae of the interrelation between linear and angular velocity when solving problems 9.2.1.14
- Apply formulae of centripetal acceleration when solving problems 9.2.1.15

Keywords

✔ circular motion ✔ angular velocity ✔ arc ✔ radians ✔ derive ✔ cycle ✔ period ✔ frequency ✔ tangent ✔ centripetal ✔ acceleration

Uniform circular motion

There are many examples of objects that move in a circular or linear path. The wheel of a car, for example, the big wheel at a fairground or a satellite orbiting the Earth are all examples of uniform circular motion.

Figure 2.1

Such objects are all very different, as are the processes that cause them to travel in a circular path, but they all are subject to simple mathematical rules that we shall consider below.

Linear and angular velocity

The velocity – remember this is a vector quantity – of an object travelling in a circle at constant speed is constantly changing. The change in velocity is not due to the magnitude changing but due to the fact that its direction is constantly changing.

The two objects in travelling on the paths in Figure 2.2 are travelling at the same speed but their velocities are different.

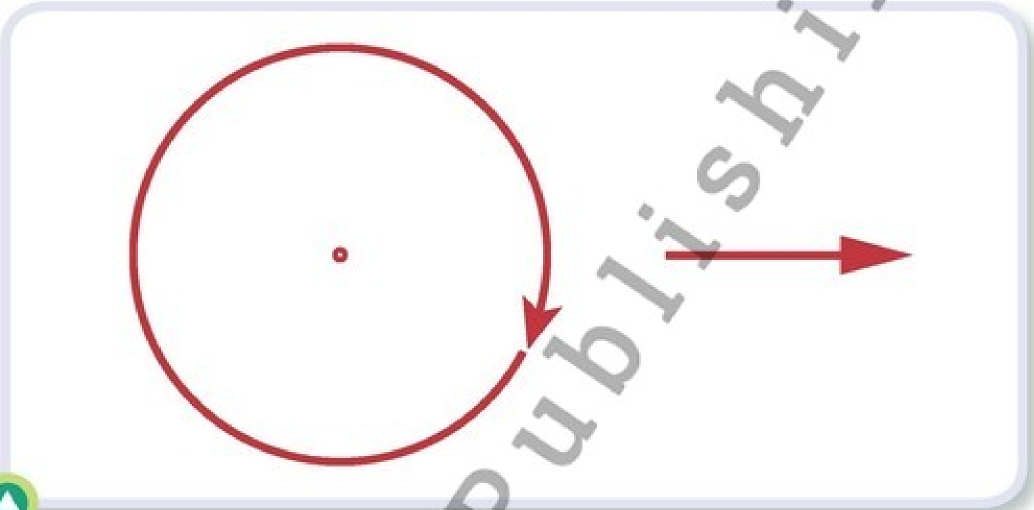


Figure 2.2

To calculate the speed of an object travelling in circular motion we need to calculate both its **linear** and **angular** velocity. The calculation for **linear velocity** is the same as if an object is travelling in a straight line. You will remember the formula for the calculation we used in Module 1:

$$\text{speed} = \frac{\text{distance}}{\text{time}} \quad \text{or} \quad v = \frac{l}{t}$$

As we can see from Figure 2.3, when an object is travelling in circular motion, the distance travelled equals **l**, forming an arc of a circle. Rather than measure the distance travelled on this arc every second, we can instead measure the angle, **θ**, through which it moves every second. Angular velocity, denoted by the letter **ω**, is thus a measurement of the angle (θ) an object moves through, measured in radians (rad), divided by the time (t) taken to move through that angle. This means that the unit for angular velocity is radians per second, rad s^{-1}.

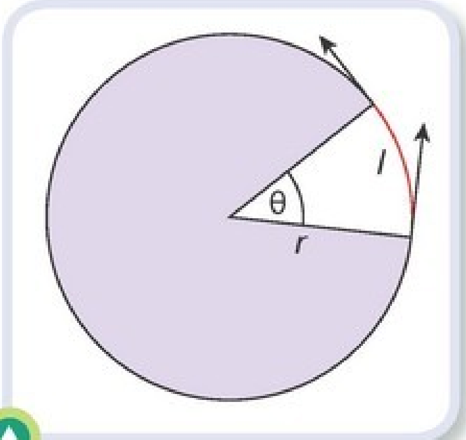


Figure 2.3

The formula for calculating angular velocity is:

$$\omega = \frac{\theta}{t}$$

There is, however, a connection between linear and angular velocity. Imagine the situation of a fairground carousel ride.

Figure 2.4

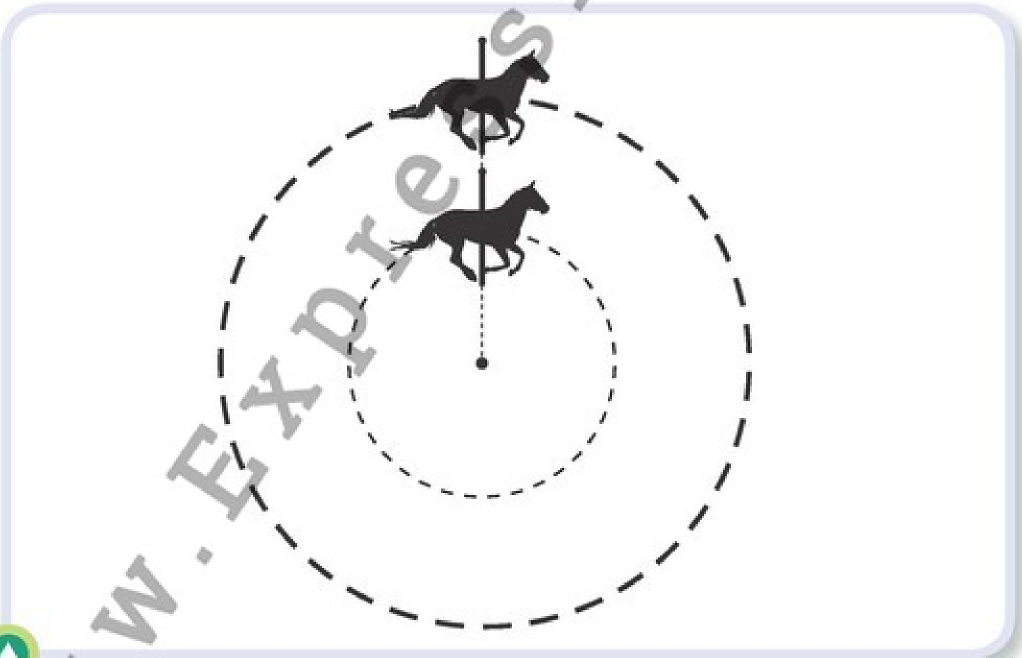


Figure 2.5

Both fairground horses are moving through the same angle each second, and therefore have the same angular velocity. However, the horse on the outside is travelling through a greater distance every second and, therefore, has a larger linear velocity than the horse on the inside. You will know this if you have been on a carousel.

We can connect the equations for linear velocity and angular velocity in the following way.

Taking the linear velocity formula:

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

and the formula for the arc of a circle, **l**, connected to the angle at its centre

$$l = r\theta$$

and substituting this into the first formula, we derive:

$$v = \frac{r\theta}{t}$$
$$v = r\frac{\theta}{t}$$

and since **$\omega = \theta t$** we can say

$$v = r\omega$$

Period and frequency

An object such as a wind turbine which travels in circular motion repeats the same motion over and over again. We call each complete motion a **cycle** and the time for the wind turbine to complete one complete cycle is called the **period**. The formula can be derived by the simple rearrangement of the formula for angular velocity.

Rearranging the equation for angular velocity :

$$\omega = \frac{\theta}{t} \quad \text{gives} \quad t = \frac{\theta}{\omega}$$

and as we know that an object travelling one complete circle moves through an angle that is **2π** radians, we can say the period, **T**, of an object in circular motion is given by:

$$T = \frac{2\pi}{\omega}$$

The **frequency** of a circular motion is the measurement of the number of full rotations, or circles, travelled in one second. Frequency is measured in hertz.

Period and frequency are linked by the formula:

$$f = \frac{1}{T}$$

We shall revisit these ideas when we study oscillations in Module 6.

Sample question 1

An object is in circular motion with an angular velocity of 12 rad s_{-1} and a radius of 34 cm. What is its linear velocity?

Answer:

$$v = r\omega$$
$$= 9 \times 0.34$$
$$= 3.06 \text{ m s}^{-1}$$

Sample question 2

A potter's wheel with a radius of 50 cm spins at 130 rpm.

(a) What is the period of its motion?

(b) What is the linear velocity of a point at its edge?

Answer:

f = 130 revolutions per minute, so revolutions per second:

(a) $T = \frac{1}{f} = \frac{130}{60} = 2.17 \text{ HZ}$

$T = \frac{1}{f} = \frac{1}{2.17} = 0.46\text{s}$

(b) $T = \frac{2\pi}{\omega}$

$\omega = \frac{2\pi}{T} = v = r\omega$

$\frac{2\pi}{0.46} = 13.66 \text{ rad s}^{-1}$

$v = r\omega$
$= (0.5)(13.66)$
$= 6.83 \text{ m s}^{-1}$

Figure 2.6

Q U2 Understanding

2.1 Calculate the angular velocity of the second hand on a clock.

2.2 What is the difference between period and frequency?

2.3 An object is in circular motion with an angular velocity of 20 rad s^{-1} and a radius of 20 cm. What is its linear velocity?

2.4 A child's spinning top spins 15 times in 2 seconds.

- **(a)** What is the frequency of rotation?
- **(b)** What is the period of rotation?

2.5 A car drives round a circular track of radius 1 km at a constant speed of 26 ms^{-1}. What is the angular velocity?

2.6 A potter's wheel of radius 45 cm spins so that it completes three complete rotations each second.

- **(a)** What is the frequency of the motion?
- **(b)** What is the period of the motion?
- **(c)** What is the linear velocity of the object?

2.7 A motorcycle on a circular speedway track with a radius of 50 m completes one lap in 14.3 s. If the motorcycle travels at a constant speed what is its acceleration?

2.8 The tyre of a small tractor rotates at the rate of 300 rpm (rotation per minute). If the diameter of the tyre is 80 cm, what are the angular and linear velocities of a point on the outer edge of the tyre?

2.9 A particle travels at a constant speed of 10 $m\ s^{-1}$ in a circle of radius 2 m. What is its angular velocity?

2.10 A ball is tied to the end of a string and is spun in a circle of radius 60 cm, as shown in Figure 2.7. If its angular velocity is 9 $rad\ s^{-1}$, what is its linear velocity?

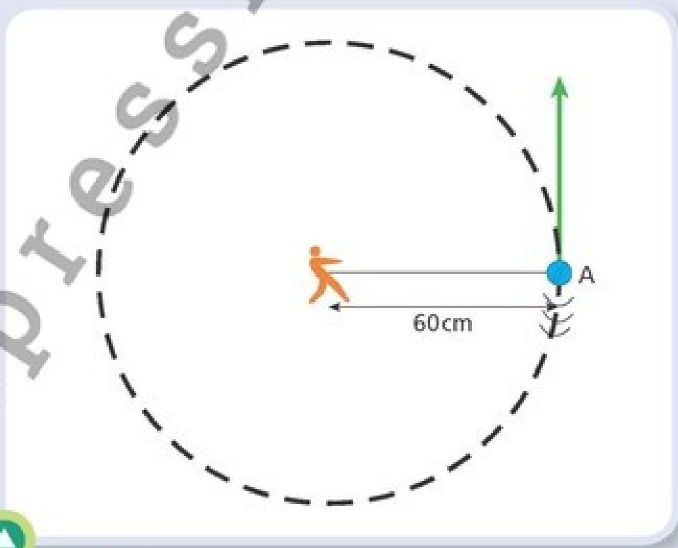


Figure 2.7

Centripetal acceleration

Centripetal acceleration is the acceleration that causes an object to move along a circular path. At every moment while an object is travelling in a circle, its direction is at a tangent to that circle. The following simple example demonstrates this. If a child is swinging a ball attached to a piece string in a circle and the string breaks then the ball will fly off at a tangent to the circle. From the point at which the string breaks the ball will continue in a straight line as indicated by Figure 2.8.

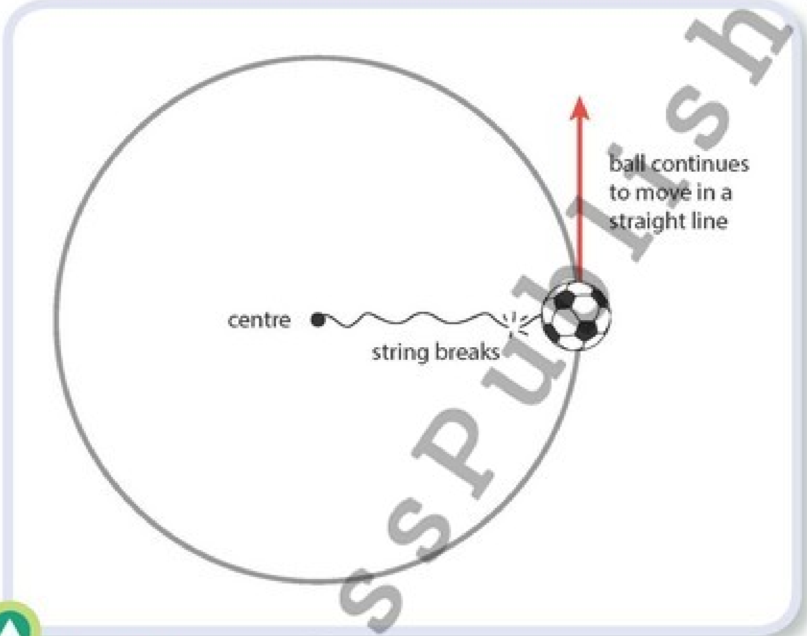


Figure 2.8

As an object travels in a circular path, its direction constantly changes. This means, since velocity is a measure of both speed and direction that:

(a) although an object moving in circular motion may be moving at a constant speed, because its direction is always changing, it cannot have a constant velocity.
(b) as acceleration is a measure of the rate of change of velocity, any process that changes the direction of an object must have an acceleration.

The idea that uniform circular motion, even when speed is constant, results in constant velocity changes and an associated acceleration can seem strange at first. This form of acceleration, however, is something that you will have experienced in a car when the car takes a curve. A car that goes around a curve at constant speed is in uniform circular motion but passengers notice a sideways acceleration as the car changes direction. This effect will be more or less noticeable depending the sharpness of the curve and the speed of the car.

Acceleration is a vector quantity and, therefore, must always have a direction. In centripetal accelerations, the direction is always towards the centre of the circle. The value of the centripetal acceleration is related to both the linear and angular velocity of an object, and to the radius of motion, using the formulae:

$$\alpha = \frac{v^2}{r} \quad \text{and} \quad \alpha = r\omega^2$$

We can use these formulae to calculate centripetal acceleration for all types of situations involving uniform circular motion such as:

- taking corners in a vehicle
- the spinning of DVDs or CDs
- clothes in a washing machine or spin drier
- playground and fairground rides like the carousel
- satellites moving in orbit around the Earth which we shall look at in Module 4.

Sample question 3

A car is travelling around a circular bend with a radius of 20 m. It has a constant speed of 22 m s^{-1}. What is its acceleration?

$$\alpha = \frac{v^2}{r} = \frac{22^2}{20} = 24.2 \text{ ms}^{-2}$$

Answer:

$$\text{speed} = \frac{\text{distance}}{\text{time}} = \frac{400 \text{ m}}{10 \text{ s}} = 40 \text{ ms}^{-1}$$

Sample question 4

The drum of a washing machine has a radius of 25 cm and spins at 1200 rpm during its spin cycle. What is its angular velocity?

Answer:

$$\text{F: } 1200 \text{ rpm} = \frac{1200}{60} = 20 \text{ rev/sec (or 20 HZ)}$$

$$T = \frac{1}{f} = \frac{1}{20} \text{ s}$$

$$T = \frac{2\pi}{T} = \frac{2\pi}{\frac{1}{20}} = 40\pi = 125.66 \text{ rads}^{-1}$$

Q Understanding U2

2.11 A bicycle travels around a circular bend with a radius of 12 m. It has a constant speed of 15 m s^{-1}. What is its centripetal acceleration?

2.12 If a car is travelling at constant speed around a circular track, does it have

(a) constant velocity **(b)** constant acceleration?

2.13 An object with an acceleration of 9.5 m/s^{-2} is travelling in a circle of radius 12.4m. What is its velocity?

2.14 The clothes in a spin drier attach to the wall of the drum as it spins at a rate of 1800 revolutions per minute. The radius of the drum is 0.26 cm.

(a) Calculate the velocity of the clothes on the wall of the drum.

(b) Calculate the acceleration of the clothes.

2.15 An object with an acceleration of 20 m/s^{-2} is travelling in a circle at a velocity of 8.8 ms^{-1}. What is the radius of its motion?

2.16 The Earth has a radius of 6.4×10^{6} m and rotates about its axis once every day. Person A is standing on the equator. Person B is at a latitude of 53°N of the equator. For each of the two people, calculate the following:

(a) the period of their motion (as they move with the Earth) in seconds

(b) their linear and angular velocities

(c) their centripetal accelerations.

2.17 A carousel has a top speed of 8.0 ms^{-1}. The radius of its circle to the outer edge, where the riders experiencing this top speed sit, is 7.4 m.

(a) Calculate the time it takes for the riders at its edge to travel one complete circle at top speed.

(b) Calculate the acceleration of these riders.

MODULE 3

Astronomy

Learning outcomes

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

- Distinguish between the apparent and absolute magnitude of stars [9.7.2.1]
- Name factors affecting the luminosity of stars [9.7.2.2]
- Name main elements of the celestial sphere [9.7.2.3]
- Define celestial coordinates of stars on a planisphere [9.7.2.4]
- Explain the range of stars visible in different latitudes [9.7.2.5]
- Correlate local, zone and world time [9.7.2.6]
- Explain the motion of celestial bodies in terms of Kepler's laws [9.7.2.7]
- Explain the parallax method of defining the distance of a body in the Solar System [9.7.2.8]

Keywords

✔ star ✔ nuclear fusion ✔ red giant ✔ nebula ✔ white dwarf ✔ luminous
✔ luminosity ✔ celestial sphere ✔ equator ✔ meridian ✔ zenith
✔ time zone ✔ UTC ✔ longitude ✔ latitude ✔ ecliptic ✔ orbit

What are stars?

When you look up at the sky on a clear night, are you amazed by the stars that exist there, shining brightly? Do you ever wonder what a star is and how it was formed?

A star is a luminous object made up of gas that can produce its own light and heat by nuclear reactions.

Q Understanding U7

3.1 **(a)** From the statement above, what do you think the term 'luminous' means?
(b) Identify another everyday luminous object.
(c) Name a non-luminous object that exists in space.

What are nuclear reactions?

Nuclear reactions that take place in a star occur between two hydrogen atoms. The nucleus of one hydrogen atom fuses with the nucleus of another hydrogen atom, forming a completely new element called **helium**.

It is the conversion of hydrogen to helium that releases the heat and light that causes our stars to shine. The heat and light released are forms of energy.

Figure 3.1 *Nuclear fusion reactions*

Figure 3.2 *Light energy from the Sun*

Society S2

3.2 How do we know that nuclear reactions are still taking place in the Sun?

Does a star last forever?

Some stars have only a small amount of matter; some stars have a large amount of matter. Every star is different and every star is at a different stage in its life cycle. A life cycle is a series of changes that an object goes through in its life.

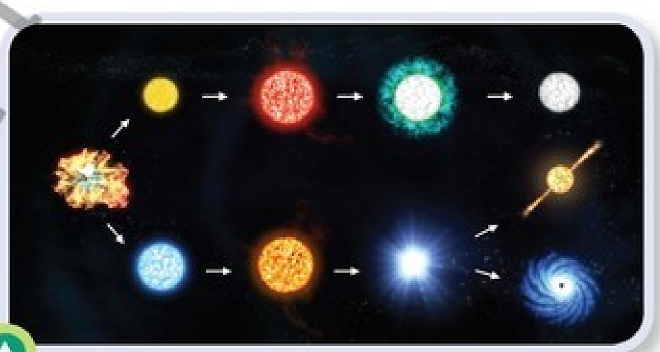


Figure 3.3 *Stages in the life of a star*

Some stars have already died. Some stars explode during the process of dying, dramatically releasing a dazzling amount of light that may be seen throughout the universe in what is called a **supernova**.

Some stars appear small and they are called **dwarfs**. A small star may be around 200,000 km across – about the same size as the planet Jupiter.

The life cycle of a main sequence star has four phases:

- Phase 1 – formation
- Phase 2 – the stable period
- Phase 3 – the red giant
- Phase 4 – the white dwarf

Figure 3.4 *Formation of a new star*

Phase 1: formation

There are large gas clouds in space, called **nebulae**. The attractive forces of gravity of the gas particles cause these gases to collapse and come together.

As temperature and pressure within the cloud increase, the gases begin to rotate rapidly, which causes the nuclei of elements to join together (i.e. nuclear fusion reactions take place) and a star is born!

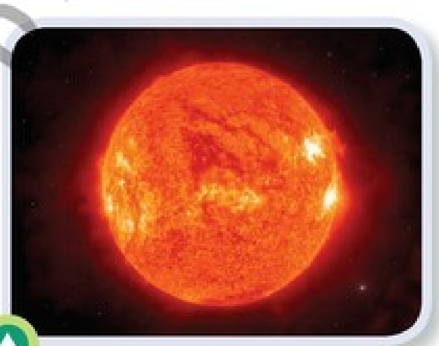


Figure 3.5 *A main sequence star*

Phase 2: the stable period

Over billions of years the star becomes stable. We call such a star a **main sequence star**.

A star spends the majority of its life as a main sequence star. It is in this phase that the star is using up all its available resource of hydrogen in nuclear reactions to emit heat and light energy.

A main sequence star balances between:

- Its own gravity trying to shrink it, and the heat energy that it is producing trying to make it expand.
- The star in this form will continue to glow for billions of years. Our own sun is in this phase of its life.

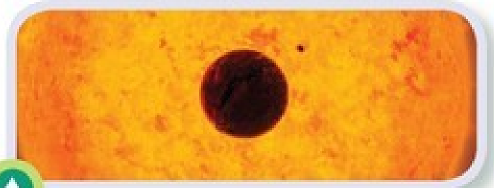


Figure 3.6 *A red giant*

Phase 3: the red giant

When the star has used up all its supplies of hydrogen in its core, it begins burning helium on its outer parts. This causes the star to release more heat. As a result, the outer part of the star expands.

The star now becomes a huge structure, and is known as a **red giant**.

When the Sun becomes a red giant it will engulf and destroy Earth. Scientists believe this will take place, but not until around five billion years from now.

Phase 4: the white dwarf

Once the red giant has turned all the hydrogen that it contains to helium – this may take from five to ten billion years, depending on the size of the star – it condenses and collapses in on itself, forming a tiny, but very dense star called a **white dwarf**. A white dwarf has only about one-quarter of its original mass left. The white dwarf will produce less and less light until eventually it produces no more light.

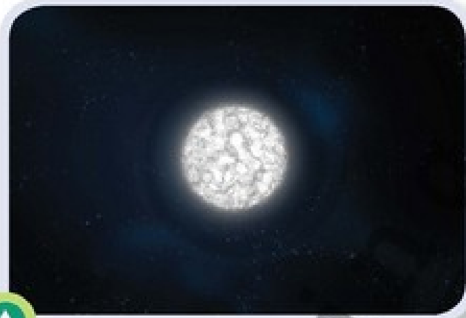


Figure 3.7 *A white dwarf*

Is that a star I see?

Stars emit light. That light takes time to travel through the vacuum of space to Earth until we can see it. So, as we look at the night sky we are in reality looking back in time – possibly millions of years.

When we see a star in the sky, the light that we see coming from that star is light from the past that has travelled through space to where we can see it now.

Figure 3.8 *Hubble Space Telescope in orbit – the stars it is photographing may not actually exist any more!*

Did you know?

Scientists estimate that there are 100 octillion stars in the observable universe – that is, 100 000 000 000 000 000 000 000 000 000!

Figure 3.9 *Stargazing*

Did you know?

The 'twinkle' from the stars is a result of turbulence in Earth's atmosphere.

Figure 3.10 *The Orion constellation – a pattern of stars that we can see in the night sky from the Northern Hemisphere*

Now that we know how stars are formed, we will consider their role within the universe.

What is in the universe?

It is mind-boggling to think about how many galaxies are in the universe, and how many stars are in each galaxy. It is fascinating to wonder whether there is life in other galaxies. Many science-fiction stories have been written imagining what those life forms would be like!

We shall start with our own tiny spot in the universe.

Galaxies

A galaxy is a collection of millions or billions of stars, along with gas and dust, all held together by gravitational forces.

There are billions of galaxies in the observable universe. Some galaxies are small, with only a few million stars. Other galaxies have 400 billion stars, or more.

Galaxies are constantly moving away from each other.

Earth is in the Milky Way galaxy. This galaxy is spiral-shaped, which is the most common galaxy shape in the universe.

Figure 3.11 *The Milky Way – our galaxy*

Figure 3.12 *A spiral galaxy*

Communicating C1 Communicating C2

3.3 Research a galaxy in the universe that is not our own. Find answers to the following questions:

(a) What is the name of the galaxy?

(b) What shape is the galaxy?

(c) Are there any similarities in the shape of the Milky Way and the galaxy you are studying?

(d) Identify the name of the galaxy closest to our own galaxy and find out what distance away that galaxy is from the Milky Way.

Luminosity

The luminosity of a star depends on how much energy it produces and its distance from Earth. The importance of the distance from Earth can be understood by using a simple analogy. A ship's searchlight has greater light intensity than a small hand-held torch. However, if the searchlight is several kilometres away from you, it may only appear as bright as the light from the torch you are holding because light intensity decreases with distance squared.

A photometer attached to the end of a telescope can be used to measure the brightness of a star which will depend on the radius of the star and its surface temperature. If the brightness of a star and the distance to the star from earth are known, then the luminosity of the star can be calculated.

Apparent and absolute magnitude

Astronomers distinguish between apparent magnitude which is a measure of how bright an object appears from Earth and absolute magnitude which is a measure of how bright the object is compared to other objects in the universe.

Figure 3.13

Astronomers calculate the brightness of a star as it would appear if it were 32.6 light-years, or 10 parsecs from Earth. This absolute magnitude scale gives astronomers a point of reference for comparing stars.

Two objects [seen from Earth] which have the same apparent magnitude, thus could be

- At the same distance from the Earth, with the same luminosity.
- At different distances from the Earth, with different values of luminosity. A less luminous object that is very close to the Earth may appear just as bright as a very luminous object that is a long distance away.

Q U7 Understanding

3.4 What distance is used to calculate absolute magnitude?

3.5 Complete the table:

	Distance (d) parsecs	Apparent magnitude (m)	Absolute magnitude (M)
Sirius	2.64	–1.47	1.41
Barnard's star	1.84	9.56	
Procyon		0.38	2.6
Polaris	132	1.99	

The celestial sphere

Although the Earth is travelling around the Sun, it appears from Earth that the Sun and the stars are travelling around the Earth when we look up at the sky. Only half the sky is visible to an astronomer at any one time, because only half the sky is above the horizon. This means that just as the sun rises and sets each day, so too does every star in the sky at night. This was well-known to ancient astronomers and navigators, who modelled the position of the stars as if they were located in a **celestial sphere** around the Earth.

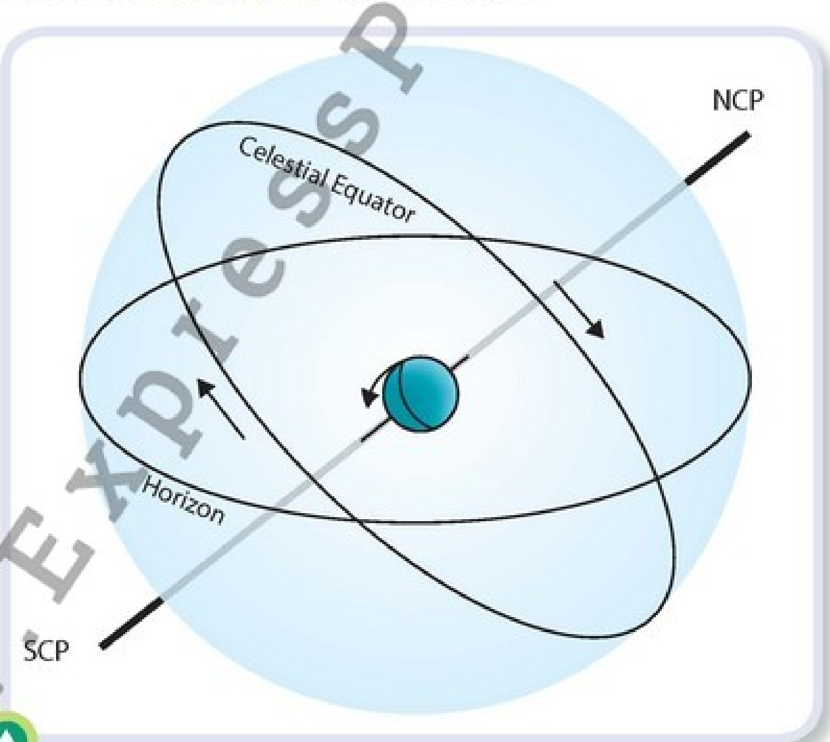


Figure 3.14 *Celestial sphere*

We can use the celestial sphere to locate the position of celestial bodies in the sky in a similar way to how we plot longitude and latitude on Earth.

The key points of reference on the celestial sphere are as follows:

- The **North Celestial Pole** (NCP) and the **South Celestial Pole** (SCP) from **Figure 3.14**, you can see that these are simply extensions of the north and south poles into space.
- The Celestial Equator, again from **Figure 3.14**, you can see that this is the Earth's equator but projected into space with a much greater radius.
- The **Horizon** which changes according to where someone is on Earth.
- The **Zenith** which is taken as the point directly overhead.
- The **Meridian** which is the line drawn on the celestial sphere between the observer's Zenith and the north and south celestial poles (see **Figure 3.15**).

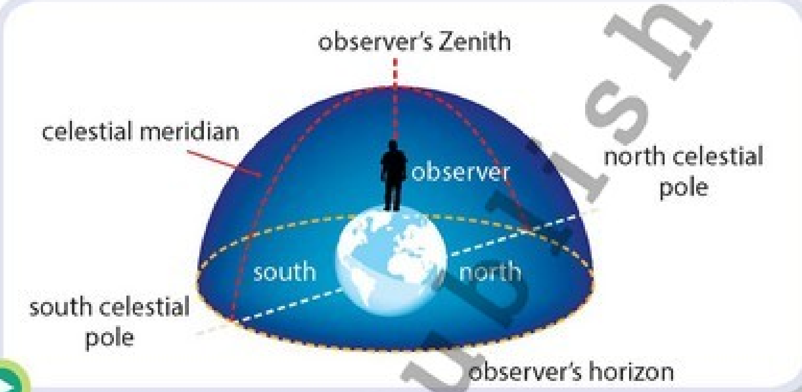


Figure 3.15

Objects are located on the celestial sphere using two sets of coordinates known as celestial co-ordinates: **Right Ascension** and **Declination**.

Right Ascension – similar to longitude on Earth – is measured along the celestial equator. It is measured in hours (h), minutes (m) and seconds (s). The zero point on this scale is taken from the position of the Sun on the spring equinox and 24 hours represents a full circle – so it is directly related to hours of time.

Declination – similar to latitude on Earth – is measured northwards and southwards from the equator. Declination is measured in degrees. The equator is 0 degrees, the North Celestial Pole, +90 degrees, the South Celestial Pole, –90 degrees.

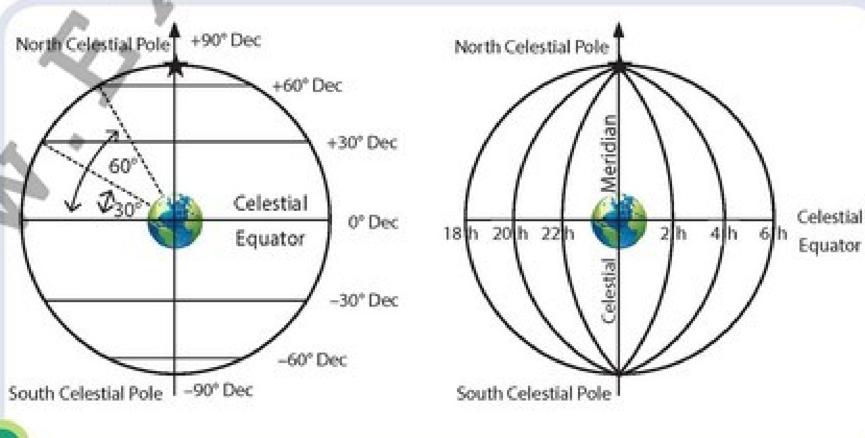


Figure 3.16 *Celestial coordinates*

PHYS Gr9 Ss Mod 3.indd 43 5/6/19 12:31 PM

Q U7 Understanding

3.6 In **Figure 3.16** which image represents Right Ascension and which image Declination? How do you know?

3.7 Calculate the number of seconds in a full circle of the celestial sphere in measuring Right Ascension.

3.8 In **Figure 3.17** below, label:

- the Earth's equator (E), North Pole (NP) and South Pole (SP)
- the Celestial equator (CE) the North Celestial Pole (N), and the South Celestial Pole (S)
- zenith (Z) of the observer
- the latitude (L) of an observer
- the meridian (M).

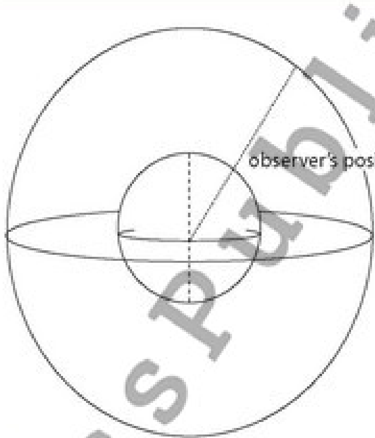


Figure 3.17

Stars have relatively fixed positions in Right Ascension and Declination. The co-ordinates of the Sun and planets, however, change so they will be seen in different places in relation to the stars across the year.

We take Polaris (the North Star) to be the star that indicates the North Celestial Pole and Sigma Octantis the star which indicates the South Celestial Pole. The range of the sky visible from any place on Earth will change depending on the latitude of the observer. The altitude of Polaris, i.e. its height above the horizon in degrees, will be equal to the degrees of latitude from which it is viewed. At the equator, it will be on the horizon as in diagram C in **Figure 3.18**. At the North Pole it will be directly overhead as in diagram A. Diagram B shows someone who is observing the sky from 45 latitude which means their zenith is at 45 declination. From this point, it is mainly stars in the Northern hemisphere which are visible.

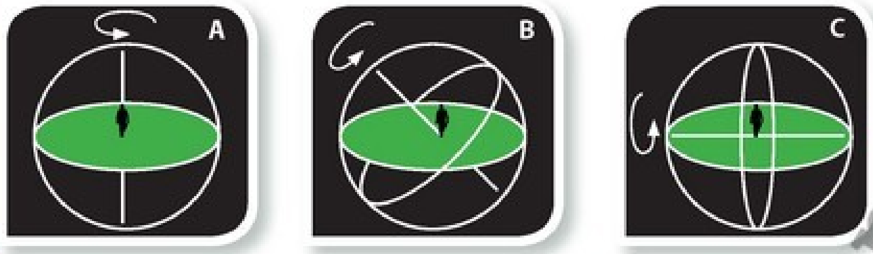


Figure 3.18 *Changing coordinates*

Circumpolar stars are stars which an observer from a given location can see in the sky all year round. From the given latitude of the observer, a circumpolar star will be one whose declination is greater than the colatitude. This can be calculated using this formula:

$D \geq 90° - L$

D – Declination
$\geq$ – Greater than or equal to
L – Latitude

90° – observer's latitude (e.g. Nur Sultan 51°) = 39°

so stars within the range +39° to +90° will be circumpolar.

For an observer in Nur Sultan, some stars below the celestial equator in the range +39° to −39° declination will be visible at certain times of the year, but from this location the observer will never see stars in the range −39° to −90° latitude.

Longitude and Time Zones

The position of places on Earth is measured in relation to the prime meridian (0° longitude) – the distance east or west of Greenwich in the UK.

Lines of longitude run from the North Pole to the South Pole. Points east of Greenwich are measured up to a maximum value of 180° E and points west of Greenwich up to 180° W.

Moving east or west away from the UK, countries have different time zones where clocks run ahead of or behind time in the UK. In general, neighbouring time zones have a time difference of 1 hour. In 24 hours the Earth rotates through 360° with respect to the Sun. Each time zone is then theoretically 15° wide, corresponding to 1 hour difference in mean solar time. In practice, however, the shape of time zones is changed to match internal and international borders.

Q Understanding U_2 Society S_2

3.9 How many UTC time zones are currently used in Kazakhstan?
3.10 In your current location how many hours ahead or behind of UTC are you?

Sample question 1

Two friends, Aigerim and Dasha, live in different locations in Kazakhstan. Aigerim lives 1.5 w of Dasha. Each night they both look at the same star due south.

(a) Who will see the star due south first?

(b) Calculate the difference in time that it is visible due south in their locations.

Answer:

(a) Dasha will see it first as she lives east of Aigerim.

(b) Aigerim will see the star due south 6 minutes later.

1 hour = 15

1 minute = 0.25

Sample question 2

Is a star of a declination of +41 circumpolar from a latitude of 53 North?

Answer:

Yes. Stars visible all year from this location:

$D \geq 90° - L = 90° - 53°$

give a circumpolar range of +37° to +90 °

Q U7 Understanding

3.11 What is the celestial equivalent of latitude?

3.12 What are the units of Right Ascension?

3.13 An observer sees Sirius due south at 03.07 GMT. At what time on the same night will another observer 3.5° W see Sirius due south?

3.14 Would a star at +26° be circumpolar in Nur Sultan?

3.15 What range of stars are circumpolar for someone who lives at a latitude of –35°?

Using a planisphere

A **planisphere** is a simple method of finding out what stars can be seen from a location at a particular time. It is basically two discs fastened to each other. The disc underneath shows a star map of the sky with every constellation that can be seen in a particular part of the world. The top disc when moved and aligned to an exact time and date on the edge shows the constellations visible in the night sky at that date and time. Today there are sites online that allow you to see and print out the constellations that you should be able to observe in the night on particular dates.

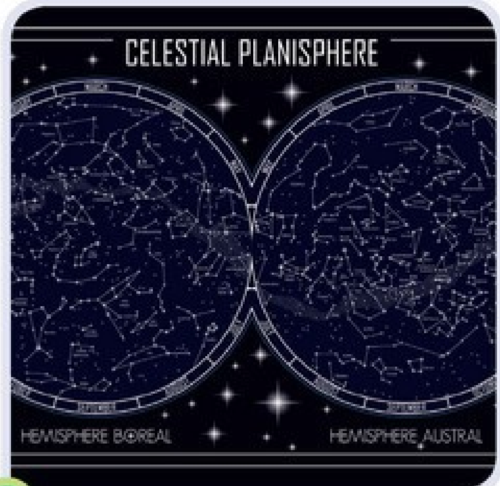


Figure 3.19

Q U2 C1 C2

3.16 Use an online virtual planisphere to get a print out of the sky in your location:

- **(a)** today at 4.00 am
- **(b)** on the March Equinox 4:00 am.

3.17 Use the hour control to see how the stars and planets move across the sky.

Kepler's laws

Johannes Kepler (1571–1630)

Produced mathematical formulae that described with great precision the motions of the planets around the Sun. These are known as Kepler's Laws and can be seen as a fundamental extension and revision of the ideas of Copernicus who postulated that the planets orbited the Sun in perfect circles.

Kepler's First Law

Kepler's First Law states that the orbits of the planets around the Sun are ecliptic – with the Sun at one focus – meaning that the distance of a planet from the Sun varies. The point at which it is closest to the Sun is called: the perihelion; the point at which it is furthest from the Sun: the aphelion.

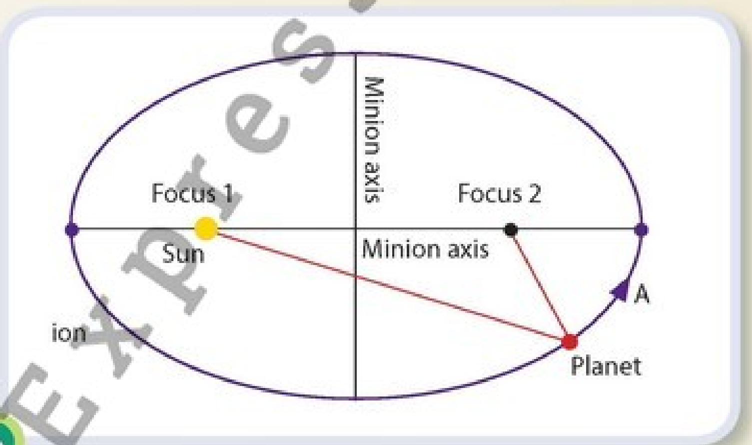


Figure 3.20

Kepler's Second Law

Kepler's Second Law states that a line that connects a planet to the Sun sweeps out equal areas in equal times, meaning that when a planet is closer to the Sun, it moves more quickly, moving through a longer path in a given time. This law arises from the Law of the Conservation of Angular Momentum.

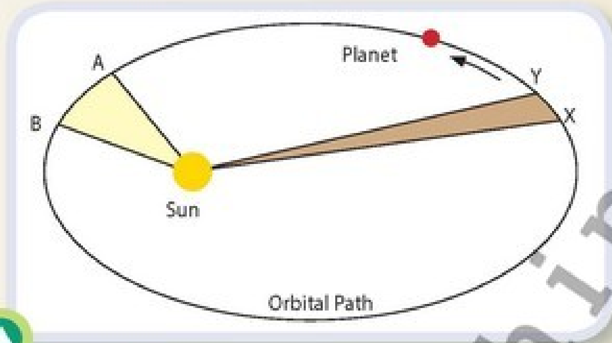


Figure 3.21

Thus in Figure 3.21, it takes the same time for the planet to move through the paths A to B and Y to X and the yellow and brown shaded areas are equal.

Kepler's Third Law

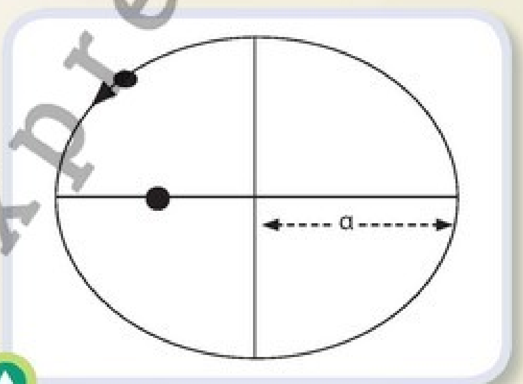
Kepler's Third Law states that the relationship between the period of a planet and the radius of its motion can be expressed as:

$$T^2 \propto \alpha^3$$

where:

T = is the period of planet
α = is the average distance of the planet fro the Sun

meaning that the square of the period of a planet is equal to the cube of its average distance from the Sun.



$T^2 \propto \alpha^3$

Figure 3.22

The unit used for measuring such distances within the Solar System is an Astronomical Unit (AU) which represent the average distance between Earth and the Sun:150 million kilometres. Time is measured in years.

Newton would go on to prove that his gravitational law fitted exactly with Kepler's third law and with the observed motion of all of the planets in the solar system.

Q Understanding U7

3.18 Using the information in the diagram below, calculate the orbital period of Mars.

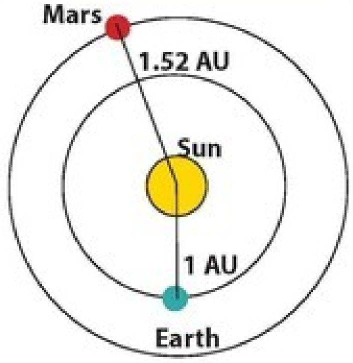


Figure 3.23

3.19 What are points A and B called in this planet's orbit?

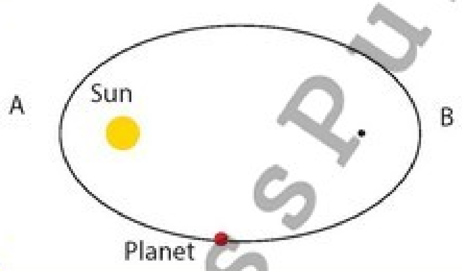


Figure 3.24

3.20 What would the orbital period of a planet with a mean orbit radius of 5,2 AU be?

3.21 Which planet in our solar system has this orbital period?

We measure the distance to nearby stars by measuring how much they appear to move against distant stars.

A measurement is taken in one month and then another six months later when the Earth is on the opposite side of the Sun. Taking 1 AU – the average distance of the Earth to the Sun – as the baseline measurement, the distance is calculated by dividing 1 by the parallax angle. So If the parallax angle were 0.741 arc seconds, then 1 divided by 0.741 is 1.35, meaning that the star is 1.35 parsecs away.

To convert this measurement into light years multiply by 3.26 , which would mean the star is 4.40 light years away. This is the approximate distance of Alpha Centauri, the third nearest star to Earth.

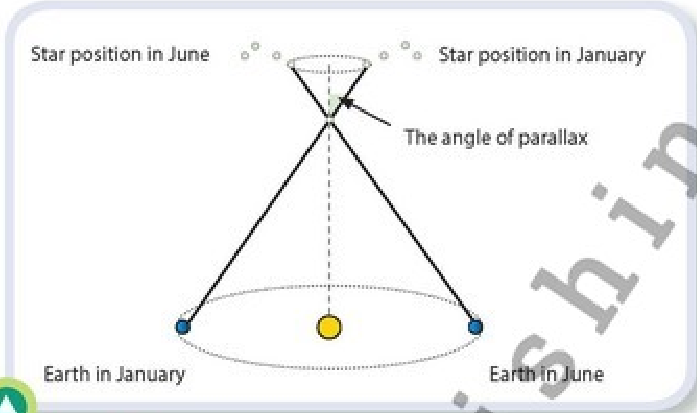


Figure 3.25

Q U7 Understanding

3.22 A star has a parallax angle p of 0.254 arc seconds. How many parsecs is this star from Earth?

3.23 A star has a parallax angle p of 0.421 arc seconds. How many light years is this star from Earth?

MODULE 4

Forces and Newton's laws of motion

Learning outcomes

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

- Explain meaning of concepts such as inertia and inertial frame of reference
- Formulate Newton's first law and apply it to solving problems 9.2.2.2
- Explain the nature of elastic force, gravitational force and friction 9.2.2.3
- Formulate Newton's second law and apply it when solving problems 9.2.2.4
- Formulate Newton's third law and apply it when solving problems 9.2.2.5
- Formulate the law of gravitational force and apply it when solving problems 9.2.2.6
- Define the concept of the weight of a body moving with acceleration 9.2.2.10
- Explain the condition of zero gravity 9.2.2.11
- Apply the formula for orbital velocity when solving problems 9.2.2.9
- Compare the features of the orbits of spacecraft 9.2.2.7
- Calculate the physical values of a body in a gravitational field 9.2.2.7

Keywords

✔ friction ✔ inertia ✔ momentum ✔ proportional ✔ orbit ✔ satellite
✔ elastic force ✔ contact ✔ wear ✔ zero gravity ✔ centripetal force
✔ lubricant ✔ gravitational field strength

Newton's laws of motion

Newton's three laws of motion can be broadly stated as:

First law

A body will continue in a state of rest or of uniform velocity unless an unbalanced external force acts upon it.

Second law

The rate of change of a body's momentum is proportional to the force that causes it and takes place in the direction of that force.

Third law

If body A exerts a force on body B, then body B exerts an equal but opposite force on body A.

Newton's first law

Figure 4.1

Few people find it difficult to accept that moving objects slow down and stop because of friction and also accept when we reduce friction objects can travel further. We have little difficulty, for example, in recognising vehicles and shapes that have good aerodynamic design.

Most people can also grasp the concept of inertia: the resistance to a change in motion and how the inertia of an object depends on its mass. Greater mass of a body equates to greater inertia and a greater resultant force needed to change the motion of the body. It is much easier, for example, to push an empty box than one that is full.

Figure 4.2 *The force of friction can slow down a bicycle*

What is more difficult to grasp is the logical conclusion from Newton's law that if there were no friction a moving object would keep moving forever. In other words, it is equally true that an object at rest will remain at rest unless a force makes it move and that once an object is moving, it will keep moving unless a force makes it stop.

Q Understanding U2

4.1 When a car suddenly stops, what happens to the passengers in the car? Why is this?

Figure 4.3 *Apollo 11 moon landing*

Newton's first law tells us that when an object is at rest the two forces acting on it are in balance. If a brick, for example, is placed on a piece of rubber foam, the weight of the brick acts as a force on the foam, indenting it slightly and the foam exerts an elastic force upwards that is equal to the weight of the brick.

An elastic material like foam will return to its initial shape and size when these forces are removed.

Newton's first law is also essential to understanding space travel. During the launch of a spacecraft, the rocket engines will use up a huge amount of fuel to generate the reverse thrust to break free of the Earth's gravitational pull. Once spacecraft are free of the Earth they typically travel at speeds of many kilometres per second with their engines off and will continue to do so indefinitely. With no friction or air resistance in space there is nothing to slow them down.

Objects on the Moon also have less inertia as the Moon has a smaller mass than Earth and thus a smaller gravitational field strength.

Friction

Figure 4.4 *The friction strip on the side of a box of matches*

Friction is a force that tends to oppose relative motion. It is encountered whenever one body slides, or attempts to slide, across the surface of another. It is both beneficial and problematic: on the one hand, without friction we could not walk or drive but would instead slide about the world; on the other hand, friction increases wear in machinery and reduces efficiency.

Figure 4.4 shows the friction strip on the side of a box of matches. This friction strip feels rough when you touch it with your fingers.

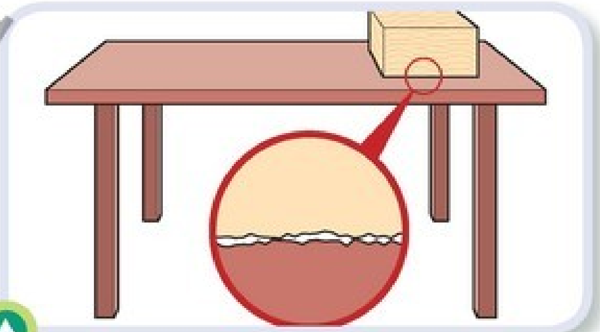


Figure 4.5 *The friction strip on the side of a box of matches*

However, all surfaces are rough even though they do not seem to be. If you could see a close-up photograph of any surface, it would appear rough and jagged.

Most people would think that the glass in a window is very smooth. If you saw a close-up of glass with a very powerful microscope, you would see a rough surface. This rough surface is what causes the force of friction.

When a block of wood is placed on a table the rough surface of the block is caught in the rough surface of the table. When you push the block, some of your pushing force will move the block and some of the pushing force will be needed to overcome the friction between the table and the block. The amount of your pushing force needed to overcome the friction will depend on how rough the surfaces in contract are.

Examples of friction

When driving a car around a corner friction is needed. If the tyres on a car are very worn, there is a risk that a lack of friction could cause the car to skid. An accident while turning a corner is more likely on a wet day because there is less friction between the tyres and the road.


Figure 4.6 *The friction between the tyres and the road is less on a wet day*

When spacecraft return to Earth there is a lot friction between the surface of the spacecraft and the gases in the atmosphere. Without a heat shield this would cause the craft to overheat with disastrous consequences.

Reducing the force of friction

To reduce the friction between two surfaces you could try to make the surfaces smoother. However, as there is no perfectly smooth surface we often use special material to reduce friction. These materials are called lubricants. Common examples you will be familiar with are oil, liquid polish and soap.


Figure 4.7 *Heat shield for lunar module re-entry to Earth*

Examples of lubrication to reduce friction:

- There are many moving parts in a car engine. Friction would lead to wearing. Friction would also generate heat which would damage the engine. Oil and grease are used as lubricants in car engines.
- The bones at the joints in the human body are surrounded by a fluid that acts as a lubricant. This greatly reduces friction.

Lubrication
Used to reduce the friction between two surfaces in contact.

Q Understanding U2

4.2 Explain the term elastic force?
4.3 What causes friction between two surfaces?
4.4 What is used to reduce wear and tear on machines from friction?
4.5 What causes friction when spacecraft re-enter the Earth's atmosphere?
4.6 Why is turning corners in a vehicle more dangerous on a wet day?

Newton's second law

Newton's **second law** explains what is meant by the term 'force' and sets out the basis on which forces can be measured, which means all his other theories can be tested. The law describes what happens when the forces acting on a body are unbalanced and a resultant force acts. The body changes its velocity, **v**, in the direction of the force, **F**, and the force is proportional to the rate of change in a the body's momentum. A body of mass **m**, changes from a velocity **u** to one of **v**:

$$F = ma$$

Where
F = force
m = mass
a = acceleration

This is the formula that is used to define the unit of force, the Newton, and from this we can derive the formula $a = F/m$ which can also be expressed as **F = rate of change of momentum**.

$$F = \Delta p/\Delta t$$

Where
p = mass x velocity
t = time

Newton's third law

Newton's third law is often commonly expressed as 'actions have an equal but opposite reaction' or as involving 'interactions between a pair of forces'. Both ways of expressing this law can be misleading because words like 'action', 'reaction', 'interaction' and 'pair' have different meanings and uses in different contexts.

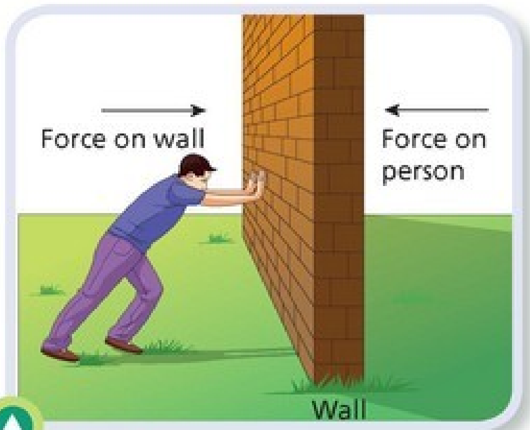


Figure 4.8

To understand the third law we need to focus on the idea that one body is creating a force on another. If a person pushes against a wall, the person is clearly creating a force. The wall will create an equal force in the opposite direction, pushing back on the person. Pushing hard is unlikely to make the wall fall, but very likely to push the person into an upright position. This is called the effect of force created by the wall.

Another common example used in explaining this law is that of a book resting on table. It is important to remember that when one object rests on another, each is creating a force on the other. The book in Figure 4.9 creates a downward force on the table and the table creates an equal, but opposite, upward force on the book. The forces involved here are: the weight of the book and the pull of the Earth on the book (gravitational forces) and the book pushing on the table and the table pushing back on the book (contact forces).

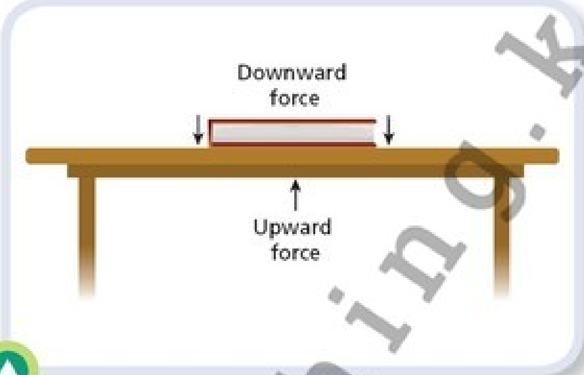


Figure 4.9

Opposing forces described by this law:

- act on two different bodies
- are equal in magnitude but opposite in direction
- are the same type of force (e.g. gravitational, magnetic, or contact).

If you stand on the ground, your weight is acting downwards, and this causes you to create a downward force on the ground. At the same time, the Earth is creating an upward force on you. So the force that we are aware of when we think about our own weight is in fact the force of the Earth pushing back and not the weight itself.

Astronauts in orbit aboard the International Space Station (ISS), are about 400 km above the surface of the Earth. This height is enough to reduce their weight, but only by a very small amount. They feel weightless, however, because the gravitational force of the Earth is less.

Astronauts at the ISS

Figure 4.10

Sample question 1

What acceleration is caused to a body of mass 70 kg when it experiences a force of 350 N?

Answer:

$a = \frac{F}{m} = \frac{350}{70} = 5ms^{-2}$

Sample question 2

A car of mass 1500 kg is travelling at a constant velocity of 20 m s^{-1}. What force is required to stop it in a distance of 50 m?

Answer:

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

$0^2 = 20^2 + (2)a(50)$

$a = \frac{20^2}{100} = -4ms^{-2}$

$F = ma$

$= 1500 \times 4$

$= 6000$ N

Q U2 Understanding

4.7 An object of mass 300 kg is observed to accelerate at the rate of 4 ms^{-2}. Calculate the force required to produce this acceleration.

4.8 A 5 kg block is pulled across a table by a horizontal force of 40 N with a frictional force of 8 N opposing the motion. Calculate the acceleration of the object.

4.9 A bowling ball rolled with a force of 15 N accelerates at a rate of 3 ms^{-2}; a second ball rolled with the same force accelerates 4 ms^{-2}. What are the masses of the two balls?

4.10 The mass of a van is 1000 kg. How much force would be required to accelerate the van at a rate of 3 ms^{-2}?

4.11 A car of mass 800 kg is simultaneously experiencing two forces, as shown in Figure 4.11. What is its acceleration?

Figure 4.11

4.12 What is the force on a 1000 kg elevator that is falling freely at 9.8 ms^{-2}?

Gravity

It is important to understand the difference between the words **mass** and **weight**. In everyday usage, these words often have the same meaning. In physics, they have very different meanings.

Table 4.1

Weight	Mass
• The weight of an object is the pull of the Earth • Weight is a force • Weight is measured in newtons • Weight has a direction, i.e. a force that acts towards the Earth • Weight gets smaller as you rise upwards from ground level • The weight of an object can change	• The mass of an object is the amount of matter in it • Mass is measured in grams or kilograms • Mass does not have direction • The mass of an object remains constant

Newton's law of gravitation

The force of attraction between any two point masses is directly proportional to the product of the masses, and inversely proportional to the square of the distance between them:

$$F = \frac{Gm_1 m_2}{d^2}$$

This law tells us that all objects with mass create gravity, and the size of the gravitational force is determined by the masses of the bodies and by the distance between them. Two small boxes of very small mass on a table in front of you are attracted to each other by gravity, just as they are attracted downwards towards the centre of the Earth. The force between them, however, is very small, as calculating the force between them in this example question shows.

Sample question 3

What is the gravitational force created by two masses of 1 kg, placed 50 cm apart?

Answer:

$$F = \frac{Gm_1 m_2}{d^2}$$

$$= \frac{(6.7 \times 10^{-11})(1)(1)}{(0.5)^2}$$

$$= 2.68 \times 10^{-10}\ \text{N}$$

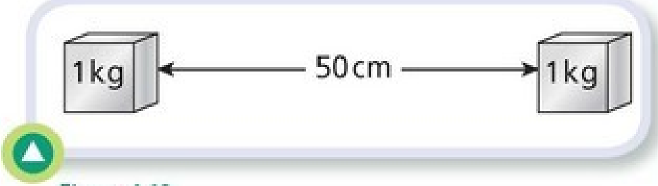


Figure 4.12

Gravitational forces are generally small unless we are considering very large objects – such as the Earth or another planet.

The gravitational force created by the Earth – or other planets – on an object is what we call its 'weight'. This is due to the size of G, the gravitational constant, which is usually given as

$$6.7 \times 10^{-11} Nm_2\ kg^{-2}$$

Figure 4.13 *Our solar system*

We use the concept of centre of gravity when finding the distance between two objects and calculating gravitational forces. For large spheres such as the Earth, this means that we measure all distances from the centre of the Earth.

Weight

The weight of the body is how we describe the force acting on the body and pulling down towards the centre of the Earth. This force can be calculated mathematically in two different ways.

The first way is to use Newton's law of gravitation which gives:

$$F = \frac{GMm}{R^2}$$

Since we know that weight is also a force we can also use the formula:

$$F = ma \quad \text{which gives:} \quad F = mg$$

Equating the two equations we get:

$$mg = \frac{GMm}{R^2} \quad \text{which can be simplified to:} \quad g = \frac{GM}{R^2}$$

Sample question 4

A person has a weight of 735 N on Earth. What is their weight on another planet, with a mass three times that of the Earth, and a radius twice that of the Earth?

Answer:

$$W_{earth} = \frac{Gm_e m}{r^2}$$

$$W_{planet} = \frac{G(3M_e)m}{(2r_e)^2} = \frac{3}{4}\left(\frac{GM_e m}{r_e^2}\right) = \frac{3}{4}(W_{earth})$$

$$= 551.25\ N$$

Q U2 Understanding

4.13 Calculate acceleration due to gravity on the surface of the Earth using the formula:

$$g = \frac{GM}{d^2}$$

where:

Radius of Earth = 6.4×10^6 m

Mass of Earth = 6×10^{24} kg

G = 6.7×10^{-11} Nm^2 kg^{-2}

The value of g is normally taken to be 9.8ms^{-2}, and this is the value we will use in these calculations.

4.14 What is the force on a 1 kg stone that is falling freely due to the pull of gravity?

4.15 Two spherical objects have masses of 200 kg and 500 kg. Their centres are separated by a distance of 25 m. Find the gravitational attraction between them.

4.16 Why is your weight less on the Moon than on Earth, but your mass is the same?

4.17 The size of the gravitational force between two objects depends on their ___ and ___

4.18 The value of gravitational pull on the Moon is 1.6 m/s. What is the weight of a 75 kg astronaut on the Moon?

4.19 Use Newton's law of gravitation and the value of 'g' at the Earth's surface to estimate the mass of the Earth. The mean radius of the Earth is 6.4×10^6 m.

Satellites

The term satellite is any object travelling in orbit around another object. Examples are the motion of the Earth and the other planets around the Sun, the movement of the Moon around the Earth, and the movement of all of the artificial satellites that have been placed in orbit around the Earth over the last few decades. All the bodies maintain their circular paths because of the effect of gravity.

This means that for satellites, the centripetal force is created by gravity and so we need to derive how the formulae we have to describe gravitational forces from Newton's law can agree with the formula we have derived for circular motion in Module 2.

Period of satellites

We can say that a satellite launched from Baikanour has mass **m** travelling in an orbit of radius **r** around the Earth **(mass, M)**. Objects in orbit experience centripetal force created by gravity. This means that the force can be described either by our formula for the centripetal force, or our formula for the gravitational force. The two must be equal.

If

$$\frac{GMm_2}{r^2} = mr\omega^2$$

And the period, **T**, of a motion:

$$\omega = \frac{2\pi}{T}$$

Then:

$$\frac{GMm}{r^2} = mr\left(\frac{2\pi}{T}\right)^2$$
$$\Rightarrow T^2 = \frac{4\pi^2 mr^3}{GMm}$$

which can be simplified to

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

It can be simplified further just to include the variables $T_2 \propto r_3$ to give the relationship between the period of a satellite and the radius of its motion. This fits with Kepler's law which we saw in Module 3.

We can also consider the motion of a satellite in terms of its speed rather than its period. In the derivation above we saw that centripetal force is equal to the gravitational force:

$$\frac{GMm}{r^2} = m\frac{v^2}{r}$$

which we can simplify to:

$$v^2 = \frac{GM}{r}$$

These equations are particularly important for space engineering because they indicate that the velocity of a satellite can be controlled only by the height of its orbit: to increase velocity, the satellite must reduce **r** – that is, it must move closer to the Earth – and to slow down it must move further away.

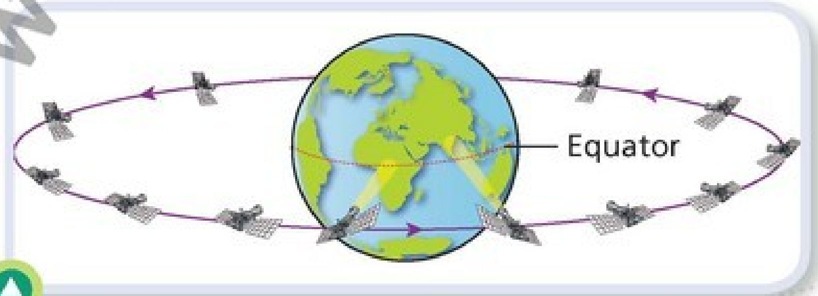


Figure 4.14

This is of particular practical importance when we think about geostationary satellites which are the satellites that beam TV and communications signals to satellite dishes. These dishes all point to the particular satellite from which they receive a signal. For this reason, it is important that the satellite stays in the same place from our perspective here on Earth. To do this, the satellite has to move with the Earth, constantly staying above one point on the Earth's surface and moving through one complete orbit every day. To match the spin of the Earth, these satellites must be above the equator and must have a period of exactly one day. This height is approximately 36 000 km above the Earth's surface, and they travel at close to 3 km s_{-1}.

Sample question 5

A satellite in orbit around the Earth has a period of 5700 s.

(a) What is the radius of its motion?

(b) How high above the surface of the Earth is it moving?

Answer:

(a) $T^2 = \frac{4\pi^2 r^3}{GM}$

$$r^3 = \frac{GMT^2}{4\pi^2} = \frac{(6.7 \times 10^{-11})(6 \times 10^{24})(5700)^2}{4\pi^2}$$

$$= 3.3084 \times 10^{20}$$

$$r = 6.92 \times 10^6 \text{ m}$$

(b) Height = $6.92 \times 10^6 - 6.4 \times 10^6 = 520\,000$ m (or 520 km)
(or 516.3 km, more accurately)

Q Understanding U2

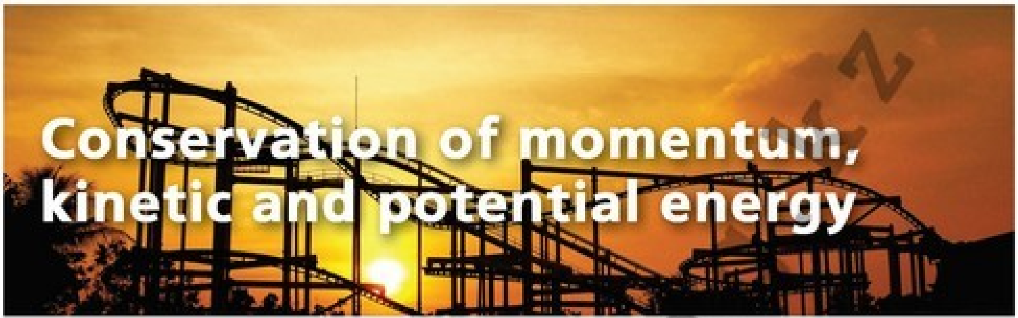
4.20 Calculate the radius of the orbit of a satellite, which always stays vertically above the same place on the Earth's surface. Such a satellite is said to be in synchronous orbit or geostationary orbit.

4.21 Give a reason why synchronous orbits are used for telecommunication satellites.

4.22 A satellite is in orbit 480 km above the Earth's surface. Its period of rotation about the Earth is 100 minutes. If the orbit is taken to be circular, calculate its linear speed. The mean radius of the Earth is 6.4×10^6 m.

MODULE 5

Conservation of momentum, kinetic and potential energy



Learning outcomes

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

- Distinguish between concepts of body impulse and force impulse 9.2.3.1
- Formulate law of conservation of momentum when solving problems 9.2.3.2
- Provide examples of jet movement in nature and engineering 9.2.3.3
- Assess the regional and international significance of the Baikonur cosmodrome 9.2.3.4
- Define mechanical work analytically and graphically 9.2.3.5
- Explain the interrelation of work and energy 9.2.3.6
- Apply mechanical energy conservation law when solving problems 9.2.3.7

Keywords

✔ vector quantity ✔ momentum ✔ conservation ✔ impulse ✔ contact ✔ collision ✔ airbag ✔ frictionless ✔ rocket ✔ jet ✔ cosmodrome ✔ cosmonaut ✔ launch thrust ✔ exhaust gas ✔ potential energy ✔ convert

Momentum

Momentum is a measurement of the mass of a body in motion. It is the measurement of **mass x velocity** and represented by the symbol **p** and the unit is kg ms^{-1}.

$$p = mv$$

Momentum is a vector quantity that depends on the direction of the object.

Sample question 1

What is the momentum of a car of mass 900 kg travelling in traffic at 5 m s^{-1} east?

Answer:

900 x 5 = 4 500 kg m s^{-1} east

We use the concept of momentum when considering what happens when two objects such as cars collide. The total momentum in this situation before the collision is the sum total of the momentum of each car. In the absence of external forces, the principle of the **conservation of momentum** states that the total momentum before and after the collision will be the same. The equation is written as follows :

$$m_1u_1 + m_2u_2 = m_1v_1 + m_2v_2$$

where:

m = mass
u = velocity before the interaction
v = velocity after the interaction

Let us take two different collision scenarios.

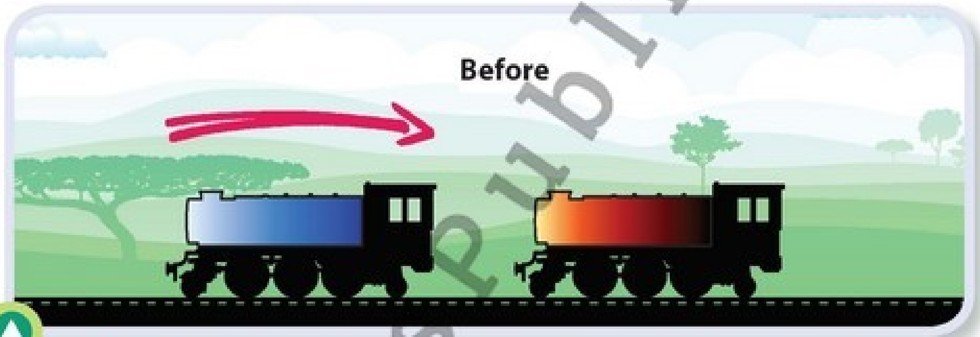


Figure 5.1 *Railway carriages*

Q Understanding U2

In the first scenario, a railway carriage which has a mass of 5000 kg and is moving at 4 m s^{-1} E collides with and attaches to an identical carriage travelling in the same direction at 3 m s^{-1} E.

5.1 Calculate the momentum of each of the two carriages before the collision.

Q Understanding U2

As the carriages stay on the same straight section of track, according to the principle of the conservation of momentum, the total momentum of the two attached carriages will be the same after the collision.

5.2 What is the initial velocity of the two carriages immediately after the collision?

Q U2 Understanding

In a different scenario, a car with a mass of 950 kg is travelling 15 m s^{-1} E, collides with another car of mass 1000 kg travelling at 5 m s^{-1} W. The cars stick together.

5.3 What is the initial velocity of the wreckage of the two cars?

5.4 In which direction does the wreckage travel?

You should note that as the second car is travelling in the negative direction, its momentum is subtracted from the momentum of the first car in the final calculation.

Sample question 2

A train carriage weighing 40,000 kg is travelling at 12 m s^{-1} east toward another train carriage which is at rest. After the two carriages collide, they move off together at 8 m s^{-1} in the direction of the moving train. What is the mass of the second train carriage?

Answer:

Before collision

momentum 1st carriage = (40 000 kg)(12 ms^{-1} east)
= 480 000 kg ms^{-1} east

momentum 2nd carriage = 0 kg ms^{-1}

After collision

Total momentum:

480 000 kg ms^{-1} east = (40 000 kg + mass 2nd carriage)(8 ms^{-1} east)

Divide both sides by 8 m s^{-1}.

60 000 kg = 40 000 kg + mass 2nd carriage

mass 2nd carriage = (60 000 – 40,000) kg
= 20 000 kg

Q U2 Understanding

5.5 In an experiment to verify the principle of conservation of momentum, a body was set in motion with a constant velocity. It was then allowed to collide with a second body, which was initially at rest. After the collision, the bodies moved off together at constant velocity.

The following data were recorded.

- Mass of first body = 500 g
- Velocity of first body before collision = 0.5 m s^{-1}
- Mass of second body = 495 g
- Combined velocity after collision = 0.26 m s^{-1}

Show that these results verify the principle of conservation of momentum.

5.6 Two cars of the same mass are each travelling at 20 m s^{-1}. One is travelling east and the other is travelling west. Do they have the same momentum?

Impulse

Impulse can be defined as the product of average force and time of contact for a collision:

$$\text{impulse } (J) = F\,t$$

J is the symbol used for impulse and its units are Newton seconds (Ns). Using the equations of motion, it can be shown that **impulse** is equal to **change in momentum**. We have seen in Module 1 that a change in velocity Δv can also be written as $a\,\Delta t$. So a change in momentum due to acceleration can be written as:

$$\begin{aligned}\Delta p &= m\Delta v \\ &= ma\Delta t \\ &= F\Delta t\end{aligned}$$

This means that the units of momentum (kg ms^{-1}) must be equivalent to the units of impulse (Ns). To calculate impulse we need to multiply force by the time it is exerted.

Sample question 3

A 72 kg block is at rest on a frictionless surface. An unknown constant force pushes the block for 3 seconds so that it reaches a velocity of 5 m s^{-1}. Show:

(a) the initial momentum of the block

(b) the final momentum of the block

(c) the force acting on the block

(d) the impulse acting on the block

Figure 5.2 *Stationary 72kg block on a frictionless surface*

Answer:

(a) $m\,v = (72\text{ kg})(0\text{ ms}^{-1}) = 0\text{ kg ms}^{-1}$

(b) $m\,v = (72\text{ kg})(5\text{ ms}^{-1}) = 360\text{ kg ms}^{-1}$

(c) $F\,t = 360\text{ kg ms}^{-1}$

Then, $F = 360\text{ kg ms}^{-1} \div 3 = 120\text{ kg ms}^{-1}$

This can also be expressed as 120 N.

(d) $F\,t = 120\text{ N} \times 3\text{ s} = 360\text{ Ns}$ or 360 kg ms^{-1}

It is important to note that a small force can cause the same change in momentum as a larger force depending on the period of time it is exerted. A large force exerted over a short period of time can produce a large change in momentum. A smaller force applied over a longer period of time, however, can cause a similarly large change in momentum.

In a collision, it is also important to note the direction the force is exerted. A force exerted in the opposite direction to the original momentum of the object will cause the momentum to decrease. A force applied in the same direction as the original momentum will lead to an increase in momentum. It is the calculation of the net impulse that helps to determine the motion of an object following an impulse.

Q U2 Understanding

5.7 A 9.00 N force acts on a 2.50 kg mass, which is initially at rest, for 4s. Calculate:

(a) the impulse which acted upon the mass

(b) the final velocity of the object.

5.8 A tennis ball of 60 g mass is thrown against a wall and rebounds as shown in Figure 5.3. Calculate the change in momentum of the ball.

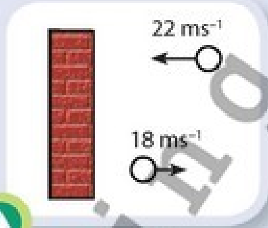


Figure 5.3

Modern cars incorporate different safety features, designed in line with impulse principles to limit injuries to those in the vehicle at the time of impact. When a collision occurs, the momentum of the driver will carry him or her forward towards the steering wheel. An airbag will change the momentum of the driver by causing a smaller force to be exerted over a longer period of time. Similarly, the fronts of modern cars are designed to crumple during a collision reducing the peak force of impact as the time of contact is extended.

Figure 5.4

Specific impulse

The concept of **specific impulse** is important in explaining how jet or rocket engines work. Engines produce a thrust force as they burn fuel. The exhaust gases produced are thrust backwards and the interaction of this force with an equal force in the opposite direction pushes the rocket forwards.

Specific impulse is a measure of the efficiency of using fuel to produce thrust in such engines. Rockets operate at much higher temperatures than the gas turbines in jet engines do. The greater temperatures and the fact that they burn liquid oxygen rather than air provides much greater thrust. Rockets will thus burn a lot more fuel in a short space of time than jet engines but only need to maintain a high level of thrust for a short time to get into orbit. Jet engines could not withstand the high temperatures needed by rockets and have lower thrust-specific fuel consumption.

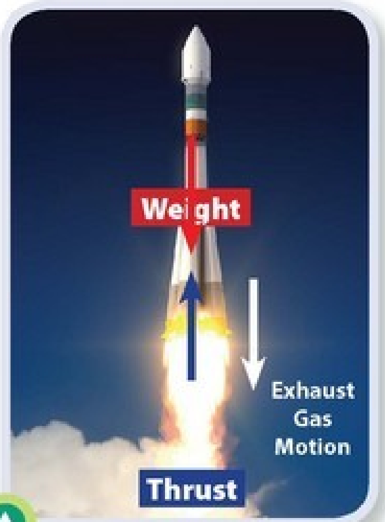


Figure 5.5 *Specific impulse at work in jet engines*

Baikonur

The space station of Baikonur in Kazakhstan has been the site of many of the world's major space project launches since 1955 and as such has been associated with the monitoring of major innovations in rocket technology.

Most importantly in recent times, Baikonur has been the site of the launch of missions involving the International Space Station.

Figure 5.6 *In 1961 Yuri Gagarin was the first human to orbit Earth*

The International Space Station (ISS) was first launched in November 1998 and took thirteen years to build. It is a habitable low-orbit satellite that has been continuously occupied by astronauts since 2000.

The ISS is a joint project involving five space agencies: NASA (USA), Roscosmos (Russia), JAXA (Japan), CSA (Canada) and the European Space Agency (ESA). The ISS has been visited by astronauts from fourteen different countries. Up to November 2014, the ISS had taken part in one hundred Russian launches and thirty-seven space shuttle launches.

Figure 5.7 *International Space Station and the space shuttle above Earth*

The ISS allows us to have a constant human presence in space. It allows crew members to conduct experiments while also allowing scientists to see the long-term effects of zero gravity on the human body.

Q S2 Society

5.9 How many cosmonauts from Kazakhstan have been to the ISS?

5.10 What percentage of all launches to the ISS have taken place from Baikonur?

Work and Energy

It is very important in science to know exactly what we mean by the words we use. We have to remember this in particular when we use words that have broad or ill-defined meanings in conversational English but much more specific or narrower meanings in physics.

Figure 5.8 *The world at night. The density of white lights indicates the cities – the areas where we use most electrical energy*

This is very noticeable when we talk about work, energy and power. In physics, 'work' does not include the concept of somebody reading a text and concentrating on its meaning, for instance. It refers only to situations in which a force makes an object move. Similarly, in physics 'energy' does not mean 'vigour' or 'liveliness'. It specifically refers to the ability to do work or, indirectly, the ability to make something move.

When we are using these words in physics we have to remember to keep their meaning very clear in our thinking, and not to use one word when strictly we mean another.

Work

We have already seen a definition of work:

Work is done when a force moves an object through a distance.

This definition also allows us to devise a method to measure how much work is done in any situation. Clearly, the bigger the force involved when work is done, or the greater the distance through which an object is moved, the more work is being done. To measure work we simply multiply these two measurements:

Work = Force x Displacement

or

$$W = F\,s$$

Displacement is a vector quantity closely related to distance. In many situations, the two are virtually interchangeable.

Energy and Work

You will have learnt before about the various forms in which energy exists. Some of these are closely connected: the amount of heat energy in an object, for example, relates to the total kinetic energy of all the atoms or molecules that make up the object, and the light energy emitted from a filament bulb is closely connected to the heat energy being released in the bulb. However, every form of energy has one thing in common: it can be converted in some way into movement.

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Remember that work is done when a force makes an object move. This is why we say that energy is the 'ability to do work'. For this reason, the two are measured in the same unit, the joule (J).

- Energy is the ability to do work.
- Work and energy are both measured in joules.

A crucial principle in science is that of the conservation of energy.

The principle of conservation of energy states that energy cannot be created or destroyed, but only converted from one form into another.

Another way of looking at what happens when energy is converted into work is to say that energy is converted into kinetic energy from some other form. Some common examples of energy transfers are:

- In a car, chemical energy is converted into kinetic energy
- In a light bulb, electrical energy is converted into light and heat energy
- In nuclear power stations, nuclear energy is converted into electrical energy.

Figure 5.9 *Heat, kinetic and sound energy are converted from electrical energy in a hairdryer*

Kinetic and Potential energy

Two particular forms of energy that we often encounter are kinetic energy and potential energy.

Kinetic energy is the energy that an object has due to its motion. The larger the mass of an object, or the greater its velocity, the more energy it has. This leads us to a formula for kinetic energy of an object of mass, m, travelling at velocity, **v**:

$$E_k = \frac{1}{2}mv^2$$

where:

E_k = kinetic energy
m = mass
v = velocity

Potential energy can come in many forms. If we stretch an elastic band, or a spring, we give it potential energy. Similarly, if we stand on a football so that we squeeze it, we know it will bounce back into shape when we release it. That is another form of potential energy. The energy that electric charges possess in an electric field is also closely related. But a situation that we come across very often is the potential energy we give an object simply by lifting it up. This is known as gravitational potential energy, and it can be evaluated using the formula:

$$E_p = mgh$$

where:

E_p = potential energy
m = mass
g = acceleration due to gravity
h = height

This equation also makes use of the value of g, the acceleration caused by gravity. For the moment you only need to be aware of the basic concept that, neglecting air resistance, all objects will accelerate at the same rate while falling and that the value of this acceleration is usually denoted by **g**, and its value is taken as 9.8 m s^{-2}.

If we lift a mass of 10 kg through a distance of 2 m, we can look at what has happened in different ways. From one perspective we have given potential energy to the mass. This follows the formula above and shows us that, altogether, the mass has gained 196 J:

$$\begin{aligned} E_p &= mgh \\ &= (10)(9.8)(2) \\ &= 196\ J \end{aligned}$$

From another perspective, though, we can say that we have done work on the object, as clearly a force was required to lift it up through the 2 m. The force required to lift the object would be equal to its weight, so we can say that the work is also 196 J. (Remember that the weight of an object is equal to its mass multiplied by its acceleration due to gravity: W = mg.)

$$\begin{aligned} W &= F\,s \\ &= (98)(2) \\ &= 196\ J \end{aligned}$$

It is no coincidence that the two calculations give the same result. It is inevitable that this will happen: the two formulae are in fact just two ways of looking at exactly the same situation. If we leave out the numbers and rearrange the formulae we can see this:

$$W = F\,s$$

but: **F = weight = mg**

and: **s = displacement or increase in height**

so:

$$\begin{aligned} W &= (mg)(h) \\ &= E_p \end{aligned}$$

This means that we can say that the work done in lifting a body through a height is equal to the potential energy gained in doing so.

Similarly, when we give an object kinetic energy, the work done will be equal to the energy gained.

Q Understanding U2

5.11 What is meant by the term 'work'?

5.12 If a force of 10 N causes an object to move through a distance of 50 m, how much work is done?

5.13 A woman of mass 50 kg participates in a high-jump competition and rises to a maximum height of 2.1 m. How much work has she done at the highest point of her jump?

Conservation of kinetic and potential energy

If a stone is dropped from the top of a high cliff, it gains velocity as it loses height.

Another way of looking at this is to say that it gains kinetic energy as it loses potential energy. In fact, the kinetic energy it gains is coming from the potential energy it loses. As no other form of energy is involved, we can see that potential energy lost must be equal to the kinetic energy gained.

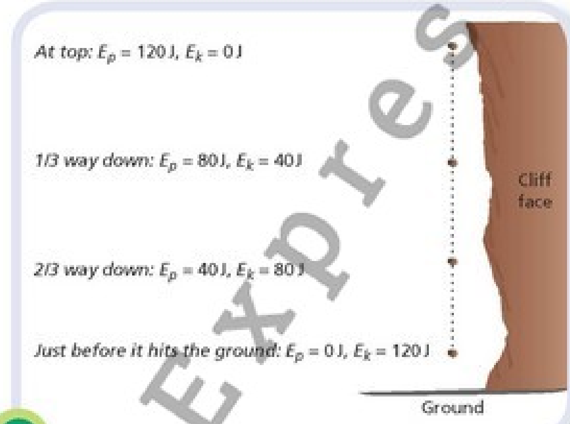


Figure 5.10 *The conservation of kinetic and potential energy*

Figure 5.11 *In a roller-coaster, the cars first of all climb to a great height – gaining potential energy. During the ride, this is converted first into kinetic energy as the cars fall and then back to potential energy as they climb again. This cycle is repeated over and over.*

Mass energy

In 1905, German-born physicist Albert Einstein (1879–1955) published a number of revolutionary scientific papers that really changed the way the world was understood. Let us look at his most famous equation:

$$E = mc^2$$

where:

E = energy
m = mass
c = speed of light

What Einstein realised and showed in this equation is that mass is in fact a form of energy, and that it can be converted into other forms of energy, such as light and heat.

The energy contained within a mass of 1 kg is therefore given by:

$$E = (1)(3 \times 10^8)^2$$
$$= 9 \times 10^{16}\ J$$

This is a huge quantity of energy – 90 thousand million million joules – and the amounts involved when mass is converted into other forms of energy tend to be enormous, too.

The energy in a nuclear explosion comes from the conversion of mass, for example. Why this happens is something we will study in Module 10.

Sample question 4

How much energy is involved if 2 µg of mass is converted into other forms of energy?

Take the acceleration due to gravity, **g**, to be 9.8 m s^{-2}.

Answer:

$$E = (2 \times 10^{-6})(3 \times 10^8)^2$$
$$= 1.8 \times 10^{11}\ J$$

Sample question 5

If a force of 2500 N causes a car to move through a distance of 20 m, how much work is done?

Answer:

$$W = Fs$$
$$= 2\,500 \times 20$$
$$= 50\,000\ J$$

Sample question 6

A man of mass 80 kg climbs a ladder of height 3 m.
How much work has he done?

Answer:

Work done = Potential energy gained
= mgh
= (80)(9.8)(3)
= 2 352 J

Figure 5.12

Sample question 7

If a car of mass 1200 kg is moving at a velocity of 30 ms^{-1}, what is its kinetic energy?

Answer:

$$E_k = \frac{1}{2}mv^2$$
$$= \frac{1}{2}(1200)(30)^2$$
$$= 540\,000 \text{ J}$$

Sample question 8

A crane lifts a mass of 1 tonne through a height of 30 m. What potential energy is gained by the mass? How much work is done in lifting the mass?

Answer:

Work done = Potential energy gained

$$E_p = mgh$$
$$= (1000)(9.8)(30)$$
$$= 294\,000 \text{ J}$$

Sample question 9

A football of mass 300 g is kicked high into the air so that it reaches a height of 18 m.

(a) What is its potential energy at that height? What is its kinetic energy at that height?

(b) At what height does it have a potential energy of 40 J?

(c) What is its maximum kinetic energy? With what speed is it travelling at that point?

Figure 5.13

Answer:

(a) At the highest point:

$$E_p = mgh$$
$$= (0.3)(9.8)(18)$$
$$= 52.92 \text{ J}$$

At the highest point, the velocity is zero and therefore the kinetic energy is zero.

(b) $E_p = mgh = 40$

$$40 = (0.3)(9.8)h$$
$$h = \frac{40}{(0.3)(9.8)}$$
$$= 13.6 \text{ m}$$

(c) Maximum kinetic energy = Maximum potential energy = 52.92 J

$$\frac{1}{2}mv^2 = 52.92$$
$$v^2 = \frac{52.92}{0.15}$$
$$= 352.8$$
$$v = 18.78 \text{ ms}^{-1}$$

Q U2 Understanding

5.14 Define the terms:

(a) 'kinetic energy'

(b) 'potential energy'.

5.15 What are the energy conversions taking place in:

(a) a car

(b) a gas-fuelled boiler

(c) a windmill

(d) a battery?

5.16 How much kinetic energy does an object of mass 1.2 kg have when it travels with a velocity of 20 m s^{-1}?

5.17 During a construction project, a crane lifts an I-beam of mass 1 900 tonnes through a height of 150 m.

(a) What potential energy is gained by the I-beam?

(b) How much work is done in lifting the mass?

5.18 What is the potential energy of a 900 kg elevator when it brings people to the top of the Empire State Building in New York, which is 380 m above street level?

5.19 A stone of mass 80 g is lifted from the ground to a height of 2 m.

(a) How much potential energy is gained?

(b) If it is then dropped, how much kinetic energy will it gain as it falls to the ground?

5.20 The International Space Station (ISS) has a total mass of approximately 390 tonnes. Its furthest point from the surface of the Earth is 460 km. At that point, the acceleration due to gravity is less than on the Earth, but only by a small percentage. For this question, take its value to be constant at 8.54 ms^{-2}.

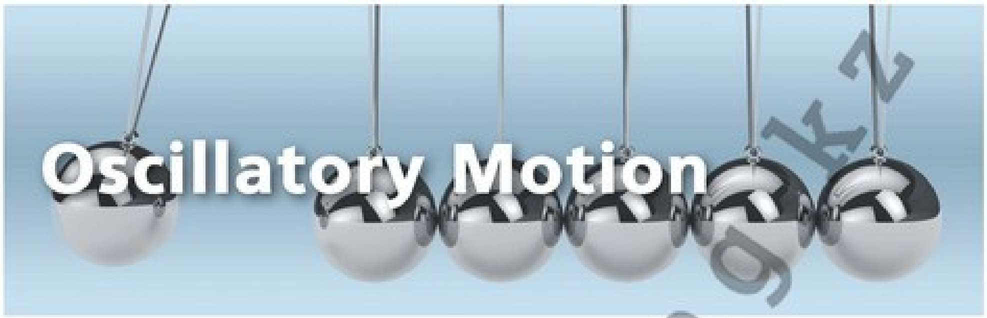
(a) How much potential energy does the ISS have due to its height?

(b) The speed of the ISS is approximately 7.7 km s^{-1}. What is its kinetic energy?

(c) How much work must be done, in total, to bring the ISS to that speed at that height?

Figure 5.14 *ISS*

MODULE 6



Oscillatory Motion

Learning outcomes

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

- Provide examples of free and forced oscillations 9.2.5.1
- Experimentally find an amplitude, period and frequency 9.2.5.2
- Calculate period, frequency, cyclical frequency and a phase using formula 9.2.5.3
- Describe conservation of mechanical energy in an oscillating process 9.2.5.4
- Write equations of coordinates, velocity and acceleration from harmonic oscillation graphs 9.2.5.5
- Explain features of simple harmonic motion 9.2.5.6
- Describe features of a spring in simple harmonic motion and use formulae to perform calculations 9.2.5.7
- Find by experiment acceleration in freefall due to gravity using a pendulum 9.2.5.8
- Plot and analyse graphs of pendulum length against time 9.2.5.9
- Explain results obtained in an experiment and draw conclusions 9.2.3.1

Keywords

✔ equilibrium ✔ restoring force ✔ damping ✔ boundary ✔ oscillation ✔ pendulum ✔ spring ✔ amplitude ✔ vibration ✔ periodic motion ✔ free oscillation ✔ forced oscillation ✔ proportional

Oscillations

A body which is at rest is said to be in its equilibrium position. There is no external force acting on it in this position. When a body is displaced a little from its equilibrium position a force acts on the body so as to return it to its equilibrium position. This force is called the restoring force and is what produces vibrations and oscillations.

Figure 6.1

Imagine, for example, the situation in which someone places a vibrating tuning fork in a bowl of water as in Figure 6.1. The vibrations of the tuning fork will cause ripples on the surface of the water to repeatedly spread out to the edge of the bowl until damping, the slow dissipation of energy, causes the vibrations to stop and the water in the bowl returns it to its equilibrium position. There are in fact two distinct types of process going on here: the oscillations of the water as they spread out repeatedly from the centre and then the process of the ripples hitting the side of the bowl and bouncing off because of the bowl which acts as a boundary to the oscillatory movement. In this module we shall consider the first type of oscillatory movement and in Module 7 give more attention to impact of boundaries on waves in such motion.

Free and forced oscillations

Oscillatory motion describes the repeated motion of an object involving the repetition of the same movement again and again. All kinds of objects experience such motion and in the study of oscillatory movement, it is important to make a distinction between free oscillation and forced oscillation. Free oscillations are those that will continue without any further influence from the force that created them. The wind on the ocean, for example, can set in motion waves that will continue for thousands of miles. A pendulum, a plucked guitar string or a child's swing are other good examples of free oscillations.

Figure 6.2 *A vibrating guitar string*

In order to study oscillatory motion, there are some important terms with which you should be familiar: frequency, period, displacement and amplitude. These will all be explained in the following pages.

A swing pushed once that then continues to move freely back and forth is a free oscillator. It will stop after some time because of energy losses at the pivots and resistance of the air. A person standing behind the child and pushing each time the child reaches them, would be an example of **forced oscillation**, that is to say, an oscillation that is dependent on the force that creates it. Other examples of forced oscillations include a building momentarily shaking during an earthquake or tidal movements.

Figure 6.3

Periodic motion

Periodic motion refers to a set of movements that repeat themselves at equal intervals of time. Imagine that the hand in Figure 6.4 pulls on the spring and then releases the weight. The spring will oscillate up and down moving through the same path again and again over the course of time.

Figure 6.4

Theoretically, if there were no damping the movement would continue endlessly. The **period**, T, is the time taken for an oscillating spring to complete one full oscillation up and down and is measured in seconds.

The **frequency**, f, of oscillations is the number of oscillations undergone in one second. This is measured in hertz (Hz) and as we saw when studying circular motion, the frequency and the period can be related as:

$$f = \frac{1}{t}$$

Sample question 1

A pendulum completes 18 full cycles in 46 seconds. Calculate the frequency and period of the pendulum.

Answer:

t = 18/46 = 0.39 s

f = 1/0.39 = 2.54 Hz

The displacement of the weight is the distance that oscillating weight moves from its equilibrium position.

The **amplitude** of the oscillation is the maximum displacement of the vibrating object from the equilibrium position.

Q Understanding U2

6.1 Explain the difference between free and forced oscillations.

6.2 Give two examples of free and forced oscillations.

6.3 What is the name of the force that returns an object to equilibrium after displacement?

6.4 What is the term for the maximum displacement of an oscillating object form its equilibrium position?

6.5 An oscillating spring completes 26 full cycles in 38 seconds. What is the frequency and period of the spring?

Simple Harmonic Motion

Any motion in which the acceleration (a) of a particle is proportional to its distance (s) from an equilibrium position, and towards that position, is simple harmonic motion (SHM).

Taking the example of the oscillating spring in **Figure 6.5**, when the weight is initially pulled down and released, it always moves back towards the central, or equilibrium, position. The further the spring is from the equilibrium position, the greater its acceleration. This is why we can say that for SHM the acceleration is always proportional to the displacement.

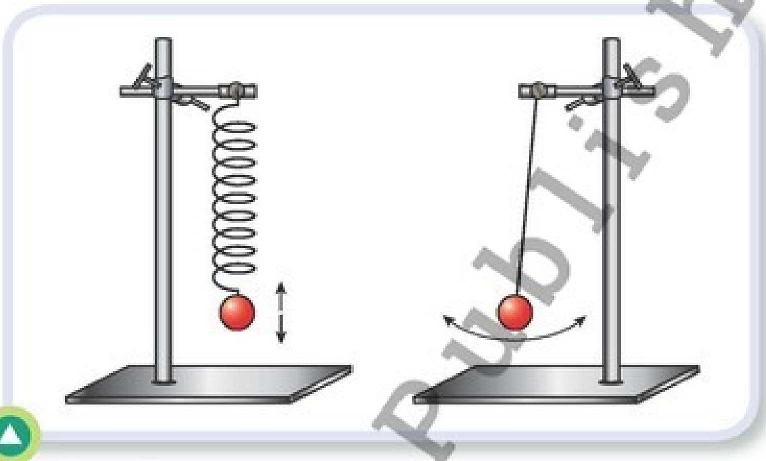


Figure 6.5

We can express this rule of simple harmonic motion using the mathematical formula

$$\alpha \propto -s$$
$$\alpha = -\omega^2 s$$

where ω_2 is a constant.

The minus sign in the formula is because acceleration and displacement are both vector quantities and both therefore have a direction. When the displacement of the weight is upwards, the acceleration is downwards, and when the displacement is downwards, the acceleration is upwards.

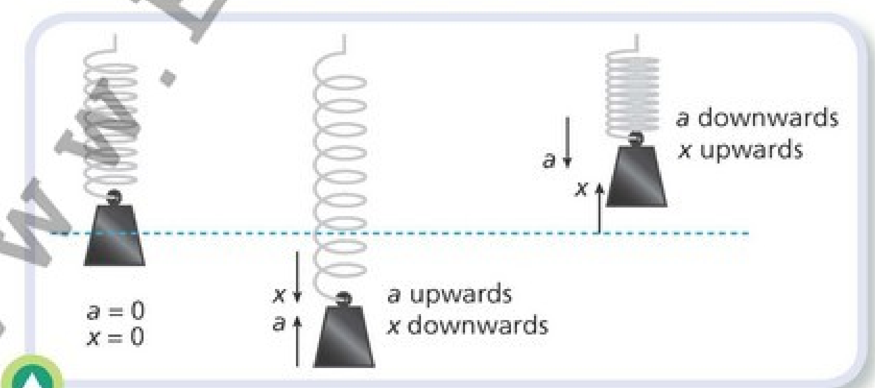


Figure 6.6

The period of SHM follows the exact same formula as that for circular motion that we saw in Module 2:

$$T = \frac{2\pi}{\omega}$$

The diagram shows the connection between simple harmonic motion and circular motion. A handle is rotating in a circular motion on a disc. The shadow of the handle created by a light source can be seen on a screen. The shadow is following SHM and has the same period [P] as the handle on the disc.

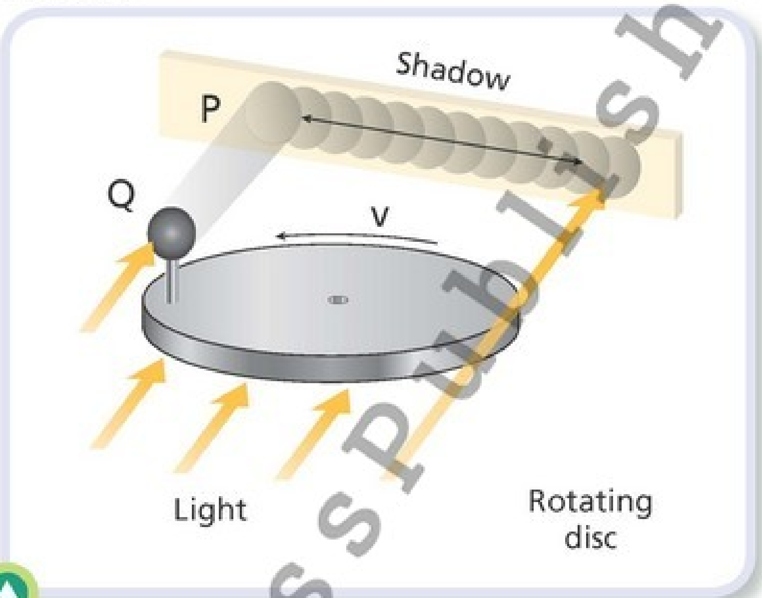


Figure 6.7

Figure 6.8 represents SHM motion of a spring graphically. When the spring is displaced from its rest position by pulling it down and then releasing it, it oscillates due to restoring force. From the action of the restoring force it accelerates, passes the rest position and is then pulled back by the restoring force.

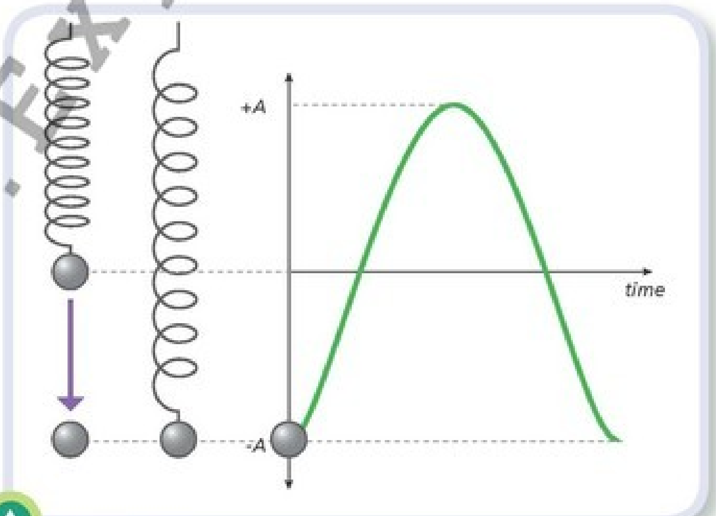


Figure 6.8

Q U2 Understanding

6.6 Which measurement on the diagram would represent the period of SHM?

6.7 Which measurement on the diagram would represent the amplitude of SHM?

6.8 Which point on the diagram represents the equilibrium point?

Graphs showing displacement, velocity and acceleration during simple harmonic motion can be plotted as follows where T represents time for one complete cycle of motion.

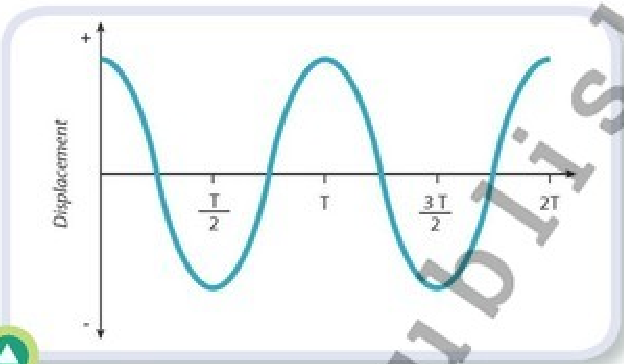


Figure 6.9

The gradient of the *displacement against time* graph represents velocity.

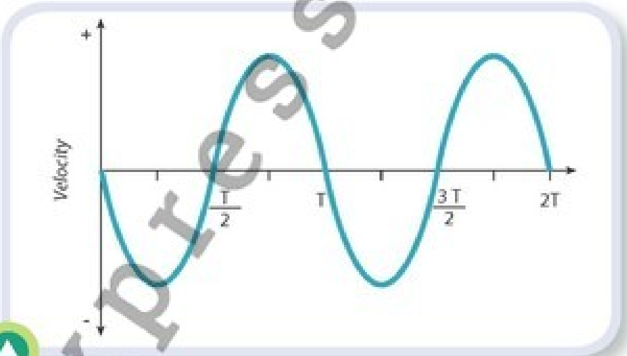


Figure 6.10

The gradient of the *velocity against time* graph represents acceleration.

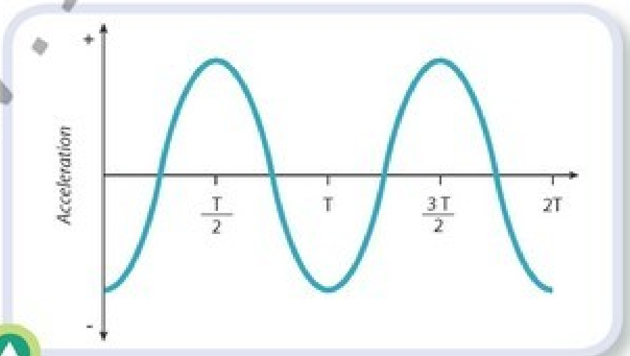


Figure 6.11

Analysing the *acceleration against time* graph, you will notice that it is the mirror opposite of the *displacement against time* graph, in line with the definition of simple harmonic motion that the acceleration (a) of an object is proportional to its distance (x) from and towards its equilibrium position.

Taking the example of the simple harmonic motion of a pendulum and superimposing the three lines on the same graph, we can see the relationships between displacement, velocity and acceleration in each phase of the cycle of the pendulum.

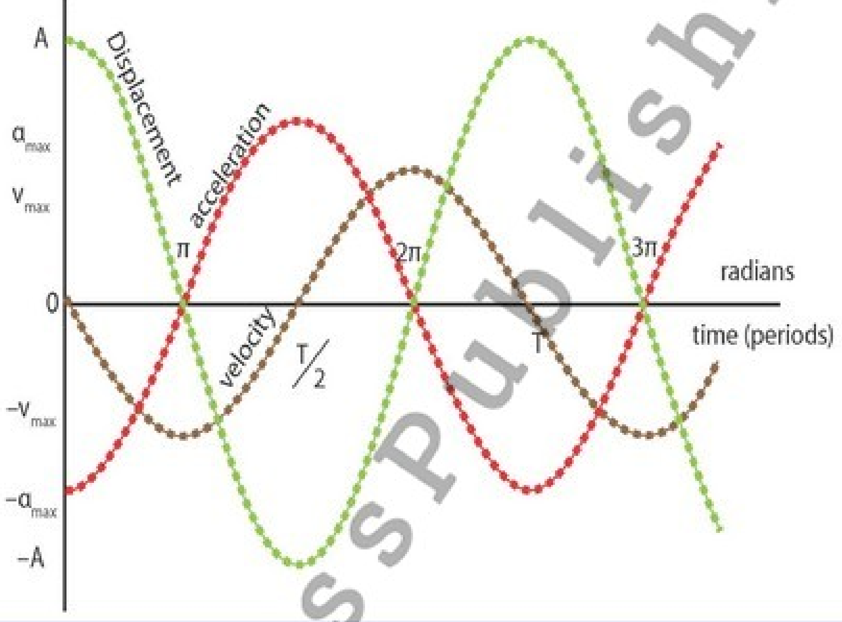


Figure 6.12

U2

6.9 Locate each point on the graph referred to as you read the explanations below.

At the point at which the pendulum has been raised before letting go:
x = maximum positive displacement
v = zero [as it is not yet moving]
a = maximum negative acceleration [as it will start by going down]

Passing through the equilibrium position as it goes down:
x = zero as its in equilibrium position
v = maximum speed down (negative)
a= zero , as no resultant force on the mass means no acceleration

At its lowest point:

x = maximum in negative displacement

v = zero as it stops momentarily before changing direction

a = maximum positive acceleration

It is important to note that:

- velocity is at zero at the peaks and troughs of the displacement graphs
- the peaks of displacement and velocity differ by a quarter of a cycle and since one cycle equals 2π, the phase difference between object velocity and object displacement in simple harmonic motion is $\pi/2$ radians.

> Formulae:
>
> $a = -(2\pi f)^2 x$
>
> $x = A \cos 2\pi ft$
>
> $v = \pm 2\pi f\sqrt{A^2 - x^2}$
>
> where:
>
> a = acceleration in ms^{-2}
>
> f = frequency in Hz
>
> x = displacement from the central position in m.
>
> v = the velocity in ms^{-1}

Q U2 Understanding

6.10 An object moving with SHM has a maximum displacement of +18 cm at time t = 0. The frequency of the motion is 10 s^{-1}. At a time t = 0.65 seconds, what is the position of the object?

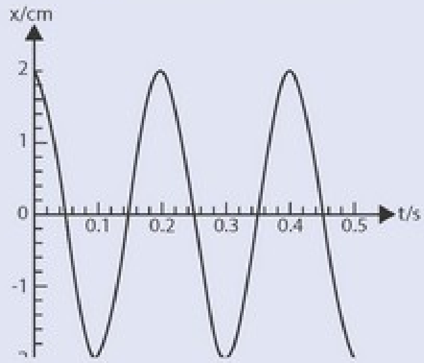
6.11 The graph shows the displacement of an object from a fixed equilibrium position.

Use the graph to calculate:

(a) the period of motion

(b) the maximum speed of the particle during oscillation

(c) the maximum acceleration experienced by the particle.



6.12 An object moves with simple harmonic motion according to the equation:

$$x = (2/\pi)\sin(2\pi t + \pi/3)$$

At time t = 2s, what is the velocity of the object?

6.13 A spring is oscillating in simple harmonic motion according to the equation:

$$x = 0.15 \cos \pi t$$

Calculate the period of the motion.

Simple pendulum

The period of a pendulum is not absolutely constant. It depends on two things: the length of the pendulum, ℓ, and the value of g, the acceleration caused by gravity expressed in the formula:

$$T = 2\pi\sqrt{\frac{\ell}{g}}$$

In activity 6.1 we will measure the acceleration due to gravity of a simple pendulum.

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Activity 6.1

Question

What is the relationship between period and length for a simple pendulum and calculation of g?

Equipment needed

stand
pendulum bob thread
two halves of split cork
timer

Safety

- Follow all normal lab safety procedures while conducting this activity.

Conducting the activity

1. Place the thread of a pendulum between two halves of a split cork, as shown in Figure 6.13.
2. Set the pendulum swinging through a small angle (<10°). Measure the time t for 30 complete oscillations. Divide this time t by 30 to get the periodic time, T.
3. Record both ℓ and T (the length is from the centre of gravity of the bob to the bottom of the cork).
4. Repeat for different lengths, ℓ, of the pendulum.
5. Draw a graph of ℓ/m against T 2/s$_2$.

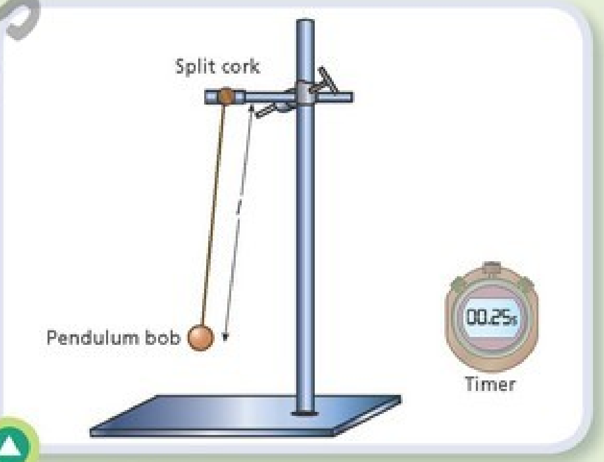

Figure 6.13

Understanding U2

6.14 What can you conclude from your observations about the shape of the line on your graph?

Q Understanding U2

6.15 What is the period of a simple pendulum 50 cm long on Earth?

6.16 A simple pendulum is 0.66 m. The pendulum bob has a mass of 310 g. It is released at an angle of 12° to the vertical

(a) What is the frequency of the oscillation?

(b) What is the pendulum bob's velocity when it passes through the lowest point of the swing?

Elasticity of springs

Springs such as those made from coiled metal are devices that are designed to maximise elasticity. When the weight at the end of a spring is pulled down and then released, it will move upwards – towards the equilibrium position. Springs that stay within their elasticity limit follow this rule known as Hooke's law:

> The greater the extension on the spring, the greater the restoring force that brings the spring back towards its original length.

These two measurements are proportional.

k is used to represent the spring constant measured in N m^{-1} units. A spring with a large value for **k** indicates a stiff spring, one that is difficult to extend or compress, whereas a spring with a small value for **k** indicates that it is very weak, and can be easily extended or compressed. The mathematical formulae are written as:

$$F = -ks$$

$$T = 2\pi\sqrt{\frac{m}{k}}$$

Sample question 2

If a pendulum has a period of 0.8s when it moves with SHM, what is its length?

Answer:

$$T = 2\pi\sqrt{\frac{l}{g}}$$

$$T^2 = 4\pi^2\frac{l}{g}$$

$$l = \frac{gT^2}{4\pi^2} = \frac{(9.8)(0.8)^2}{4\pi^2} = 0.1589\text{ m}$$

Sample question 3

A spring experiences an extension of 7 cm and has a spring constant of 285 N m^{-1}. What is the restoring force on the spring at that point?

Answer:

F = ks = 285 x 0.07 = 19.95 N

Q U2 Understanding

6.17 What is the length of a pendulum that swings back and forth in 1.6 s?

6.18 What force would be needed to extend a spring by 0.3m, if the spring has a spring constant K=5?

6.19 If a swing is 3 meters long what is the period of the swing?

6.20 If we hung two identical springs in parallel, would this make the 'total spring constant' more stiff or less?

6.21 If a force of 12 N is applied to a spring, it creates an extension of 3 cm.

- **(a)** What is the value of the spring constant?
- **(b)** What would the restoring force on the spring be if the extension were 8 cm?

SHM and kinetic and potential energy

To displace a body at rest from its equilibrium position work needs to be done on it and in this process it gains potential energy. A simple example of this is a child on a swing. To set the swing in motion the person doing the work can either pull the swing back and release it or push the child on the swing forwards. Once the swing is in motion, the gravitational potential energy changes into kinetic energy.

Figure 6.14

The kinetic energy for an object in SHM at any moment of time can be expressed by the following formula:

$$EK = \frac{1}{2} mv^2$$

where

$$E_K = \text{constant} \times v^2$$

Plotting a graph for *kinetic energy against time* gives a graph that represents the shape of the velocity expression for SHM squared. We have seen above that the velocity curve has sinusoidal form.

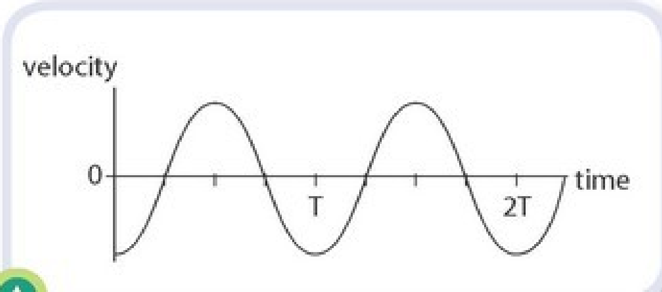

Figure 6.15

What distinguishes the kinetic energy curve is that in comparison to the velocity curve there is no negative value. The squaring of the velocity results in the frequency of the curve doubling.

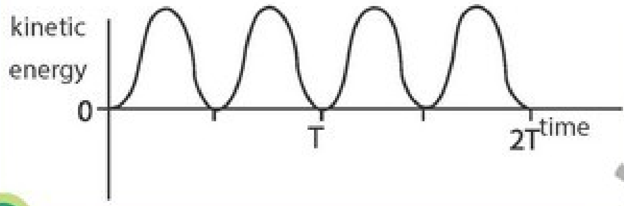

Figure 6.16

In SHM as the potential gravitational energy of a pendulum or the stretch energy of a spring increases so the kinetic energy decreases. This can be represented thus:

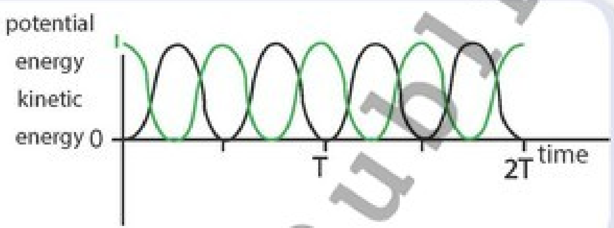

Figure 6.17

In a displacement diagram such as Figure 6.18 It can be seen that kinetic energy will have its maximum value when a body is in equilibrium position and potential energy will have a value of zero.

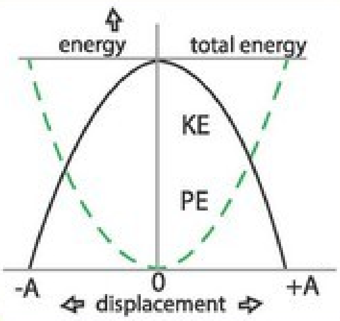

Figure 6.18

Q U2 Understanding

6.22 A 2.5 kg weight is attached to a spring of force constant k = 4,5 kN/m. The spring is stretched 10cm from the equilibrium position and released. Calculate the kinetic energy when the weight is 5cm from its equilibrium position.

6.23 Displacement in simple harmonic motion is at a maximum when
- (a) kinetic energy is at a maximum
- (b) acceleration is zero
- (c) potential energy is at a maximum
- (d) velocity is at a maximum.

6.24 A spring with a spring constant 19.6 N/m is compressed to 5 cm. A mass of 0.3 kg is attached to the spring and it is released from rest. What is the maximum elastic potential energy stored in the spring?

MODULE 7

Waves and Wave motion

Learning outcomes

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

- Apply velocity, frequency and wavelength formulas for solving problems 9.2.5.12
- Compare transverse and longitudinal waves 9.2.5.13
- Experimentally define velocity of surface wave distribution 9.2.5.12
- Compare properties of electromagnetic and mechanical waves 9.4.4.2
- Describe and provide examples of electromagnetic waves of different ranges 9.4.4.3
- Characterise light dispersion as light passing through a glass prism 9.5.4.4

Keywords

✔ frequency ✔ wavelength ✔ trough ✔ peak ✔ period ✔ light dispersion ✔ prism ✔ transverse ✔ longitudinal ✔ microwave ✔ infrared ✔ ultraviolet ✔ gamma rays ✔ transmitter ✔ aerial

Waves

We are all familiar from a young age with the idea of waves. We see waves breaking on the beach, ripples spreading out around an object dropped in water and the uneven surface of a busy swimming pool. All of these examples involve waves moving through water, but there are many other waves around us all the time, although not so easily noticed. Sound travels as a wave. So does light. Radio and TV signals, and the conversations we have on mobile phones, all travel in waves.

Figure 7.1 *Waves on the surface of water*

As waves, all these phenomena have one thing in common. In each case, energy is transferred from one place to another, but at the same time there is no overall movement of the medium through which the wave is moving. The ripples we see moving out from the point where a stone enters a pool of water, for example, show how a vibration is moving through the pool, but when the wave has died away, all the water will be where it was before – the vibration moves through the water but the water itself has no net movement.

This gives us a definition of what a wave is:

> A **wave** is a means of transferring energy through a medium, without any net movement of that medium.

In order to study waves there are some important terms with which you should be familiar: wavelength, frequency, period, wave speed and amplitude. These will all be explained in the following pages.

Wavelength

Wavelength is an obvious way of measuring a wave: we simply take the wave and measure its length, in metres. We can measure from the **peak** (top) of one wave to the peak of the next, or we can measure from the **trough** (bottom) of a wave to the trough of the next. The symbol usually used for wavelength is the Greek letter **λ** (pronounced **'lamb-da'**).

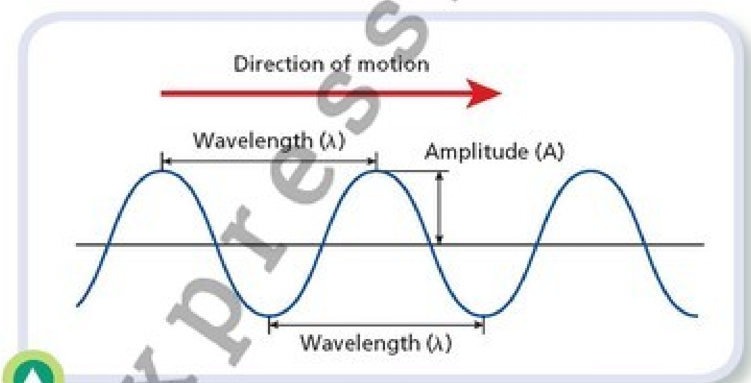

Figure 7.2 *A wave, with key measurements*

> Wavelength, **λ**, is the distance between two identical points in adjacent cycles of a wave motion.

Frequency

> The frequency, **f**, is the number of cycles completed at any one point per second.

Did you know?

One hertz is one wave per second.

If you could stand in one spot and watch a wave pass by, the number of complete waves that pass every second is the frequency of the wave. **Frequency** can be measured very simply as waves per second or as cycles per second – until the 1960s, this was the unit that was most often used. However, because it is such a key measurement in physics, the unit of frequency is given its own name: the hertz (Hz).

Heinrich Hertz

Gregor Heinrich Hertz was a German physicist who, in 1886, created the first radio wave transmitter and receiver. Although this work did eventually help to create the form of radio as we know it today, Hertz was not trying to do that – he was trying to prove the existence of electromagnetic waves, and to show that light is simply one form of these waves. He died tragically young, aged just 36, in 1894.

Figure 7.3 *Heinrich Hertz (1857–1894)*

Period

The period of a wave, T, is the time taken to undergo one complete cycle.

The period of a wave is a concept closely connected to frequency. With the period, however, instead of measuring how many waves pass a particular point every second, we instead measure how long it takes one complete wave to pass a particular point.

Frequency and the period are connected by the formula:

$$f = \frac{1}{T}$$

Speed

The speed of a wave, c, is the speed of propagation through a medium.

If you were to drop a stone into water, the speed of the wave would be the rate at which the first wavefront spreads out from the point where the stone entered the water. As we shall see, light and other electromagnetic radiations such as radio waves and X-rays all travel at 300 000 000 m s^{-1}. However, most waves travel at just a tiny fraction of that speed. Sound waves in air, for example, travel at about 340 m s^{-1}.

Speed, frequency and wavelength are all interconnected. If we think of any one wave passing a point, we can find its speed using a simple distance, speed and time calculation:

$$\text{Time} = \frac{\text{Distance}}{\text{Speed}}$$

As a wave passes a particular point, we can think about the length of one full wave (wavelength, **λ**) as the distance travelled. The time it takes for this wave to pass is the period, **T**. This means that the speed, **c**, of the wave is equal to the wavelength divided by the period:

$$\text{Speed} = \frac{\text{Wavelength}}{\text{Period}}$$

or

$$c = \frac{\lambda}{T}$$

As we have seen already:

$$f = \frac{1}{T}$$

or

$$T = \frac{1}{f}$$

This means that we can replace T in the equation with $\frac{1}{f}$. This leads us to:

$$c = f\lambda$$

This equation shows us that if the wavelength is reduced while the speed stays the same, the number of waves per second (frequency) must increase. Also, if the frequency increases while the wavelength stays the same, the speed of the wave must also increase. This equation is very important in physics and it is one with which you will become increasingly familiar.

When we talk about a wave moving at a particular speed, we are not saying that any individual particles move at that speed. If you think of a wave moving through a slinky, as shown in Figure 7.6 below, the wave moves forward through the slinky very quickly. You can see this clearly if you try it out for yourself. However, the vibrations of any one part of the slinky as it moves up and down are considerably slower. The speed of the wave is not the speed of any of the vibrating particles through which the wave is moving.

Amplitude

The amplitude of a wave is a way of measuring the size of the wave. In straightforward situations, we do this by measuring the height of the wave, as shown in Figure 7.4. Note that we do not measure the distance from the peak (top) of the wave to the trough (bottom) of the wave. Instead we measure the distance between the peak of the wave and the 'middle'. In the case of a wave on water, for example, we measure from the peak of the wave to the point where the water was sitting before the wave was created. In the case of a long string being continuously moved up and down at one end and through which a wave then passes, we measure from the high point of the wave to where the rope was lying before the wave was created.

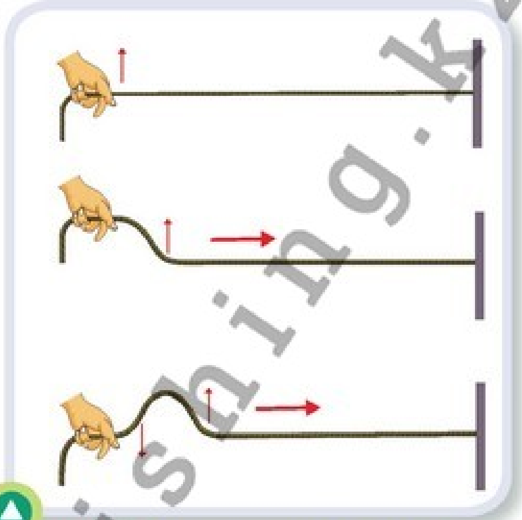

Figure 7.4 *A wave passing along a string*

Amplitude is not always measured as a distance. When a sound wave passes through air, for example, amplitude can be measured as the difference in pressure in the air at the peak of the wave compared with the pressure before the sound wave was created.

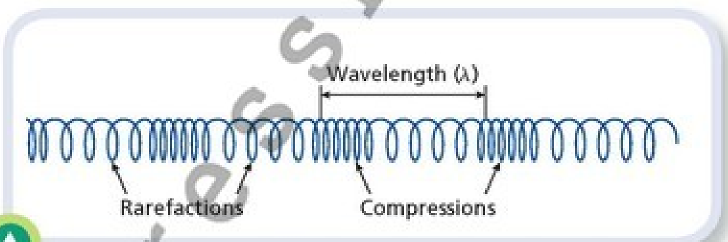

Figure 7.5 *A longitudinal wave*

7.1 What is a wave?

7.2 Complete the table with the words:

frequency **period** **amplitude** **wavelength**

	measurement from peak of one wave to peak of next
	number of cycles completed at any one point per second
	time taken to undergo one complete cycle
	measurement of the size of the wave

7.3 The frequency of a wave is 5 Hz.

(a) How many waves are passing a particular point every second?

(b) What is the period of the wave?

Transverse and Longitudinal waves

Waves can be either **transverse waves**, as seen on the surface of a liquid such as water, or **longitudinal waves**, such as sound waves.

- In a transverse wave, the movement of the particles of a medium is perpendicular to the movement of the wave.
- In a longitudinal wave, the movement of the particles of a medium is parallel to the movement of the wave.

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Activity 7.1

Question

How can we create waves using a slinky?

Equipment needed

A slinky

Conducting the activity

Transverse waves

1. Two students hold a slinky between them.
2. One of the students keeps his/her hand motionless. The other moves his/her hand up and down, as shown in Figure 7.6.
3. Observe the wave motion as it moves along the slinky.

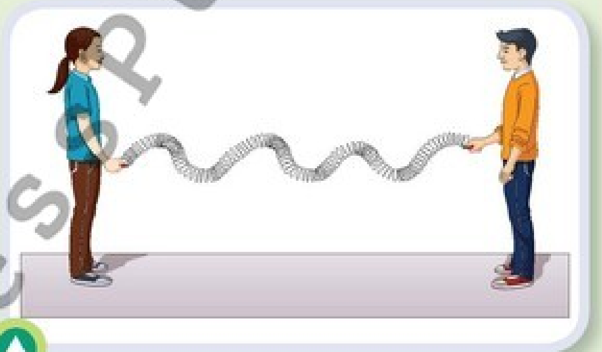

Figure 7.6 *A transverse wave*

Longitudinal waves

1. Two students hold a slinky between them.
2. One of the students keeps his/her hand motionless. The other moves his/her hand back and forth rapidly, as shown in Figure 7.7.
3. Observe the wave motion as it moves along the slinky.

Figure 7.7 *A longitudinal wave*

U2 R4

7.4 How would you describe the difference in motion between the two kinds of wave?

Mechanical waves and Electromagnetic waves

Most of the waves we have mentioned so far in this module are classed as mechanical waves. This means that they are moving through a medium such as water or air. We can often see the vibrations in the medium as the waves passes – even if we cannot, it is not difficult to picture the motion of the atoms or molecules involved.

Sometimes waves seem to travel without passing through any obvious medium. When light travels to us from the Sun, for example, it passes through over 150 000 000 km of empty space. We know, however, that in the space through which it travels there are rapidly changing electric and magnetic fields. Effectively, the electric and magnetic fields create the medium through which the wave travels. We call the waves **electromagnetic waves** for that reason.

Sample question 1

Every minute 25 waves pass a particular point.

(a) What is the frequency of the waves in hertz?

(b) If the wavelength is 20 cm, what is the speed of the waves?

Answer:

(a) frequency = number of waves per second

$$f = \frac{25}{60} = 0.42\,\text{Hz}$$

(b) $c = f\lambda$

$= (0.42)(0.2)$

$= 0.084\ \text{ms}^{-1}$

Sample question 2

(a) If the microwaves produced in a microwave oven are of frequency 2.5 GHz, how many waves are produced per second?

(b) If the waves travel at $3 \times 10^8\ \text{m s}^{-1}$, what is the wavelength of the waves?

Answer:

(a) $2.5\,\text{GHz} = 2.5 \times 10^9\,\text{Hz} = 2.5 \times 10^9$ waves per second

(b) speed (c): 3 x 108 m s^{-1} frequency (f): 2.5 x 109 Hz

$$c = f\lambda$$
$$3 \times 10^8 = 2.5 \times 10^9 \lambda$$
$$\lambda = \frac{3 \times 10^8}{2.5 \times 10^9}$$
$$= 0.12\,\text{m}$$

Q U2 Understanding

7.5 **(a)** If 10 waves pass a particular point every second, what is the frequency of the wave?

(b) If 5000 waves pass a particular point every minute, what is the frequency in hertz?

(c) If 72 000 waves pass a particular point every hour, what is the frequency of the wave in hertz?

7.6 The frequency of a sound wave to which you are listening is 280 Hz.

(a) How many waves arrive at your ear every second?

(b) How many arrive every minute?

(c) What is the period of the wave?

7.7 The frequency of a wave pattern produced in a ripple tank is 40 Hz. The waves are of wavelength 7.5 mm. What is the speed of the waves?

7.8 The waves produced by the radio station 2FM are of frequency 97 MHz. They travel at 3×10^8 m s^{-1}. What is their wavelength?

7.9 X-rays used to examine broken bones are of wavelength 0.01 nm. If they travel at the speed of light, what is their period?

7.10 The right-most key on a standard piano produces a note of frequency 4186 Hz. If the speed of sound is 343 m s^{-1}, what is the wavelength of the waves produced?

Wave phenomena

There are various phenomena that we associate with all waves. Some of these are already familiar. For example, we know that all waves reflect and refract from our study of the **reflection** and **refraction** of light. Here we shall focus on two other phenomena common to all waves: **diffraction** and **interference**.

Diffraction is the spreading out of waves after they pass through a small opening, or after they pass by an obstacle.

R2 R3 R4 Portfolio 46

Activity 7.2

Question

How can we demonstrate diffraction?

Equipment needed

ripple tank

metal bar

Safety

- Be careful when moving around the ripple tank as parts are breakable.

Conducting the activity

1. Set up a ripple tank as shown in Figure 7.8.
2. Use a metal bar to create waves. Observe the wave pattern on the surface below.
3. Place a barrier across the path of the waves, so that it leaves a small gap, and observe the behaviour of the waves as they pass through the gap.
4. Vary the width of the gap and observe the effect this has on the diffraction of the wave. When is the diffraction most clearly visible?
5. Place a barrier across the path of the wave so that it blocks much of the movement of the wave. Observe how the wave diffracts as it passes the barrier.

Figure 7.8 *A ripple tank*

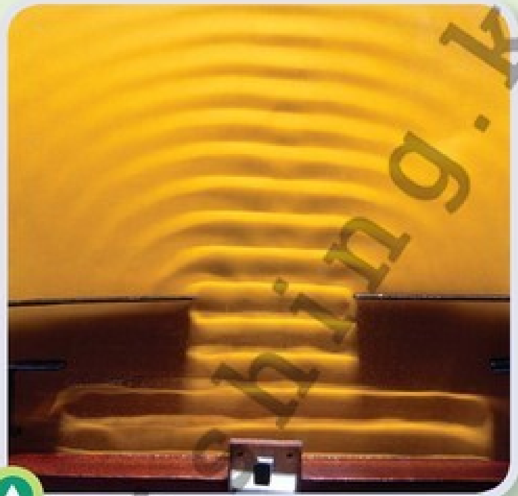

Figure 7.9 *Waves in a ripple tank passing through a gap, demonstrating the principle of diffraction*

Q R4 R5

7.11 What did you notice as the wave passed the gap?

7.12 How did the length of the wave affect diffraction?

You should note during the demonstration that if any wave energy at all survives when a wave passes through, or past, a barrier, the wave will undergo diffraction. In some cases, however, the diffraction can be very slight – the wave hardly fills the 'shadow' of the obstacle at all. In other cases, it is very strong, and the wave spreads out very quickly to fill almost all of the area past the obstacle.

In general, you should find that if a wave passes through a gap in an obstacle where the size of the gap is close to the wavelength, the diffraction will be strong. If the wave passes through a gap that is either much smaller or much bigger than the wavelength, the effect will be slight (see **Figure 7.10**).

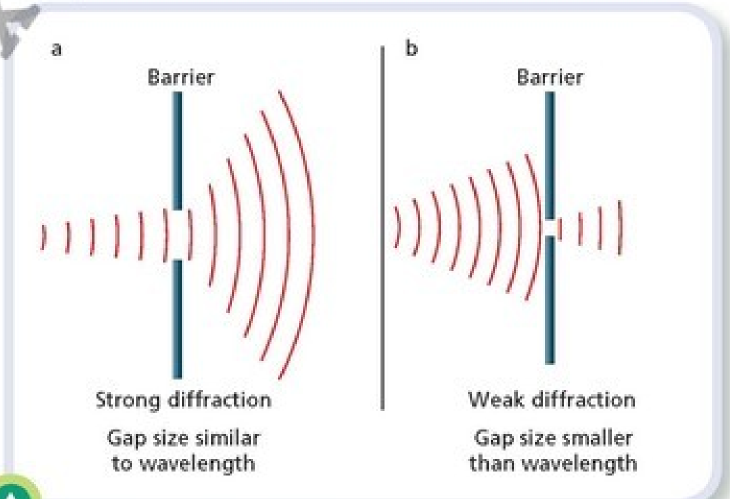

Figure 7.10 *Diffraction of waves*

If a wave hits a single large obstacle, there will still be diffraction. This is important in modern life. If it was not the case we would not be able to receive a signal to our mobile phones unless there was a clear path between us and a nearby mast. Similarly, homes in mountainous areas would be unable to receive TV or radio signals (see Figure 7.11). In general, when waves encounter large single obstacles, the diffraction is strongest for longer wavelengths.

Figure 7.11 *Unfortunately, in some situations when waves encounter large single obstacles, the diffraction is not perfect, and this does cause weak or unreliable mobile coverage and radio and TV signals in some areas*

Diffraction of sound waves and light waves

Sound and light both travel as waves, but those waves are very different. Light, and all electromagnetic radiation, travels as waves through electric and magnetic fields. It does so at enormous speed – the speed of light – and often has an extremely short wavelength. Visible light, for example, has wavelengths measured in tens of millionths of a metre.

Sound, by contrast, has relatively long waves, varying from a few centimetres up to several metres in length. For this reason, the diffraction of sound waves is very obvious. A typical doorway or window, for example, is often around a metre in width and close to the wavelength of many sound waves. A sound wave encountering an open doorway is therefore a wave coming up to a gap close to its own wavelength. This means that when the sound wave passes through, the diffraction will be very strong, and the sound will spread out into the area beyond the door.

A light wave, encountering the same doorway, is a wave meeting a gap in no way comparable in size to its own wavelength. Therefore, there will not be any measurable diffraction. The light does not spread out into the space beyond the door.

Along with the way in which sound waves reflect off hard surfaces such as walls and ceilings, this explains why we can often hear people that we cannot see.

Interference

When waves meet, they combine with each other to create an **interference pattern**. This pattern can take on many different forms. On water, the choppy surface of the sea is a very complex interference pattern, created by the many hundreds of different waves travelling across the surface of the ocean. Sometimes we get poor reception on a radio or TV, or on a mobile phone. This is also caused by interference.

Research R2 Research R3 Research R4 Portfolio 47

Activity 7.3

Question

How can we demonstrate interference?

Equipment needed

ripple tank

two metal balls

Safety

- Be careful not to drop the metal balls and take care when moving around the ripple tank.

Conducting the activity

3. Set up a ripple tank as shown in figure Figure 7.12 as before
4. Use a metal ball to create waves. Observe the wave pattern on the surface below.
5. Add in a second metal ball, so that two waves are created.
6. Observe the pattern created when the two waves meet and overlap.

Figure 7.12 *An interference pattern*

Research R4 Research R5

7.13 What did you observe in this activity?

When two waves or more waves meet, the total displacement will be equal to the algebraic sum of the individual displacements.

If we think about interference created by just two waves meeting, there are two extreme situations that could occur. If the peak of one wave meets the peak of another, we get a new wave created that has the same frequency and wavelength as the original but has a larger amplitude – in effect, the two waves have been added together. Think of this on the surface of a body of water. When two waves overlap so that both are trying to push the water up, the water will move up, and to a greater degree than either wave would have caused by itself. This is known as **constructive interference** (see Figure 7.13).

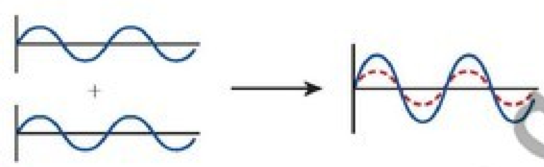

Figure 7.13 *Constructive interference*

If, however, the peak of one wave meets the trough of another, the two waves cancel each other out. Think of a situation like this on the surface of a body of water. If two waves meet so that at one particular point one wave is pushing the water up and the other wave is pushing the water down, the water will simply not move at all. At that point the wave has been destroyed. This is known as **destructive interference** (see Figure 7.14).

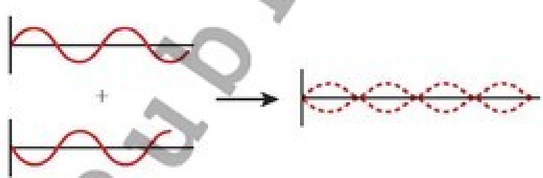

Figure 7.14 *Destructive interference*

Interference patterns

The reality is that it is very unusual to come across a situation in which two waves meet in such a way as to continuously create either perfect constructive or perfect destructive interference. Usually they meet so that in some places there is constructive interference and in other places there is destructive interference. In the area of overlap, there will also be areas with partial constructive and partial destructive interference. Overall, the pattern created in the area of overlap between the two waves is known as an interference pattern.

Imagine the undisturbed surface of a swimming pool. When a swimmer enters the water, particularly if they dive in an elegant manner as shown in Figure 7.15, a wave will spread out symmetrically around their point of entry. This wave is usually very clearly visible and each

Figure 7.15 *A diver enters the water*

wave crest is easily identified. A minute or two later, though, as the person continues to swim, the surface of the water becomes choppy and there are no clearly identifiable individual waves.

What is happening is that the motion of the swimmer is creating several separate waves: each hand as it moves through the water, each leg, each shoulder, all create separate waves that spread out across the surface of the water. All of these waves then meet and overlap. In some places they meet so that they create larger motions – constructive interference – and in other places there is destructive interference and the waves cancel each other out. Everything between the two extremes is happening, too. The choppy surface is essentially an interference pattern of sorts. However, the overall mix of constructive and destructive interference is far too complicated to be easily analysed.

Coherent waves

When two identical, or coherent, waves meet, the interference pattern created is stationary, or unchanging. This makes it relatively easy to observe and analyse, and is therefore of great use in science. As we have seen, for two waves to be coherent they need to have the same wavelength and frequency. **Figure 7.16a** shows waves that are also **in phase**, meaning that both peaks and troughs coincide when the waves meet.

The waves in figure **Figure 7.16b** and **c** are not in phase but still form coherent waves. Observe that, although the peaks and troughs do not coincide, the relationship between the two waves is constant: one wave is always 'ahead' by exactly the same distance. We say that such waves have a **constant phase difference**.

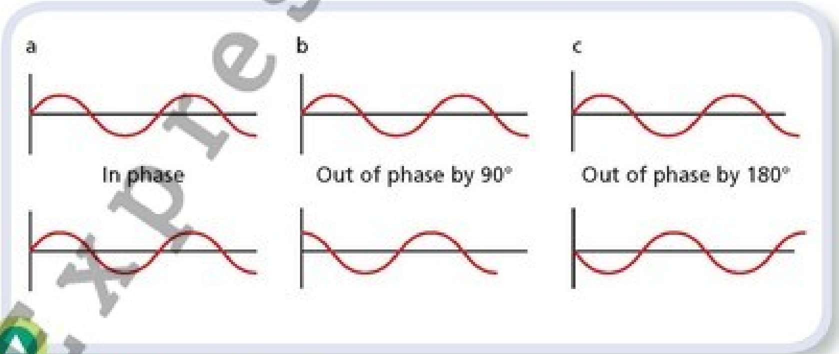

Figure 7.16 *Coherent waves*

Coherent waves are waves that are of the same frequency and wavelength and that maintain a constant phase difference.

Sample question 3

Bats use high-frequency waves to detect obstacles. A bat emits a wave of frequency 68 kHz and wavelength 5.0 mm towards the wall of a cave. It detects the reflected wave 20 ms later. Calculate (a) the speed of the wave and (b) the distance of the bat from the wall.

Answer:

(a) $c = f\lambda$

$= (68 \times 10^{3})(5 \times 10^{-3})$

$= 340\ ms^{-1}$

(b) Distance the wave travels $=$ Speed x Time

$= 340 \times 20 \times 10^{-3}$

$= 6.8\ m$

Distance to the wall $= \frac{6.8}{2} = 3.4\ m$

Sample question 4

A sound wave of frequency 512 Hz travels through a liquid at speed 1500 m s^{-1} and then moves into air, where it refracts and produces a wave travelling at a speed of 330 m s^{-1}.

(a) What is the wavelength in the liquid?

(b) What is the wavelength in air?

Answer:

$c = f\lambda$

so $\lambda = \frac{c}{f}$

(a) $\lambda = \frac{1500}{512}$

$= 2.93\ m$

(b) $\lambda = \frac{330}{512}$

$= 0.64\ m$

Did you know?

When waves go from one medium to another the frequency usually stays the same but the wavelength changes.

Q Understanding U2

7.14 What is meant by the term 'coherent waves'?

7.15 A sound wave of wavelength 1 m travels through air so that it comes to a wall in which there is an open doorway and an open window. The door is 90 cm wide and the window is 40 cm wide. The sound wave will pass through both gaps, but after which one will the diffraction be strongest?

7.16 Will a light wave diffract after passing through a doorway 90 cm wide? Explain your answer.

7.17 Explain the difference between constructive and destructive interference.

7.18 If a wave of wavelength 1.5 m moves from one medium to another so that its speed doubles, what is the wavelength in the new medium?

Stationary waves

A stationary wave is produced when two waves of the same frequency and wavelength, travelling in the opposite direction, meet.

Stationary waves (or standing waves) are fairly common and are frequently encountered in everyday life. Microwave ovens use stationary waves, as do most musical instruments. Children playing with a skipping rope set up a stationary wave as they do so. A glass of water on a vibrating surface may create a stationary wave.

Figure 7.17 *A stationary wave on a skipping rope*

All the waves discussed so far can be described as **periodic travelling waves**: it is clear when observing them that there is a constant forward movement. Our definition of a wave as a means of transferring energy from one place to another was based on this concept. This is still essentially true with stationary waves: there is still forward movement within each wave involved. However, because two waves meet while travelling in opposite directions, this movement is no longer apparent: instead the wave appears to stand still. In fact, because two very similar waves are moving in opposite directions, not only is there no overall movement of the particles through which the waves move, but there is not even any net movement of energy. The most obvious example of this is in a guitar string.

Figure 7.18 *A stationary wave on a guitar string*

The stationary wave is an example of interference. Think of a transverse wave moving through a string as shown in Figure 7.19. A second wave is then created, also moving through the string but in the opposite direction, as shown in Figure 7.20. It is very often the case that this is just the original wave, being reflected back along its own path.

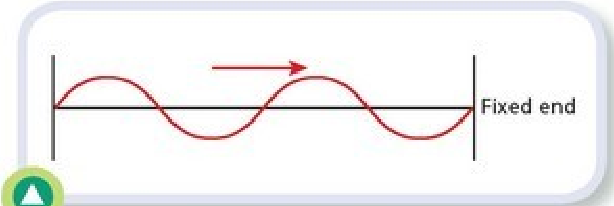

Figure 7.19 *A wave moves to the right*

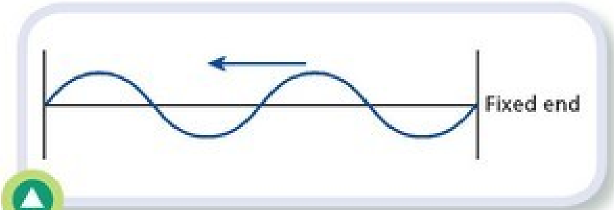

Figure 7.20 *The reflected wave moves to the left*

When these two waves meet they will do so in a way that creates interference (see Figure 7.21).

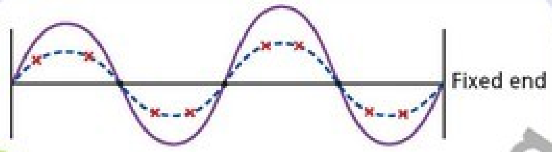

Figure 7.21 *The two waves meet and create a stationary wave*

When the peak of one wave coincides with the peak of the other, constructive interference in produced: the wave's amplitude increases. When the peak of one coincides with the trough of the other, we get destructive interference and the wave cancels itself out: the string is flat.

If a wave is applied to a string in such a way as to allow it to reflect along itself, there will always be interference between the two waves. However, only for very specific frequencies will the resultant pattern be a stationary wave: one in which the peak vibrations remain fixed in place. The lowest frequency that will create a standing wave within a body is known as the **natural frequency** of the body.

The natural frequency of a body is the lowest frequency standing wave that can be created within that body.

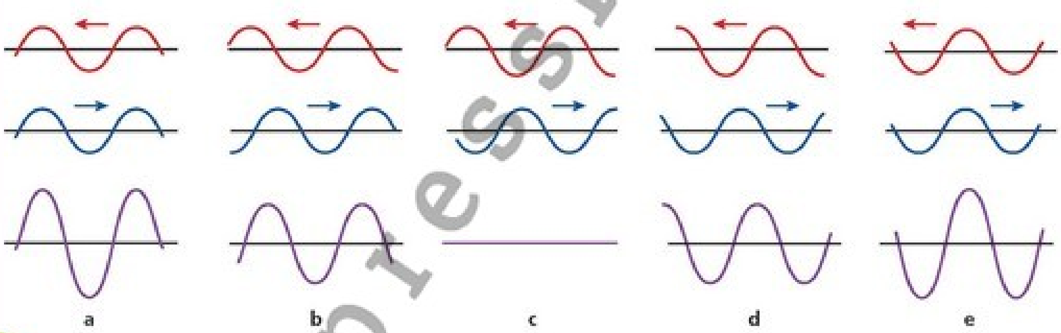

Figure 7.22 *The creation of a standing wave*

The points at which there is no movement in the string are known as **nodes**. The points at which we get the most movement are known as **antinodes**. Looking at Figure 7.23, you can see that the distance between any two nodes is equal to half the wavelength.

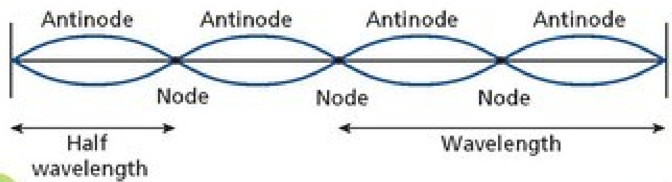

Figure 7.23 *The distance between nodes is half the wavelength*

Activity 7.4

Question

How can we create standing waves?

Equipment needed

frequency generator   vibrating contact   rubber band

Safety

- Be careful moving around equipment and securing the rubber band.

Conducting the activity

1. Set up a frequency generator, vibrating contact and rubber band, as shown in diagram.
2. Set the frequency generator so that the amplitude of waves is towards the maximum setting.
3. Set the frequency at 'low', only a few hertz.
4. Slowly increase the frequency, constantly observing the waves on the string.
5. At some frequency, f, a standing (stationary) wave will be created.
6. Continue to increase the frequency.
7. Record your observations.

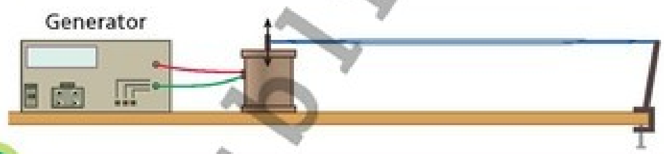

Figure 7.24 *Experimental apparatus*

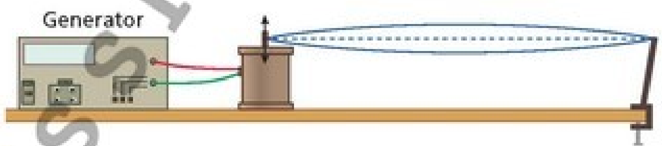

Figure 7.25 *The fundamental frequency (f)*

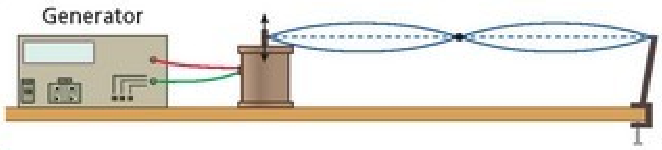

Figure 7.26 *Twice the fundamental frequency (2f)*

7.19 What did you observe?

7.20 What can you conclude from this?

The electromagnetic spectrum

In 1865, Scottish scientist James Clerk Maxwell (1831–1879) published a scientific paper called 'A Dynamical Theory of the Electromagnetic Field'. In it, he explained his ideas about how electric and magnetic fields are interconnected and how light travels as a wave through this electromagnetic field. He mentioned, almost in passing, that there was no reason to believe that the longest wave of visible light (red) was in fact the longest wave to move through this field. It was also entirely possible that there were waves with wavelengths far shorter than violet light also passing through the electromagnetic fields. The fact that we cannot see these waves, is no reason to believe that they do not exist.

Twenty years later, Heinrich Hertz carried out experiments that confirmed the existence of these waves, showing not only that they exist but that they reflect, refract and diffract just as light waves do. In the subsequent years, the full range of waves passing through the electromagnetic field has been thoroughly studied. We refer to this range as the **electromagnetic spectrum**. The different parts of the electromagnetic spectrum are shown in **Figure 7.27**.

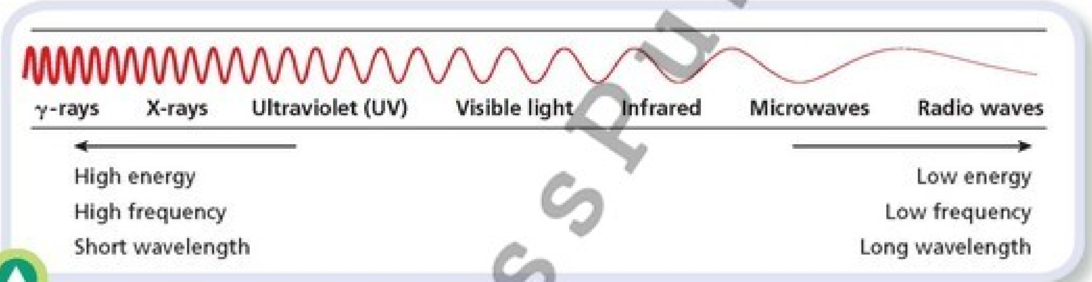

Figure 7.27 *The electromagnetic spectrum*

Different regions of the spectrum

It is important to understand that the division between the different parts of the spectrum are not generally very precise. The wavelengths just longer than red light are known as infrared. They have wavelengths anywhere between 750 nm and 1 mm.

This region of the spectrum is notable because all warm bodies – such as ourselves – tend to emit radiation in this range. Waves that are a little longer, from 1 mm up to 1 m, are microwaves. These are notable for their ability to cook food, for example – particularly food with a high water or fat content. Wavelengths above 1 m are radio waves.

However, taking the boundary line between the different regions to be 1 mm or 1 m is a little arbitrary, and the distinctions between the different regions of the electromagnetic spectrum are not at all clear-cut. Infrared radiation, for example, can also be used to heat food and is often used in restaurants to keep already cooked food warm until it is served. And microwave radiation is often picked up by nearby radios.

You might notice this if you leave a mobile phone – which uses microwaves – close to a radio. As the phone searches for a signal, you will probably hear its signal create interference on the radio.

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Remember that all the radiation has the same basic nature, travelling as waves through an electromagnetic field. All the waves demonstrate reflection, refraction and diffraction. **And they all travel through a vacuum at the same speed: the speed of light, or 300 000 000 m s^{-1}**. The differences between the various parts of the spectrum are all just by-products of the frequencies or wavelengths of those waves.

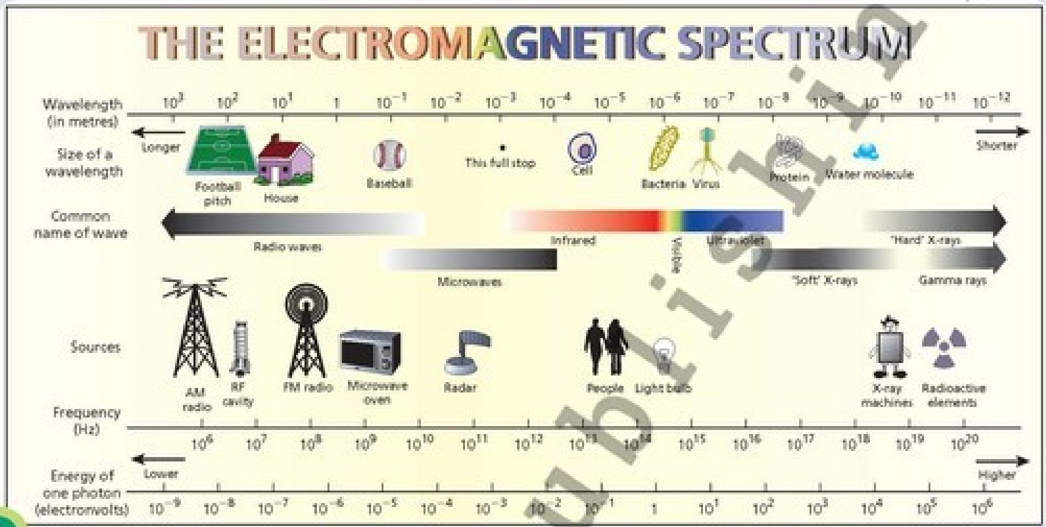

Figure 7.28 *A table showing the frequencies and wavelengths of parts of the electromagnetic spectrum*

Visible light

There is nothing remarkable about visible light. It consists of a tiny range of frequencies located about the middle of the spectrum, and very little distinguishes it from the ultraviolet at one end or from infrared at the other. What makes radiation from this region of the spectrum of particular interest to us is that when it strikes the retina at the back of our eye, it creates tiny electric currents that flow to the brain and create our sense of sight. In other words, what is unique to visible light has little to do with the radiation itself and far more to do with our ability to detect it.

Imagine how different life would be if we had the ability to 'see' infrared radiation. Some animals, such as cats, can do so. It gives them a great advantage in hunting at night, when they can detect the radiation given out by a warm-blooded animal even when that animal is otherwise hidden from them. However, if we could detect infrared radiation instead of visible light, it would mean that we would lose other abilities we take for granted, such as face recognition. Look at Figure 7.29. Do you think you would be able to recognise a friend if you saw something like that when you looked at them?

Let us look at each section of the spectrum in turn.

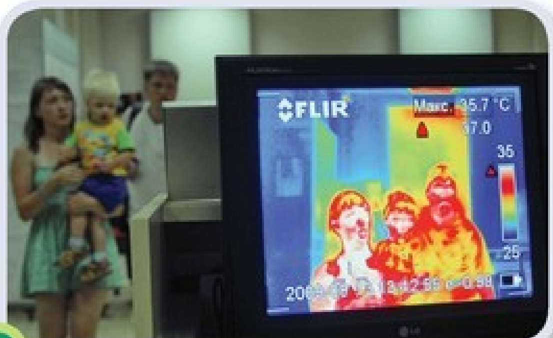

Figure 7.29 *An infrared image of passers-by*

Radio waves

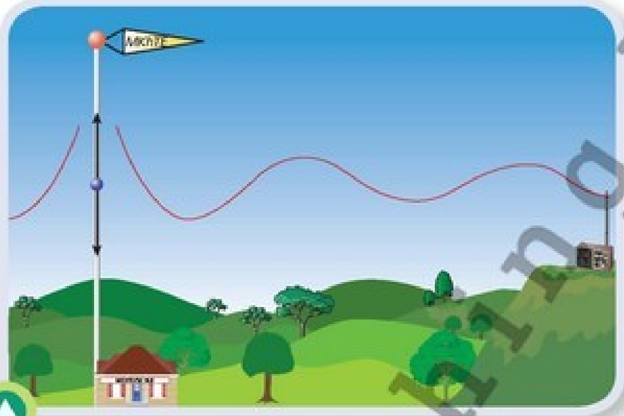

Figure 7.30 *The field created by the transmitter is picked up by the aerial in the receiver*

Radio waves are of great use to us in allowing modern communications and entertainment.

We do not generally distinguish between the wavelengths used for radio and for TV. They range in wavelength from one metre up to thousands of kilometres. When a radio station broadcasts a signal they create a constantly changing electric current in their **transmitter.** This current creates a wave that spreads through the electromagnetic field in the surrounding area. When this wave strikes the reception **aerial** in a radio (or TV) it creates a small current, which is increased through **amplification** and recreates the music or speech in the speakers to which we can then listen.

AM radio uses long waves – typically a few hundred metres in length. Like all long waves these diffract well when they encounter obstacles, and a single transmitter can cover an enormous area. If you scan through the AM region on a radio, particularly at night, you will often hear stations broadcasting from as far away as Russia or China, or even Germany. The reception is not perfect at such distances, and for this reason AM is often used for talk stations, and propaganda services, where the quality of reception is not of enormous importance. AM stands for **amplitude modulation.** This means that the wave is of a fixed wavelength or frequency, and what varies in the signal is the amplitude of the wave.

FM radio uses shorter waves, usually only a few metres or less in wavelength. Short waves like this do not diffract well around obstacles, so even strong transmitters still create a signal that can be detected only over a small range. However, the signal tends to be very clear when it is received, so FM is usually used for music radio. FM stands for **frequency modulation**. The wave consists of tiny variations in the frequency of the wave as it travels through space.

Microwaves

Microwave radiation ranges in wavelength from 1 mm up to 1 m. This range overlaps the range often thought of as radio waves, and the two types of wave have similar uses in communication. Most mobile phone signals, for example, are microwaves.

Figure 7.31 *A microwave oven uses microwaves for cooking food*

The ability of microwaves to heat our food might be considered surprising when you consider that microwaves are of a similar frequency, and therefore contain a similar amount of energy, to radio waves. This happens because of a phenomenon known as **resonance**, the transfer of energy between two bodies of the same natural frequency. We will learn more about this Module 8. Essentially what happens is that the energy in the microwaves is absorbed by water within a piece of food. As the water heats up, it very rapidly cooks the food around it.

Q U4 Understanding

7.21 **(a)** Who proposed, in 1865, the concept of the electromagnetic spectrum?
(b) Who confirmed the existence of the spectrum, experimentally, some 20 years later?
7.22 Give two properties common to all parts of the electromagnetic spectrum.
7.23 At what speed do electromagnetic waves pass through a vacuum?
7.24 Which has the highest energy: electromagnetic waves of high or low frequency?
7.25 **(a)** What is meant by the terms 'AM' and 'FM'?
(b) Which is more suitable for broadcasting over a large distance, and why?
7.26 Briefly explain how microwave ovens heat our food.

Infrared

Infrared light is emitted by all warm bodies (such as ours). We cannot see infrared light ourselves, but some cameras can detect it, and we can see the images produced as a result. These images are used for tracking objects in the dark. They also have medical uses. Areas of the body that are diseased may give off too little or too much heat, and this can be detected using infrared cameras.

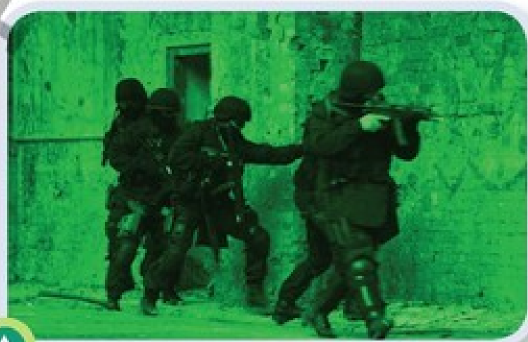

Figure 7.32 *Police during a tactical exercise, viewed through a night vision device, using infrared.*

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Activity 7.5

Question

How can we detect the presence of infrared radiation?

Equipment needed

A glass prism — A thermometer — A screen

Safety

- Be careful not to drop the glass prism.

Conducting the activity

1. Set up a prism, white light source and screen, as shown in Figure 7.33.
2. Hold a thermometer for a few minutes just beyond the red end of the spectrum.
3. Check the temperature recorded by the thermometer.

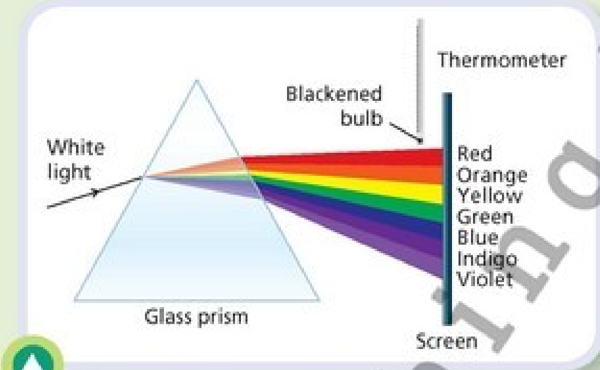

Figure 7.33 *The infrared has a heating effect*

Q Research R4 Research R5

7.27 Did you record a change in temperature?

7.28 What did you conclude from this?

Ultraviolet

Ultraviolet (UV) light causes sunburn; as well as being particularly unpleasant in its own right, sunburn can lead to skin cancer. Much of the UV radiation coming from the Sun is absorbed by the **ozone layer** at the top of the atmosphere, but ozone is destroyed by a type of gas called chlorofluorocarbons (CFCs), which are less used now but are still used in some technologies today. One of the main reasons it is so important to monitor the ozone layer and to maintain it, is that without it we would be exposed to greater amounts of UV radiation.

It is often difficult to say precisely why a particular cancer should be more common in some places than others and among the members of a particular population. Contributing factors could be the fact that, although some people are hardly overexposed to sunshine, they live at a latitude where the ozone layer is relatively thin and so are more exposed to UV radiation than they might expect. It could also have to do with skin types and a tendency to overexpose oneself to the Sun's rays, whenever they appear, without putting on sunscreen. Thankfully, that is a tendency less noted in recent generations.

UV also causes white objects to fluoresce or to shine brightly in the dark. This characteristic can be used to detect its presence.

Figure 7.34 *Sunburn is caused by UV radiation*

R2 R3

Activity 7.6

Question

How can we detect the presence of ultraviolet radiation?

Equipment needed

A quartz prism

A piece of white cloth

A screen

Did you know?

It is important to use a quartz prism in this activity, as UV does not pass through most types of glass.

Safety

- Take care not to drop the prism.

Conducting the activity

1. Set up a quartz prism, white light source and a screen, as shown in Figure 7.35, to produce a spectrum on the screen.
2. Hold a piece of white cloth just beyond the violet end of the spectrum. Observe what happens to the cloth.

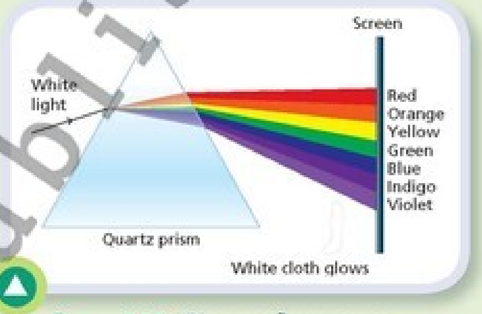

Figure 7.35 *UV causes fluorescence*

R4 R5

7.29 What did you observe during the activity?

7.30 What can you conclude from this observation?

The **greenhouse effect** is a natural phenomenon caused by the Earth being heated by energy coming from the Sun and then emitting infrared radiation into the atmosphere. In the past most of this radiation would escape into space, but it is increasingly blocked by the growing amount of carbon dioxide and methane (gases that trap heat) in the atmosphere. This enhanced greenhouse effect may be the main cause of global warming.

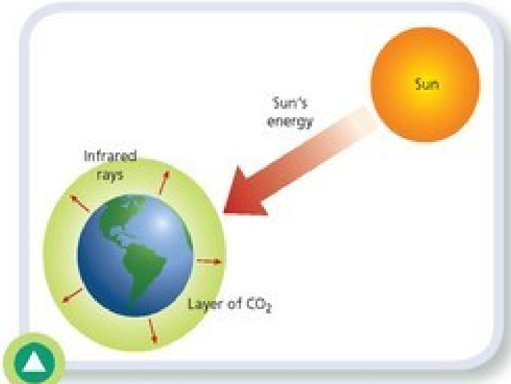

Figure 7.36 *The greenhouse effect*

X-rays

X-rays were discovered in 1895 by German physicist Wilhelm Röntgen (1845–1923), a discovery for which he won the first Nobel Prize in Physics in 1901. X-rays are a form of electromagnetic radiation, of very high energy. As such, they pose a considerable danger to anybody exposed to them without precautions. If overexposed, they cause a severe burn, similar to sunburn, and can cause cancer.

Figure 7.37 *A doctor examines a chest X-ray*

The very short wavelength of X-rays allows them to pass through many materials, such as skin and muscle tissue. They will not pass, however, through more dense material such as bone. This allows them to be used in medicine, where they can effectively create an image of internal organs or bones. The same effect allows them to be used for security purposes – in particular in airports.

It is important to remember that neither medical nor security applications would be practical if it was not for the fact that X-rays also affect photographic plates, allowing the images created to be recorded and analysed. X-rays will be studied in more detail.

Gamma rays

The electromagnetic waves of the highest energy are known as gamma-rays, or γ-rays. They are waves of extremely high frequency and short wavelength. To make a comparison, visible light typically has a wavelength measured in millionths of a metre. Gamma rays, however, typically have wavelengths close to one picometre, or one-trillionth of a metre (1/1 000 000 000 000 m). That is considerably smaller than most atoms.

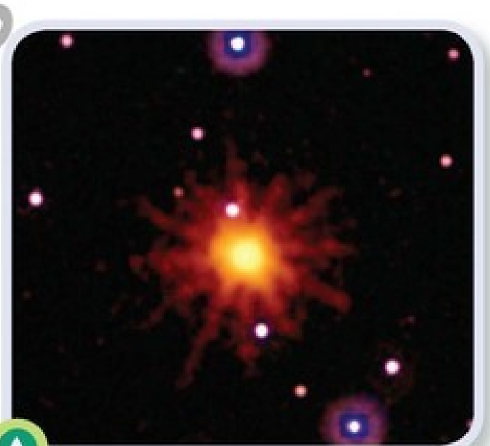

Figure 7.38 *A supernova explosion causes a bright gamma-ray burst*

As we will see, most electromagnetic radiation is released by electrons moving within atoms. Gamma rays, however, are released when the protons and neutrons rearrange themselves inside the nucleus of the atom. As such, they are associated with **nuclear** energy and are considered a form of radioactivity.

As with X-rays and UV rays, gamma rays pose very real dangers to us. They are of such high energy that they cause severe burns to those overexposed to them and tend to damage human cells, causing cancer.

Unlike most forms of radioactivity, gamma rays have very high penetrating power and can only be absorbed by thick layers of dense material such as lead.

Sample question 5

An electromagnetic wave has a frequency of 2×10^{14} Hz.

(a) To what part of the electromagnetic spectrum does it belong?

(b) What would be the wavelength of this wave?

Answer:

(a) With a frequency of 2×10^{14} Hz, the wave is in the near infrared range.

(b) $c = f\,\lambda$

$$\lambda = \frac{c}{f} = \frac{3 \times 10^{8}}{2 \times 10^{14}} = 1.5 \times 10^{6}\text{ m}$$

Sample question 6

An electromagnetic wave has a wavelength of 250 m. What is its frequency?

Answer:

$c = f\,\lambda$

$$f = \frac{c}{\lambda} = \frac{3 \times 10^{8}}{250} = 1.2 \times 10^{6}\text{ Hz}$$

Q Understanding **U4**

7.31 Assign waves of each of these wavelengths to an appropriate section of the electromagnetic spectrum: 10 mm, 250 m, 2 km, 1×10^{-7} m, 1×10^{-12} m.

7.32 If an X-ray has a frequency of 2×10^{18} HZ, what is its wavelength?

7.33 A wave has a frequency of 343 Hz and a wavelength of 1.1 m.

(a) What is its speed?

(b) Could it be an electromagnetic wave?

MODULE 8

Learning outcomes

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

- Describe the conditions necessary for the appearance of sound and sound distribution 9.2.5.15
- Compare sound characteristics with frequency and amplitude of a sound wave 9.2.5.16
- Describe sound resonance and provide applied examples 9.2.5.17
- Describe the nature and application of echoes 9.2.5.18
- Provide examples of the use of ultrasound and infrasound in nature and technology 9.2.5.19

Keywords

✔ vibration ✔ resonance ✔ tuning fork ✔ oscilloscope ✔ acoustics ✔ echo ✔ pitch ✔ loudness ✔ quality ✔ audible ✔ frequency ✔ ultrasound ✔ infrasound ✔ longitudinal ✔ wave

Sound

Sound is a form of energy. In particular, it is closely associated with kinetic energy, as all sounds are created by moving objects. Sometimes this movement is very obvious: clap your hands beside your ear and you will always hear a sound, and the harder you clap, the louder the sound will be. Sometimes the motion is more subtle: the vibrations of most speakers can be very small, but if you remove the protective covers and watch carefully they are usually visible on larger, bass speakers (often called 'woofers'). Sometimes the motion can be so small it is almost impossible to see directly: a concert flute works when the tiny vibrations in the player's upper lip are transmitted through the air inside. But whether the movement is obvious or not, it is always present.

Figure 8.1 *Tiny vibrations in a musician's lip create the sound in a concert flute*

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Activity 8.1

Question

How can we detect movement in a tuning fork?

Equipment needed

Tuning fork

Bowl of water

Safety

- Be careful not to spill the water to avoid the danger of someone slipping.

Conducting the activity

1. Set up a trough, almost filled with water, as shown in Figure 8.2.
2. Strike a tuning fork, and verify that it is producing a sound by very briefly holding it close to your ear.

Figure 8.2 *Tuning fork on surface of water*

3. Gently touch the tip of one prong of the fork to the surface of the water and note what happens.

Q Understanding Research U2 R5

8.1 What did you observe on the surface of the water?

8.2 What can you conclude about the tuning fork from this?

Sound as a wave

Thomas Young showed in his 1803 experiment that light is a wave by demonstrating that it possesses all the characteristics of waves: reflection, refraction, diffraction and interference. Something similar can be done with sound.

As with light, there is no question that reflection and refraction are present in sound. We know that sound reflects because of the existence of echoes – the use of echolocation in nature and sonar in technology rely on this fact. And there are a number of situations in which the refraction of sound waves is also obvious: most notably, sound waves travel better and appear louder on a cold night compared with a warm one. This is because the sound waves are constantly refracted downwards as they pass through the air, keeping them close to the ground and therefore audible.

However, just as was the case with light, the presence of reflection and refraction does not prove that sound is a wave. If sound was travelling by the transmission of tiny particles through space, they would still demonstrate something very close to both reflection and refraction. The key to establishing that sound is a wave is to show that it demonstrates diffraction and interference.

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Activity 8.2

Question

How can we show that sound is a wave?

Equipment needed

Signal generator
Speakers
Tuning fork

This experiment can be difficult to carry out in many rooms. If the sound waves reflect off the walls, ceiling and floor so that they then meet the waves coming from the speakers, there should still be interference between the waves, but there will no longer be a clear interference pattern formed.

Conducting the activity 1

1. Set up the apparatus as shown in Figure 8.3.
2. Set the signal generator to produce a steady sound of constant frequency. Because the same generator is connected to two speakers, coherent waves are created.
3. Walk along a line in front of the speakers, as indicated in Figure 8.3.
4. Note your observations.

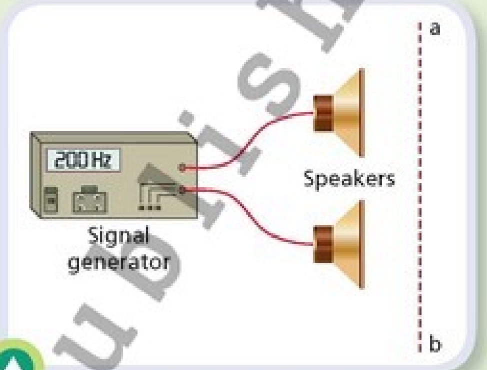

Figure 8.3 *Experimental apparatus*

Conducting the activity 2

1. Take a tuning fork and strike it so that it vibrates, giving out a clear steady sound.
2. Hold it to your ear and rotate it, as shown in Figure 8.4.
3. Note your observations.

Figure 8.4 *Method 2*

Q Understanding U2 Research R5

8.3 What did you notice about the sound in each version of the activity?

8.4 What two effects of sound explain your observations?

8.5 What can you conclude about sound?

Wave characteristics of sound

Sound shows all the characteristics of waves: reflection, refraction, diffraction and interference. Sound is a **longitudinal wave**. This can be proven by the fact that there is no method by which sound waves can be polarised, and longitudinal waves cannot be polarised.

Acoustics

The existence of echoes within enclosed spaces, as well as the tendency of waves to create either constructive or destructive interference when they meet, causes a great deal of difficulty in music venues. When a band is touring and playing a number of venues, they often repeat more or less the same set each evening. Despite their familiarity with the music, though, they still have to perform sound checks at every new venue, and they are heavily dependent on sound engineers to create a good sound.

This is because each venue has different acoustics: sound waves reflect off hard surfaces throughout the venue and tend to be absorbed by softer materials, such as curtains. As the sound waves will be reflected off a number of different surfaces this means that in some places in the venue the sound will be louder due to constructive interference and in other places quieter due to destructive interference. This effect is further complicated by the fact that some frequencies tend to travel and reflect more than others, so that in some places bass sounds might be too loud and in other places the higher-pitched notes could predominate.

There is no easy way to deal with this. Sound engineers do their best to create a good sound in each venue by carefully choosing the placement and alignment of the speakers and by varying the loudness of each set of frequencies for each of the musicians involved. Also, the presence of many people in a room affects the acoustics, so the sound engineers have to monitor the sound throughout the performance.

In purpose-built concert halls, a lot of these problems are dealt with at the design stage. One typical feature is that there should be soft fabrics on the rear of each seat, so that the sound will be absorbed in a similar way whether or not there is somebody sitting in it. Even with such careful planning, it is only when a hall is complete that the engineers will know how well their design has worked.

Figure 8.5 *A concert hall*

Q U2 Understanding

8.6 What do we normally call the reflection of a sound wave?

8.7 Why is it that we can hear around corners when we cannot see around the same corners?

8.8 Does sound travel as a longitudinal or as a transverse wave? What evidence supports your answer?

8.9 Briefly describe an experiment that proves that sound is a wave.

Characteristics of a musical note

The main characteristics of a musical note, and their corresponding wave characteristics are:

- Pitch, which corresponds to frequency
- Loudness, which corresponds to amplitude
- Quality, which corresponds to the presence of harmonics.

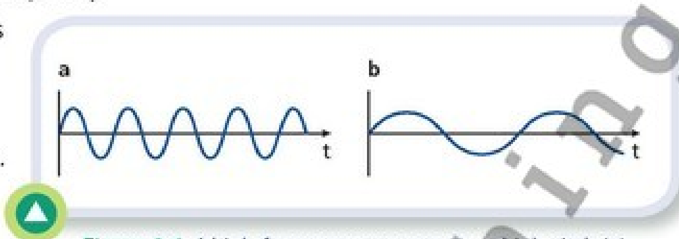

Figure 8.6 *A high-frequency wave creates a high pitch (a); a low-frequency wave creates a low pitch (b)*

Pitch

A high-pitched musical note, often described in musical terms such as **treble or soprano**, is one created by a high-frequency wave. A low-pitched, or **bass**, note is one created by a low-frequency wave.

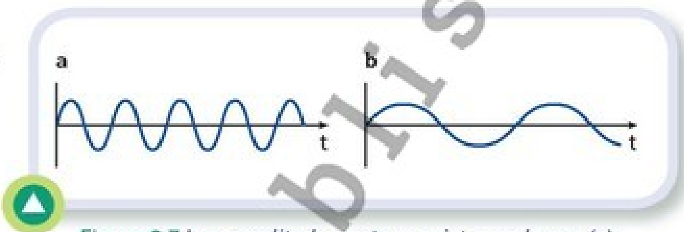

Figure 8.7 *Low amplitude creates a quiet sound wave (a); high amplitude creates a loud sound wave (b)*

To an extent, the loudness of a sound corresponds in a simple way to the amplitude of the wave producing it. Basically, bigger waves are louder. What we usually refer to as the volume of a wave, however, is a very difficult thing to measure in a meaningful way. We hear some frequencies better than others, for example, and it also requires an enormous increase in the amount of energy in a wave to create an audible difference.

Quality

Even a person without musical training is usually able to tell the difference between, say, the musical note A (440 Hz) played on a piano and the same note played on a guitar. Yet if both notes are of the same frequency and loudness, what is the actual difference in the sound waves that we hear so clearly? The answer lies in the fact that we rarely hear a single frequency note. Most instruments create a mix of frequencies alongside the note being played. These are called harmonics.

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Activity 8.3

Question

How can we investigate sound waves using an oscilloscope?

Equipment needed

Oscilloscope Frequency generator Speaker

Safety

- Take care not to damage the equipment.

Conducting the activity

1. Set up an oscilloscope, frequency generator and speaker, as shown in Figure 8.8.
2. Set the frequency at 1 kHz. Vary the volume so that the sound is clearly audible.

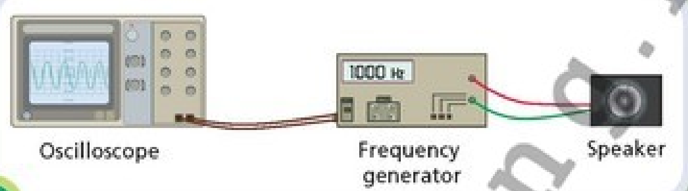

Figure 8.8 *Experimental apparatus*

3. Adjust the oscilloscope settings so that the sound wave is clearly represented on the screen.
4. Alternately increase and decrease the loudness of the sound and note how the amplitude of the sound wave varies with it.
5. Increase the pitch, or frequency, of the sound produced and note how the wave visible on the screen varies.
6. Note your observations.

Q Understanding U2 Research R5

8.10 What did you notice at higher frequency?

8.11 What did you notice at lower frequency?

8.12 What can you conclude from this activity?

Speed of sound

The speed of sound in air is usually taken as about 340 m s^{-1}, though this is not a fixed value. It varies according to temperature, humidity and atmospheric pressure. At 0°C, it is usually closer to 331 m s^{-1}. Sound travels much faster in liquids, and more so again in solids (see Table 8.1).

Table 8.1

Medium	Speed (ms^{-1})	Medium	Speed (ms^{-1})
Helium	970	Rubber	1600
Pure water	1493	Aluminium	5100
Sea water	1533	Diamond	12000

As with all waves, the speed of sound is related to the frequency and the wavelength by the expression:

$$c = f\,\lambda$$

This expression can be used to compare the wavelength, frequency or speed of sound between one medium and another.

Sonar and Ultrasound

Some animals can find their way through dark caves or water using echolocation, a form of sonar. This is a system in which high-frequency waves are sent out by the animal, which can also detect the arrival of reflections of this sound wave. It can then judge, using the delay in the arrival of the sound wave, the distance to the object from which the wave reflected.

A similar system is used by ships to detect the distance to the seabed. Some fishing boats also use the system to detect large shoals of fish.

Noise pollution

Noise pollution can be very dangerous to animals that use sonar. The baiji was a species of dolphin found only in the Yangtze River in China. It was almost blind but had developed a very sophisticated sonar system to find its way through the muddy waters of the river. The noise created by mechanical motors in the water, however, confused the animals, who could no longer hear the sound waves reflecting off the edges of the river or off other objects, such as boats. This caused the dolphins to collide with boats and be injured. In the 1950s there were at least 6000 baiji dolphins in the Yangtze. Today this species is almost certainly extinct.

Figure 8.9 *Motorised boats on the Yangtze River*

Ultrasound is a development of sonar. This is used most notably with pregnant women, providing a non-invasive way to 'look' inside the womb at the developing baby. With ultrasound, a high-frequency sound wave is transmitted and its reflection is detected, just as in sonar. Because sound travels at different speeds through different materials, such a wave transmitted through the womb allows a detailed picture of the baby to be created by a computer programmed to analyse the reflected wave.

Figure 8.10 *3-D ultrasound of a baby in the womb*

Did you know?

Infrasound is a sound with a frequency of less than 20 Hz; below the range that humans can hear. It can be detected using a microphone. Elephants use infrasound to communicate between herds.

Sample question 1

A sound wave has frequency 262 Hz and a wavelength of 1.32 cm. What is its speed?

Answer:

$c = f\lambda$

$= (262)(1.32)$

$= 345.84\ ms^{-1}$

Sample question 2

A sound wave is travelling at $330 ms^{-1}$ through air. Its frequency is 256 Hz. What is the wavelength of this wave?

Answer:

$c = f\lambda$

$\lambda = \frac{c}{f} = \frac{330}{256} = 1.29\ m$

Sample question 3

(a) A sound wave moves through a guitar string at $500\ m\ s^{-1}$ and creates a wave of wavelength 90 cm. What is its frequency?

(b) The string creates a sound wave in air that moves at $340\ m\ s^{-1}$. What is the wavelength of the sound wave as it moves through the air?

Answer:

(a) $c = f\lambda$

$f = \frac{c}{\lambda} = \frac{500}{0.9} = 555.6\ Hz$

(b) $c = f\lambda$

$\lambda = \frac{c}{f} = \frac{340}{555.6} = 0.61 m$

Q Understanding U_2

8.13 Does sound travel faster in a solid or in air? Does it tend to travel faster in warm air or cold air?

8.14 Figure 8.11 represents two musical notes travelling through air. Which one would have the higher pitch? Which one would be louder?

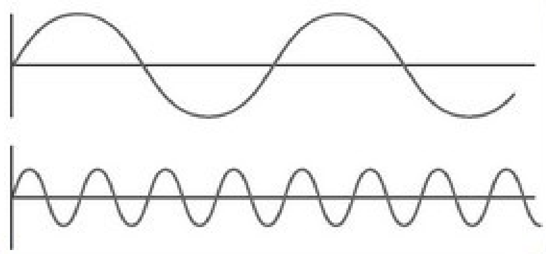

Figure 8.11

8.15 What is meant by the term 'sonar'? Give an example of its use.

8.16 A sound wave has wavelength 78.4 cm and a frequency of 440 Hz. What is its speed?

8.17 A sound wave is travelling at 331 m s^{-1} through cold air. Its frequency is 494 Hz. What is the wavelength of this wave?

8.18 **(a)** A sound wave is created in the vibrating string of a piano and has a frequency of 262 Hz (middle C). The wavelength of the wave moving through the string is 2 m. With what speed does the wave move through the string?

(b) In air, a sound wave of the same frequency is created and travels at 330 m s^{-1}. What is its wavelength in air?

Natural frequency and Resonance

Strike a piano key and you will hear a particular musical note, or frequency. Strike a different key and a different frequency is produced. Tap on the skin of a drum, and again a particular frequency is created. Larger drum skins generally create lower frequencies and smaller skins tend to produce higher frequencies. You can pluck a guitar string or blow into a saxophone or trumpet. In each case you hear a distinctive frequency. The same is true even with objects not designed as musical instruments: tap on the surface of your desk, or on a windowsill or on a door. In each case you will hear a particular sound. What you are hearing in each case is the natural frequency of vibration of the object in question. Remember that the frequency, or frequencies, at which an object will vibrate when disturbed is known as the **natural frequency of the body**.

The natural frequency of a body is the lowest frequency standing wave that can be created within that body.

Although we will often encounter a natural frequency as an audible sound, it does not have to be: a child's swing, for example, will oscillate at a particular frequency when pushed. You can push harder and it will move more rapidly, but it will still tend to complete the same number of 'swings' or oscillations every second – that is its natural frequency.

Investigating natural frequencies

If you cup your hands together over one ear and listen carefully, you will probably hear a gentle hissing sound. This is the sound you also hear when you hold a shell to your ear – children are sometimes told that it is the sound of the sea. The air moving about inside your hands is setting up a standing wave in a manner similar to how the air inside the wooden box of an acoustic guitar sets up a standing wave. If you change the shape you have created with your hands, you will notice that the sound either rises or falls in pitch. This is because the shape created by your hands has changed, and this new shape has a new natural frequency.

Resonance

When a body is vibrating at its natural frequency and is brought into contact with a body of the same natural frequency, a transfer of energy takes place. This is **resonance**.

> Resonance is the transfer of energy between two bodies of the same natural frequency.

Resonance is an interesting phenomenon with many applications, and it can be demonstrated in a number of ways (see **Activities 8.4** and **8.5**).

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Activity 8.4

Question

How can we demonstrate resonance?

Equipment needed

Materials for constructing support stands and pendulums as shown in diagram

Safety

- Take care not to drop weights to avoid injury.

Conducting the activity

1. Set up the apparatus as shown in Figure 8.12, with several pendulums of different lengths hanging from the same support. One pendulum should have the same length as the driving pendulum (A).
2. Set the driving pendulum in motion and observe what happens.
3. Record your observations.

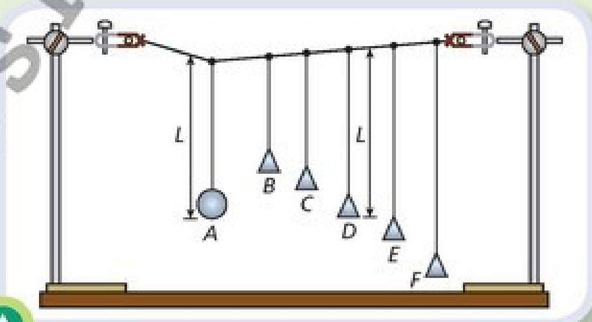

Figure 8.12

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8.19 What did you observe about the pendulum which was the same length as the driving pendulum?

8.20 Explain what caused the second pendulum to vibrate.

Activity 8.5

Question

How can we demonstrate resonance using tuning forks?

Equipment needed

2 similar tuning forks

Hollow sound boxes

Safety

- Be careful when handling the forks.

Conducting the activity

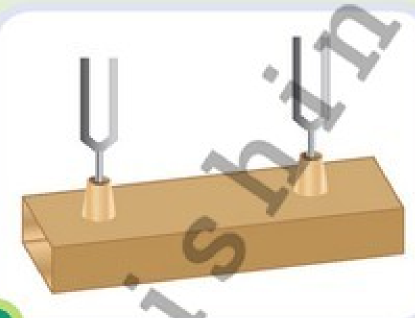


Figure 8.13

1. Set up two tuning forks of the same frequency on top of hollow sound boxes, as shown in Figure 8.13.
2. Strike one of the tuning forks so that an audible note is produced.
3. After a moment, use your hand to stop this tuning fork.
4. Note your observations.

8.21 What did you observe when you put your hand on the tuning fork?

8.22 How can you explain this observation?

Effects of resonance

Earthquakes

Over the last few decades there have been many incidences of videos being shot during earthquakes. If you examine even a small number of these you will generally see some variation on the common themes of people running for safety while ceilings, walls and large pieces of furniture fall around them. The forces unleashed in an earthquake are very large, so it is hardly surprising that so much damage can be caused. However, if you think about it for a moment, it may seem odd that the people running for safety are worried that falling debris may hurt them, not that they will be knocked over by the forces of the earthquake directly. What sort of force will cause a large building to fall over, but not a relatively small person?

The explanation is that the frequency of the vibrations produced in an earthquake tend to be about 2 Hz, close to the natural frequency of vibration of most types of stone and concrete. Due to resonance, the energy of the earthquake is transferred to the structure of the building itself, which essentially then shakes itself to the point where it collapses. The people inside are not made of stone and do not vibrate at the same frequency. As long as they can find a safe area, they will not be directly affected by the earthquake.

Music

Without resonance, most musical instruments would be barely audible. The vibration of a guitar string creates a very quiet sound, for instance, but through resonance, the air inside the box picks up the energy from the string and creates a much louder sound. Something similar happens in a piano. In other instruments, such as a saxophone, the tiny vibrations created in the reed are picked up by the air inside the rest of the instrument.

Percussionists also have to be aware of resonance. Many drum skins will vibrate, because of resonance, if another musician in the group plays the musical note 'E'. This creates an unpleasant effect, particularly in recorded music. To avoid the issue, percussionists are trained to hold their hand on the drum skin when they are not playing.

Figure 8.14 *A percussionist holds his hands on the drum skins when not playing*

Other effects

Divers learn to jump up and down on a diving board at the natural frequency of oscillation of that board. This causes it to oscillate to a much larger extent than can otherwise be achieved, creating a larger upward force when they dive.

TV and radio aerials pick up all transmitted signals available in the vicinity. When we tune to a particular station, we vary the electrical capacitance so that it will only produce a large oscillating voltage at a particular frequency.

Microwave ovens work using resonance. The water inside the food has a natural frequency of vibration close to that of the microwaves. They therefore pick up energy very efficiently from the oven and vibrate at high speed, creating heat and essentially cooking the food from the inside out.

Bridges often move slightly in the wind, but occasionally the movements can be exaggerated because of resonance. The collapse of the Tacoma Narrows Bridge near Seattle in 1940 is an example of this. Although some experts argue that the collapse was in fact caused by what they call 'forced oscillations', the effect is at least closely related to resonance. It was caught on video footage and still makes compelling viewing.

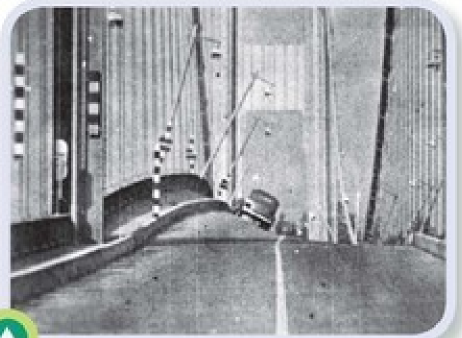


Figure 8.15

Understanding U2

8.23 Define the term 'resonance'.

8.24 Explain how resonance is involved in the damage caused by earthquakes.

8.25 Describe three other effects of resonance.

MODULE 9

The electron

Learning outcomes

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

- Understand the context and significance of the discovery of the electron
- Describe the dependence of thermal radiation energy on temperature 9.6.1.1
- Apply the Planck formula in solving problems 9.6.1.2
- Describe the phenomenon of the photoelectric effect and examples of its uses in technology 9.6.1.3
- Apply Einstein's formula of the photoelectric effect in solving problems 9.6.1.4
- Compare X-ray radiation with other types of electromagnetic radiation 9.6.1.5
- Define the spheres of the application of X-rays 9.6.1.6

Keywords

✔ cathode ✔ anode ✔ vacuum ✔ thermionic emission ✔ electronvolt
✔ fluorescence ✔ re-emit ✔ Planck's constant ✔ photoelectric effect
✔ threshold frequency ✔ wave-particle duality ✔ photon ✔ quanta

Modern Physics

When we talk about modern physics, we mean the discoveries made and theories developed since the late 1800s. This might not seem very 'modern', but remember that we are comparing this period to the discoveries made by people such as Newton and Galileo between three and four hundred years ago.

When you learnt about the structure of the atom and how it is made of protons, neutrons and electrons, you were learning about theories that are less than a century old, and that are in many ways not yet complete.

A lot of what we now know about physics we know only because of many of the experiments that were carried out in this period – such as those involving the cathode ray tube, and Rutherford's experiments with gold foil.

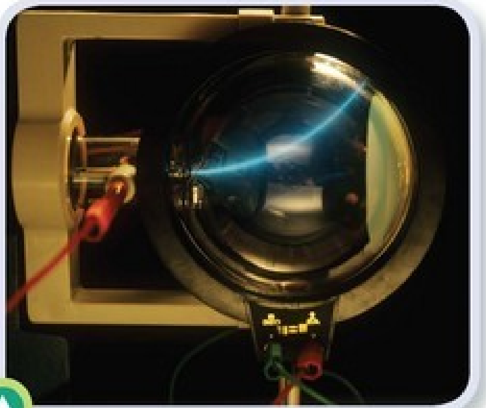


Figure 9.1 *Cathode ray tube, with the electron beam deflected by magnetic fields*

Cathode ray tubes

To understand the importance of the cathode ray tube (CRT), you have to understand that in the late 1800s people had no idea that protons, neutrons and electrons even existed. The idea that atoms could be broken up into smaller components had not yet been considered, and the existence of atoms on the scale that we now understand was still some years from being firmly established.

Interestingly too, although scientists had being studying electricity for hundreds of years and some cities already had electric lighting, nobody knew what exactly moved within electric circuits. In fact, most scientists believed that it was positively charged particles that moved, and for this reason electric circuits are still usually shown with current moving from positive to negative. An obvious way of trying to study electric current to determine what precisely is moving when a current flows would be to leave a gap in the circuit and see what might jump across this gap. We know that in ordinary circumstances a gap in a circuit means that no current flows, but it had occurred to English scientist and inventor Michael Faraday (1791–1867) and others that maybe this was due to the presence of air in the gap, and that the molecules in the air prevented any movement.

Faraday had tried to check this out using **evacuated tubes**– that is tubes from which the air has been removed – but the technology of the time did not allow anything like a full vacuum to be created, and his experiments led nowhere.

By the late 1800s, however, vacuum technology had improved sufficiently for this work to continue. A British scientist named William Crookes (1832–1919), in particular, contributed to designing an early version of the CRT, following the basic design shown in Figure 9.2.

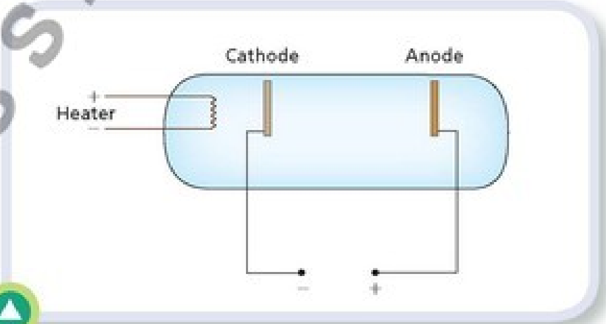


Figure 9.2 *The basic design of a CRT*

The negative connection, or electrode, is known as the **cathode** and the positive connection is the **anode**. These are terms that will be used a lot in the coming modules, and it is important to remember which is which.

The heater behind the cathode is very important. Without it no current flows. This is due to **thermionic emission**, which we will return to soon.

When the circuit was set up as shown in Figure 9.2, with enough of the air removed so that the pressure inside the tube was only a tiny percentage of atmospheric pressure, an electric current flowed even though there was a gap in the circuit. That in itself was interesting, but what Crookes and others noted was that when the current flowed, the glass behind the anode began to glow. Sometimes the small quantity of gas inside the tube also glowed. The glowing rays created in this way seemed to follow straight lines. As they seemed to originate in the cathode, they became known as **cathode rays**, and the device was therefore called the **cathode ray tube**.

Initially people thought that the cathode rays might be some form of electromagnetic radiation, but that was shown to be impossible when it was discovered that they did not travel quickly enough. Crookes added a paddle wheel to the centre of the device and showed that when it was struck by the rays it began to spin. This showed that the rays were made of particles that had to possess mass. Following this and other experiments, the following information about cathode rays was slowly assembled.

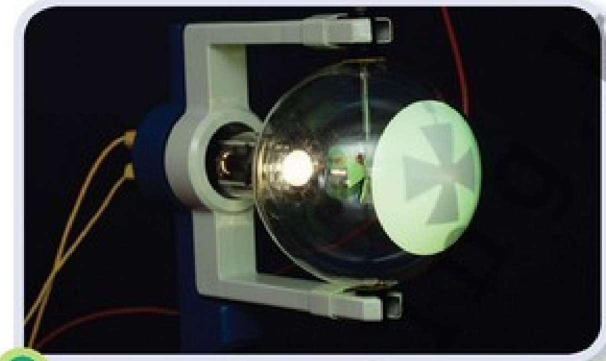


Figure 9.3 *A modern variation of the Crookes tube. On the application of an electric current, electrons are emitted from the cathode. They cause fluorescence on the screen. By placing a shape called a Maltese cross in front of the cathode, Crookes showed from the resulting shadow that cathode rays travel in straight lines*

Properties of cathode rays

- Cathode rays consist of electrons travelling at high speed.
- They travel in straight lines from the cathode to the anode.
- They cause certain substances to fluoresce (give out light) when struck.
- They have kinetic energy.
- They can be deflected by electric and magnetic fields.

Analysing all of this information, it was finally decided that the rays consisted of tiny, fast-moving, negatively charged particles. These particles became known as **electrons**.

Nowadays we would simply call them electron beams, but the name helps remind us that the main historic significance of the CRT is that it helped us to identify the electron and therefore to understand electric circuits more thoroughly.

The CRT also became a key feature for twentieth-century technology, as it was the basis for the design of TV and computer screens; it was also used in oscilloscopes.

Thermionic emission

All CRTs have a small electric heater behind the cathode. This is needed to release electrons from the cathode in a process known as **thermionic emission**.

Remember that the cathode is the negative electrode. That means that it is connected to the negative pole of whatever battery or power supply is being used. This creates a build-up of electrons on the surface of the cathode, and as these electrons are negatively charged, they are attracted to the positive charge on the anode nearby.

However, the electrons are still associated with atoms within the metal from which the circuit is built. This means that they cannot instantly leave the metal and travel across the gap to the anode. The heater provides energy in the form of heat, which is enough energy for the electrons to escape from the metal. Once they have done so they can travel across the gap to the anode.

Thermionic emission is the emission of electrons from the surface of a hot metal.

Q U6 Understanding

9.1 What is meant by 'thermionic emission'?

9.2 What are the properties associated with cathode rays?

9.3 What particle moves in cathode rays?

9.4 Name three applications of cathode ray tubes.

Mathematical treatment

The operation of the CRT can be analysed mathematically using formulae that you have encountered elsewhere. The energy gained by the electron as it travels towards the anode follows the same mathematical principles that govern any charged object moving through a potential difference. In particular, the following formula is useful:

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

where:

V = voltage applied to the tube
W = energy gained by the electron
q = charge on the electron

As the energy gained by the electron is kinetic energy (E_k), the formula can be reworked as:

$$E_k = q\,V$$

The electronvolt (eV)

The mass of an electron is so small (9.1×10^{-31} kg) that even when it is travelling at very high speed, its kinetic energy is still low. Even an electron travelling at half the speed of light has just over 1.02×10^{-14} J of kinetic energy. For this reason, scientists working in this area have devised a different unit of energy, the **electronvolt**, for convenience. It has the advantage of being more easily applied on this scale, but it is not an SI unit, and therefore cannot be inserted into formulae. When working with formulae, the quantity of energy involved should be in joules (J).

The **electronvolt** is the amount of energy gained or lost by a single electron when it moves through a potential difference of one volt (1 V).

A single electron moves because of the presence of a potential difference of 1 V (see Figure 9.4). The energy gained by the electron is the value of one electronvolt (1 eV), and will follow the formula:

$$E = q\,V$$

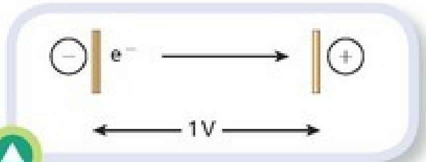


Figure 9.4 *The energy gained by the electron is 1e V*

We know the charge on the electron is 1.6×10^{-19} C, and the voltage here is 1 V.

Therefore,

$$1\,eV = 1.6 \times 10^{-19}\,J$$

It also helps to recall that the kinetic energy formula we encountered when studying mechanics still applies:

$$E_k = \frac{1}{2}mv^2$$

Sample question 1

An electron has a kinetic energy of 7 eV. What is that equal to in joules?

Answer:

To change from electronvolts to joules, we multiply by the charge on the electron:

$$7\,eV = 7 \times 1.602 \times 10^{-19}$$
$$= 1.12 \times 10^{-18}\,J$$

Sample question 2

What is the value of 1.8×10^{-16} J in electronvolts?

Answer:

To change from joules to electronvolts, we divide by the charge on the electron:

$$1.8 \times 10^{-16}\,J = \frac{1.8 \times 10^{-16}}{1.602 \times 10^{-19}}$$
$$= 1123.6\,eV$$

Sample question 3

If a voltage of 4000 V is applied to a cathode ray tube, how much energy does an electron gain as it moves from the cathode to the anode?

Answer:

$$E = q\,V$$
$$= (1.602 \times 10^{-19})(4\,000)$$
$$= 6.408 \times 10^{-16}\,J$$

Sample question 4

If a voltage of 2000 V is applied to a cathode ray tube, with what velocity does the electron reach the anode?

Answer:

$$E_k = qV$$
$$= (1.602 \times 10^{-19})(2\,000)$$
$$= 3.204 \times 10^{-16}\,J$$
$$E_k = \frac{1}{2}mv^2$$
$$\frac{1}{2}mv^2 = 3.204 \times 10^{-16}$$
$$v^2 = \frac{(2)(3.204 \times 10^{-16})}{9.109 \times 10^{-31}}$$
$$v = 2.65 \times 10^7\,ms^{-1}$$

Q U6 Understanding

9.5 Express the following quantities of energy in joules:

(a) 5 eV (b) 1.2 MeV

9.6 Express the following quantities of energy in electronvolts:

(a) 5×10^{-16} J (b) 8×10^{-19} J

9.7 If a voltage of 3000 V is applied to a cathode ray tube, how much energy do the electrons gain in travelling to the anode?

9.8 (a) If an electron is accelerated though a voltage of 7000 V, what energy does it gain before reaching the anode?

(b) With what velocity does it reach the anode?

X-rays

The history of science contains many examples of discoveries made by accident. Fleming's discovery of penicillin in 1928 is an oft-quoted example. Becquerel's discovery of radioactivity is one we will study in Module 10. Röntgen's discovery of X-rays is another.

Wilhelm Röntgen (1845–1923) was a German physicist who in 1895 was working with a cathode ray tube, trying to determine the nature of the rays, when he noticed that a sheet of material some distance from the tube had begun to fluoresce (shine). He knew that this effect could not be caused by cathode rays themselves, as they could not travel that far through the air.

As is always the case with these 'accidental' discoveries, the story would end there and be of no interest if Röntgen was not an experienced scientist who was always working to explain the unexplained and deepen his understanding. He spent 7 weeks working exclusively on this phenomenon. He learnt that whatever was causing the fluorescence could pass through human flesh, but not anything as dense as bone, and confirmed this by taking a photograph that showed the bones of his wife's hand (see Figure 9.5).

Figure 9.5 *This is the first X-ray picture, made by Wilhelm Röntgen. It shows the hand of his wife, who is wearing a ring*

He slowly came to understand that he had discovered a new type of electromagnetic radiation, which became known as X-rays (or 'Röntgen rays' in Germany). Their medical uses were very quickly identified, although there was some initial paranoia about the risks of being able to 'see' through solid objects and the attendant risks to one's privacy and modesty.

Properties of X-rays

- They are electromagnetic radiation, of very high energy.
- They pass through many materials, such as skin and muscle tissue.
- They do not pass through denser material, such as bone.
- They affect photographic film.

X-rays are still produced in a manner very similar to the way CRTs work. The main difference is that the anode is not hollow, and so it is struck by the fast-moving electrons. Generally speaking, the voltage applied to the machine is much higher than used in a CRT and there are no X- or Y-plates.

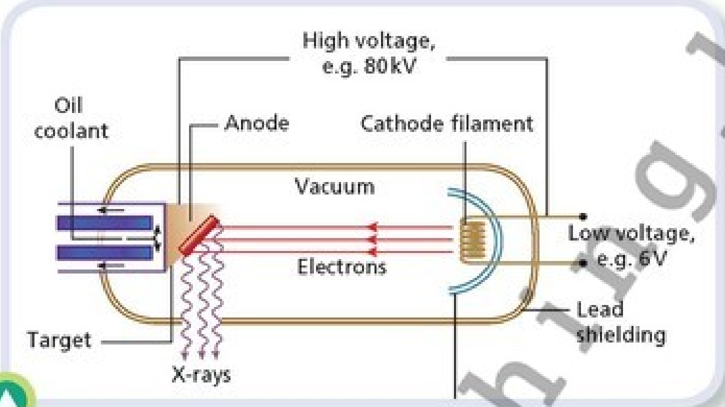


Figure 9.6 *An X-ray tube*

In a vacuum tube similar to that used for CRTs, a very high voltage, upwards of 100 kV, accelerates a beam of electrons to a high speed. These strike the anode, which absorbs most of their energy. Because the X-ray machine uses such high voltages, there is a considerable amount of energy involved, and the anode becomes very hot. For this reason, it must be made from a metal with a very high melting point, such as tungsten, and a cooling system must also be built into the design to stop it overheating.

A small amount of the electron's energy (often less than 1%) is absorbed by individual atoms within the anode, which hold on to this energy for a short period of time and then re-emit it in the form of X-rays.

Exactly how the energy of the electrons is converted into electromagnetic radiation is something we will study in Module 10.

These X-rays will travel in every direction, but X-rays are very high-energy waves and exposure to them is dangerous. For this reason, the device is covered by lead shielding in which a narrow gap is created. The X-rays that strike this gap create a beam of X-rays.

Applications of X-rays

We all know that X-rays can be used to 'photograph' inside the human body for medical purposes, and are used in airports for security reasons. However, they can also be used in a similar way to search for structural flaws in the construction industry.

It is important to remember that X-rays are a form of electromagnetic radiation with a frequency higher than that of ultraviolet (UV) radiation. UV is the radiation that causes sunburn, and exposure to X-rays can also cause very severe burns to human tissue, with an attendant risk of cancer.

We can be protected from X-rays using lead plates, which are usually built into the machines used in hospitals and also into the working areas of the radiographers, who would otherwise be at risk of repeated exposure.

Figure 9.7 *An X-ray of a wheeled suitcase*

Mathematical treatment

All of the mathematical formulae that were useful with the CRT are also helpful with X-rays. There is also one new formula that is very important, both here and in other areas of modern physics. It is known as the **Planck relation**, and it allows us to quantify the energy contained within electromagnetic radiation, and to link it to the frequency of the wave:

$$E = h f$$

where:

E = energy associated with electromagnetic radiation
f = frequency of the radiation
h = Planck's constant

Planck's constant is named after Max Planck (1858–1947), a German physicist who discovered in 1900 that energy cannot exist in just any quantity, but must always be found in one of a large number of specific values. This is the basis of **quantum theory**, which is the foundation of much of modern physics.

The value of Planck's constant is extremely small: $6.6260693 \times 10^{-34}$ J s. This is why 'quantum effects' are very hard to notice in everyday life.

Sample question 5

What energy value is associated with an X-ray of frequency 3×10^{17} Hz?

Answer:

$$E = h f$$
$$= (6.626 \times 10^{-34})(3 \times 10^{17})$$
$$= 1.99 \times 10^{-16}\ \text{J}$$

Sample question 6

An X-ray has energy of 8 keV.

(a) What is its frequency?

(b) What is its wavelength?

Answer:

(a) To change from electronvolts to joules, we multiply by the charge on the electron:

$$8\ \text{KeV} = 8\,000 \times 1.602 \times 10^{-19}$$
$$= 1.2816 \times 10^{-15}\ \text{J}$$

$$E = h f$$
$$f = \frac{E}{h}$$
$$= \frac{1.2816 \times 10^{-15}}{6.626 \times 10^{-34}}$$
$$= 1.934 \times 10^{18}\ \text{Hz}$$

(b)

$$c = f \lambda$$
$$\lambda = \frac{c}{f}$$
$$= \frac{2.9979 \times 10^{8}}{1.934 \times 10^{18}}$$
$$= 1.55 \times 10^{-10}\ \text{m}$$

Sample question 7

(a) If an X-ray machine operates with a voltage of 100 000V, how much energy do electrons gain in crossing to the anode?

(b) What is the maximum energy of the X-rays produced?

(c) What is their frequency?

Answer:

(a)
$$E = q\,V$$
$$= (1.602 \times 10^{-19})\,(100\,000)$$
$$= 1.602 \times 10^{-14}\,J$$

(b) The maximum energy of the X-rays = 1.602×10^{-14} J.

(c)
$$E = h\,f$$
$$f = \frac{E}{h}$$
$$= \frac{1.602 \times 10^{-14}}{6.626 \times 10^{-34}}$$
$$= 2.42 \times 10^{19}\,Hz$$

Q Understanding U6

9.9 What is an X-ray?

9.10 Name some of the applications of X-rays.

9.11 In the diagram of the electromagnetic spectrum in **Figure 9.8**, which of the letters A, B or C represent X-rays? What do the other letters represent?

γ-rays	A	UV	Visible	B	Microwaves	C

Figure 9.8

9.12 An X-ray has 3.9×10^{-15} J. What is its frequency?

9.13 If an X-ray machine operates with a voltage of 95 kV, how much energy do electrons gain in crossing to the anode? What is the maximum energy of the X-rays produced?

9.14 If an X-ray operates with a voltage of 110 kV, what is the maximum frequency of the X-rays produced?

The photoelectric effect

In 1888, German physicist Heinrich Hertz (1857–1894) noticed that when UV light was shone onto a negatively charged electroscope, the electroscope lost its charge. If the electroscope had a positive charge, however, the UV did not cause it to lose its charge. This became known as the **photoelectric effect**.

The **photoelectric effect** is the emission of electrons from a metal, caused by the incidence of electromagnetic radiation of suitable frequency.

Activity 9.1

Question

How can we demonstrate the photoelectric effect?

Equipment needed

Gold leaf electroscope | UV lamp | Zinc plate

Safety

- Be careful when handling the gold leaf electroscope and UV lamp.

Conducting the activity

1. Take a negatively charged electroscope, with a zinc plate covering the cap. Note that the leaves have spread out.
2. Shine a UV light on the zinc plate, and again observe what happens.
3. Note your observations.

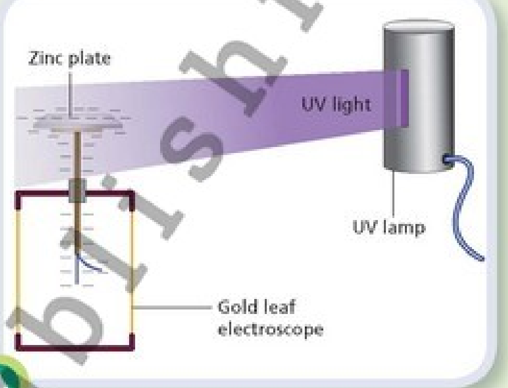


Figure 9.9 *The photoelectric effect*

9.15 What happened when a UV light was shone on the zinc plate?

9.16 What can you conclude from this observation?

It was subsequently discovered that the photoelectric effect can take place using visible light, and even infrared light, for some metals. However, we will concentrate on the more typical example of zinc for the moment.

The photocell

Initially the photoelectric effect was not considered of great importance. It was assumed that the electrons could escape from the metal because sufficient energy had been absorbed from the radiation for them to do so. It seemed that whatever was happening, it was similar to thermionic emission and was, in general, unsurprising.

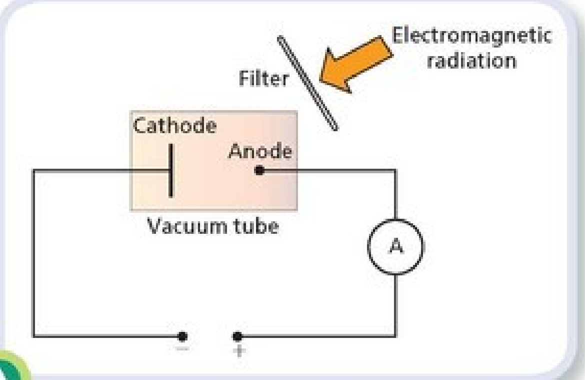


Figure 9.10 *A photocell used here to study the photoelectric effect*

When the effect was studied in more detail using a circuit like that shown in Figure 9.10, however, the effect was seen to be a little more intriguing. This circuit is the basis of the **photocell**.

In this arrangement both the frequency and intensity of the incident radiation can be varied:

- The frequency is controlled by the filter in front of the light.
- The intensity is controlled either by a dimmer-type switch, or by the distance between the energy source and the photocell.

This allows the exact frequency of the radiation required to create the photoelectric effect to be noted. This is known as the **threshold frequency** (f_0). For the metal in question:

- Below the threshold frequency, the photoelectric effect will not occur.
- Above the threshold frequency, the photoelectric effect will occur.

Details of the arrangement not shown here, allowed the researchers to measure both the number and the speed of the electrons as they crossed the tube to the anode. It was when they did so that they began to realise that the effect was not as easily explained as they had originally thought.

The researchers realised that although reaching the threshold frequency allowed electrons to escape and to cross the gap, further increasing the frequency did not increase the number of electrons that did so. What it did do, however, was cause the electrons to cross the gap at higher speed.

When they varied the intensity of the radiation (what we would think of with visible light as the 'brightness') they learnt that, above the threshold frequency, greater intensity did increase the number of electrons that escaped from the cathode and crossed the gap to the anode. In summary:

Table 9.1

	Under f_0, electrons do not escape	Over f_0 electrons escape
Increasing frequency	No effect on electrons	Increases the speed of electrons
Increasing intensity	No effect on electrons	Increases the number of electrons

The surprising thing about this was the different effects the intensity and frequency had.

With the simplistic explanation that the photoelectric effect was similar to thermionic emission, this would make no sense: increasing either the intensity or the frequency would increase the amount of energy available to the electrons on the cathode. On the one hand, why was it that, beneath the threshold frequency, increases in intensity could not make up for the energy missing, lost due to low frequency? On the other hand, above the threshold, why could the number of electrons not be increased by further increases in the frequency?

The theories of the time could not fully explain the effect, but nevertheless few considered it a major problem for science. Most of those who thought about it at all presumed that some bright young student would come along soon and see what everybody else was missing, and that their explanation would fit in with everything else that was already known.

Such a bright young man did indeed come along, but his explanation was so shocking that it changed the course of physics history and made life for scientists far more confusing than had previously been the case. It also forced them to doubt much that they had previously considered firmly established. The young man's name was Albert Einstein.

Albert Einstein (1879–1955)

Albert Einstein was born in Germany, although he later renounced his German citizenship to avoid military service and took Swiss citizenship instead. He remained a committed non-militarist throughout his life. As a teenager he was an erratic student, outstanding in some areas but lacking interest and commitment in others.

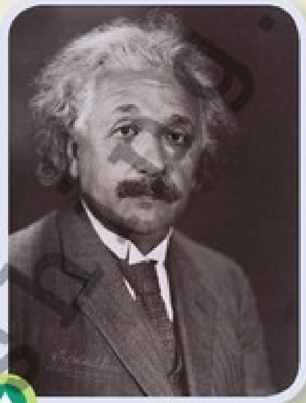


Figure 9.11 *Albert Einstein*

In 1900 Einstein qualified with a degree in maths and physics from the polytechnic in Zurich, but struggled to find the academic work he wanted to do. Instead he took a series of part-time teaching positions until he got a job as a civil servant in the Patent Office in Bern, where he had to evaluate the quality of the science behind patent applications.

Working by himself he completed a PhD, and continued to work in the evenings and weekends on his developing interest in theoretical physics. He submitted academic papers to a number of scientific journals, and in 1905 four of these works were famously published in the *Annalen der Physik*. In these papers he:

- established finally that atoms do exist as we now understand them
- introduced the idea of **special relativity**, showing that the speed of light is a constant but that time is not
- showed that mass is in effect a form of energy, and introduced the equation $E = mc^2$
- explained the photoelectric effect.

Initially these papers, revolutionary as they were, were ignored. However, Max Planck, on whose work Einstein had built, recognised the importance of the work on the photoelectric effect, and it was for this that Einstein finally won recognition – and ultimately the Nobel Prize.

Einstein moved to the United States later in life, and again changed nationality, to avoid living under the Nazi regime. He worked in Princeton University for the rest of his life and became a key figure in the development of quantum physics, if only because he refused to believe much of it was true. He once famously said of the theory, which depends to a large extent on probability, that 'God does not play dice with his creation'.

In 1939 a group of physicists were encouraging the United States to develop nuclear weapons and persuaded Einstein to use his prestige to write a letter to President Roosevelt warning him that the Germans might soon do so if he did not. A lifelong pacifist, he played no other role in the development of the new weapons and remained conflicted about his role in their design for the rest of his life.

Wave–particle duality

Einstein's explanation of the photoelectric effect rests on the idea that light – and all electromagnetic radiation – consists of tiny particles called photons. This was a revolutionary idea in itself, and it restarted an age-old argument in science as to the exact nature of light: a beam of particles or a wave?

Remember that:

- Isaac Newton, in the early 1700s, had argued that light is made up of particles, and all his study of optics was founded on this belief
- A century later, in 1803, Thomas Young showed with his famous double-slit experiment that light undergoes both diffraction and interference and is therefore a wave.

Young's experiment had stood the test of time and was firmly established. So when in 1905 Einstein said that light (and all electromagnetic radiation) consisted of particles, many scientists immediately rejected the idea. However, Einstein said that he was not contradicting Young. He accepted that light is a wave. But he argued that it also consists of particles.

This is a very confusing idea. Note that Einstein did not suggest that light was a wave passing through some particles, and nor did he argue that light was either really a wave that sometimes appeared to be a particle, or vice versa. He said that light is *fully* a wave and *fully* a beam of particles. How it can be both is quite simply beyond human intuition, and Einstein and everybody else studying this field really struggled with the concept. However, we must accept the evidence and do our best to understand. We describe this concept as the **wave–particle duality** of light.

Wave–particle duality describes the fact that electromagnetic radiation has the nature of both a wave and a particle.

Einstein's explanation

Einstein's explanation for the photoelectric effect works like this:

Electromagnetic radiation consists of a beam of **photons**. Photons are essentially little packets (or **quanta**) of energy that contain the characteristics of both waves and particles. In many situations the wave nature is more evident, but in the photoelectric effect, the particle nature is the more important.

Photons are the quanta, or packets, of energy associated with electromagnetic radiation.

The energy, E, in each photon is given by the Planck relation:

$$E = h f$$

where:

f = frequency of electromagnetic radiation
h = Planck's constant

When the UV radiation is shone onto the cathode, it consists of a beam of photons, or particles. As the beam hits the cathode, where a number of electrons has built up, each photon hits one electron and gives its energy to that electron. If the photon contains sufficient energy – i.e. if the radiation is above the threshold frequency – the electron can then escape from the metal and travel to the anode. We use the term 'work function' to describe this amount of energy.

As each photon can strike only one electron, increasing the energy (or frequency) of the photons does not increase the number of electrons released, and therefore does not affect the current. Any extra energy the photon has is given to the electron as kinetic energy, and this explains why an increase in frequency increases the speed of the electrons as they cross the tube, but not the number of electrons.

Only by increasing the number of photons – or the intensity of the radiation – can the number of electrons, and hence the current, be increased.

Mathematical treatment

Einstein's photoelectric law can be expressed mathematically as:

$$E_{in} = \phi + E_k$$

where:

- E_{in} = the energy of the incident proton
- ϕ = the work function of the metal (the energy required for an electron to escape from the cathode)
- E_k = the kinetic energy of the electron once it has escaped

Each of these terms can be expressed in other ways:

$$E_{in} = h\,f \qquad \phi = hf_0 \qquad E_k = \frac{1}{2}mv^2$$

Applications

Photocells can be used by professional photographers: the intensity of the natural light determines the size of the photocurrent, and this allows a detector in the camera to quantify how bright or dark it is. A similar device is sometimes used in cricket to decide if it has become too dark to play on.

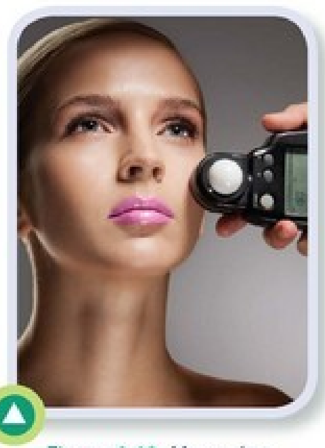


Figure 9.12 *Measuring light from studio lights before a photo shoot, using a photocell*

In industry, photocells are used to count the number of items on a conveyor belt: a constant beam of light shines across the belt and therefore a current flows until an object travels along the belt and breaks the beam of light.

Photocells are also used at electrically controlled gates so that the gates will not close when a car has not yet cleared the gateway.

Sample question 8

How much energy is contained within a photon of light of frequency 6×10^{15} Hz?

Answer:

$$E = h\,f$$
$$= (6.626 \times 10^{-34})\,(6 \times 10^{15})$$
$$= 3.976 \times 10^{-18}\ \text{J}$$

Sample question 9

The threshold frequency of a metal is 1.13×10^{15} Hz.

(a) What is its work function?

(b) What is the longest wavelength that would create photoemission?

Answer:

(a)
$$\phi = h\,f_0$$
$$= (6.626 \times 10^{-34})\,(1.13 \times 10^{15})$$
$$= 7.487 \times 10^{-19}\ \text{J}$$

(b)
$$c = f\,\lambda$$
$$\lambda = \frac{c}{f}$$
$$= \frac{3 \times 10^{8}}{1.13 \times 10^{15}}$$
$$= 2.65 \times 10^{-7}\ \text{m}$$

Sample question 10

The cathode of a photocell is made from a metal with a work function of 1.01×10^{-18} J. A photon of light with energy 4×10^{-18} J falls on the cathode. Will an electron be emitted, and if so, what is the maximum kinetic energy of the emitted electron?

Answer:

Energy in photon $= 4 \times 10^{-18}$ J

Energy required for photoemission $= 1.01 \times 10^{-18}$ J

As $4 \times 10^{-18} > 1.01 \times 10^{-18}$, photoemission will occur.

$$E_{in} = \phi + E_k$$
$$E_k = E_{in} - \phi$$
$$= 4 \times 10^{-18} - 1.01 \times 10^{-18}$$
$$= 2.99 \times 10^{-18}\ \text{J}$$

Sample question 11

A photocell has a work function of 1.6 eV. If light of wavelength 289 nm falls on the cathode, what is the maximum kinetic energy of the emitted electrons?

Answer:

$$c = f\,\lambda$$
$$f = \frac{c}{\lambda}$$
$$= \frac{2.9979 \times 10^{8}}{289 \times 10^{-9}}$$
$$= 1.04 \times 10^{15}\ \text{Hz}$$

$$\phi = 1.6\ \text{eV}$$
$$= (1.6)(1.602 \times 10^{-19})$$
$$= 2.56 \times 10^{-19}$$

$$E_k = E_{in} - \phi$$
$$= (6.626 \times 10^{-34})(1.04 \times 10^{15}) - 2.56 \times 10^{-19}$$
$$= 4.33 \times 10^{-19}\ \text{J}$$

Q U6

9.17 Briefly explain the photoelectric effect.

9.18 What is meant by the term 'threshold frequency'?

9.19 What is meant by the term 'photon'?

9.20 Explain the term 'wave–particle duality'?

9.21 A photon contains 41 eV of energy.

- **(a)** What is this in joules?
- **(b)** What is its frequency?

9.22 The threshold frequencies of three metals are given below. Find the work function of each.

- **(a)** Zinc: 1.038×10^{15} Hz
- **(b)** Gold: 1.23×10^{15} Hz
- **(c)** Aluminium: 9.85×10^{14} Hz

9.23 **(a)** If the work function of a metal is 2.7 eV, what is the threshold frequency?

- **(b)** What is the longest wavelength that would cause photoemission?

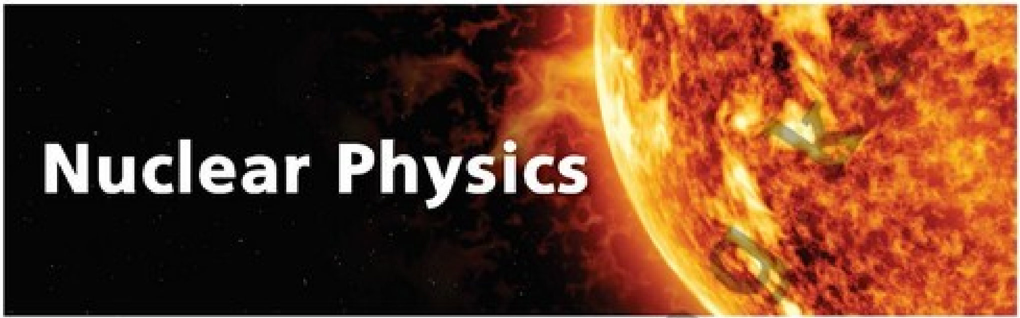
9.24 **(a)** If the work function of a metal is 3.2 eV, what is the threshold frequency?

- **(b)** If light of energy 6×10^{-19} J strikes the cathode and photoemission occurs, what is the maximum kinetic energy of the emitted electrons?

9.25 If light of wavelength 240 nm falls on a metal with a work function of 1.2 eV, what is the maximum kinetic energy of the emitted electrons?

MODULE 10

Nuclear Physics



Learning outcomes

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

- Explain the nature and properties of α, β and γ radiation 9.6.2.1
- Describe Rutherford's gold foil experiment 9.6.1.7
- Describe the properties of nuclear force 9.6.1.8
- Describe the process of nuclei disintegration 9.6.1.9
- Perform calculations using nucleus binding energy formula 9.6.1.10
- Solve equations relating to the laws of charge and mass number in nuclear reactions 9.6.1.11
- Explain the probabilistic nature of radioactive decay 9.6.2.2
- Apply the law of radioactive decay in solving problems 9.6.2.3
- Describe the conditions under which a radioactive chain reaction occurs 9.6.2.4
- Explain the working principles of a nuclear reactor 9.6.2.5
- Compare nuclear fission and nuclear decay 9.6.2.6
- Provide examples of applications of radioactive isotopes 9.6.2.7
- Outline different methods of protection against radiation 9.6.2.8

Keywords

✔ collision ✔ deflect ✔ repel ✔ ion ✔ isotopes ✔ proton ✔ neutron ✔ quantum leap ✔ electromagnetic spectrum ✔ spectroscopy ✔ radioactive ✔ transmutation ✔ stable ✔ decay ✔ ionise ✔ half-life ✔ nuclear fission ✔ chain reaction ✔ critical mass ✔ fuel rods ✔ nuclear fusion

Rutherford's gold foil experiment

By the early 1900s, the world of physics had become very complacent. Many scientists thought that they had come close to the point where all that could be discovered had been discovered: they believed that soon all scientific knowledge would be complete and ready to pass down through the generations.

That complacency was shaken by Einstein in 1905, and by his explanation for the photoelectric effect in particular. And in 1911 a young New Zealand-born physicist went to Cambridge and carried out an experiment that astonished the world of scientists and opened up a field of study that is still far from complete. That physicist was Ernest Rutherford (1871–1937).

To understand fully the significance of Rutherford's experiment, it is important to remember that you already know more about the atom than Rutherford did when he performed the experiment in 1911, even though he was already a Nobel Prize winner. Rutherford at that time knew nothing about protons and neutrons, and he would never have even considered the idea that the atom had a central nucleus around which the electrons were in orbit. We know all of that because of the work that Rutherford, and others, did in the early years of the twentieth century.

The atom

The idea that all matter is made up of atoms, and that each of the 92 naturally occurring elements have a different type of atom, was well-established by the end of the 1800s.

Initially the concept had been that the atom could not be broken up, that it was the smallest possible structure, but this idea had been challenged by the discovery of the electron in the last years of the nineteenth century.

It was understood that the electron was negatively charged, but it was also known that the atom had no charge overall, so it seemed reasonable that there must also be some positive charge in there. However, what the inside of an atom might look like was still a mystery.

In 1904, British scientist J.J. Thomson (1856–1940) had proposed what became known as the 'plum pudding' model of the atom. A plum pudding is a type of fruit cake traditionally eaten at Christmas, and for reasons seemingly lost to history the custom was to cook them in a spherical shape.

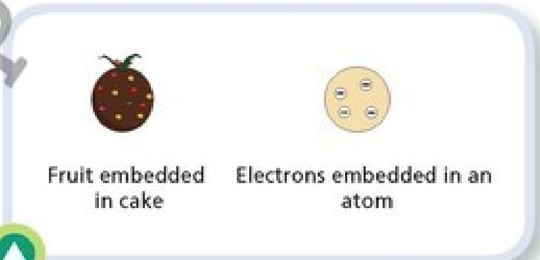


Figure 10.1 *The plum pudding model of the atom*

Thompson suggested that the electrons were embedded in the atom in much the same way as the fruit is embedded in pudding, meaning that they were more or less randomly distributed. He also suggested that the positive charge was spread throughout the structure of the atom, comparable to the 'cake' part of the pudding.

This still left a lot of unanswered questions, not the least being what exactly the positively charged material was.

Rutherford wanted to probe the inside of the atom to learn more. He decided to use the newly discovered phenomenon of radioactivity to do so. In particular he decided to use alpha particles, which he knew were emitted from radium. All that was understood about alpha particles at that time was that they were small, very fast moving and positively charged. He hoped they would have sufficient energy to penetrate any atoms with which they were in collision.

Rutherford organised a radium source near to a thin sheet of gold foil. He also had a zinc sulfide screen that would give off a little flash of light, or **scintillation**, whenever it was struck by an alpha particle, allowing him to see where they had gone. He chose gold because it can be pressed very thin – so thin that it is only a few atoms from front to back – while still retaining some strength.

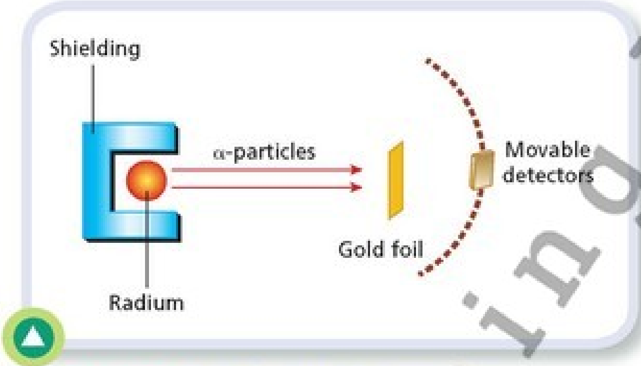


Figure 10.2 *Rutherford's gold foil experiment*

He expected that most of the alpha particles would travel straight through the atoms in the gold sheet, but that some of them might be slightly deflected by the positive and negative charges within the gold atoms. By seeing how the alpha particles were deflected, he hoped to be able to figure out how the charges were distributed, and perhaps learn more about the material from which the atom was built.

Rutherford actually had limited hopes for the success of the experiment and assigned the work to two junior scientists in his team, Hans Wilhelm Geiger (1882–1945) and Ernest Marsden (1889–1970). Geiger later became famous for his part in designing a machine to detect the presence of radioactivity.

In the event, the results were very surprising. They found that a large majority of the alpha particles did indeed pass straight through the gold atoms, but that a sizeable minority of them were deflected through large angles – and, most surprisingly, a small number were repelled from the gold back towards the source.

The most interesting result was the very small percentage that seemed to bounce back. Rutherford compared it to firing artillery shells at a piece of tissue paper and seeing some of them bounce back. If you were to see such a thing, you would hardly remark that it only happened a few times out a thousand – it clearly should never happen. Indeed, so surprised was he that he insisted on the experiment being repeated over and over again with all the scientists in his team of researchers carrying out the experiment separately. They all agreed that a small percentage of alpha particles were indeed bouncing back from the gold sheet.

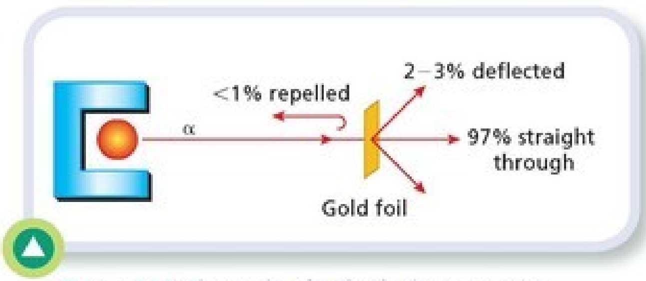


Figure 10.3 *The results of Rutherford's experiment*

It took a long time to make sense of the experimental findings, but eventually Rutherford realised that the only way the positively charged alpha particles could rebound is if they were being repelled from another, comparable, positive charge. And the fact that it happened infrequently suggested that this area of positive charge was very small compared to the overall size of the atom. This small area of positive charge become known as the **nucleus** and soon it was discovered that the nucleus contained both positively charged protons and electrically neutral neutrons.

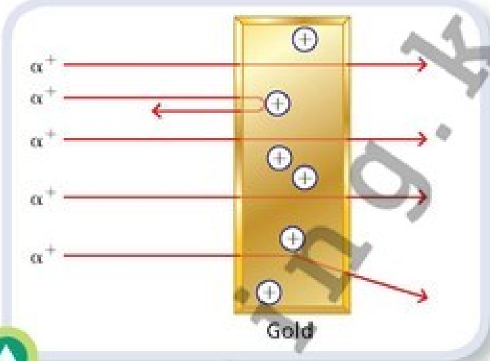


Figure 10.4 *The conclusion of Rutherford's experiment*

Many other scientists became involved, and Danish scientist Niels Bohr (1885-1962) came up with the idea that the electrons surrounded the nucleus in shells, rotating around it in much the same way as the planets orbit the Sun.

In this way, what is known as the **Rutherford–Bohr model of the atom** was created in 1913. Although later experiments showed that this model had a few flaws and that the arrangement and structure of the particles within the atom is a little more complicated than initially thought, it is still the basis of our understanding of the atom today.

In this model:

- Most of the atom is empty space
- There is a positively charged nucleus, which contains the protons and neutrons
- The nucleus is surrounded by several 'shells' of negatively charged electrons.

In summary:

- Rutherford fired alpha particles at gold foil:
  - 97% went straight through
  - A little over 2% were deflected through various angles
  - A small number, less than 1%, were repelled back towards the source.
- From this Rutherford realised that:
  - The atom is mainly empty space
  - The atom contains a small positively charged nucleus
  - The electrons move around the nucleus in shells.

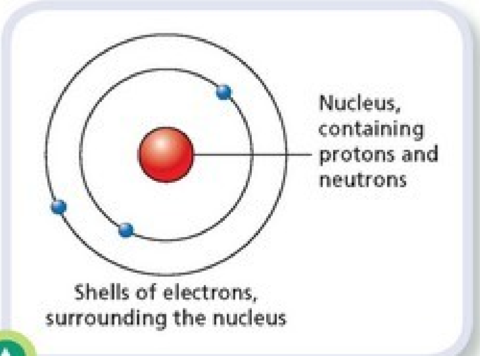


Figure 10.5 *The Rutherford–Bohr model of the atom*

It is worth stressing just how small the nucleus is. The diameter of an atom is 100 000 times larger than that of the nucleus. This means that it is effectively impossible to draw an atom to scale. If the atom had a radius like that in Figure 10.5, the nucleus would in fact be invisibly small. If the atom was the size of a football stadium, the nucleus would be about the size of a football at the centre of the pitch.

Q U6 S1

10.1 Briefly outline the procedure Rutherford followed in the gold foil experiment.
10.2 What were the results of the experiment?
10.3 How was the presence of alpha particles detected?
10.4 What was the significance of the experiment?

Atomic number and Mass number

Because of Rutherford's experiment, we now know that all atoms are built from protons, neutrons and electrons. The number and arrangement of these subatomic particles within the atom is what distinguishes the atoms of one element from another. We use the atomic and mass numbers to represent this information.

Each element is defined by its **atomic number** – the number of protons in the nucleus. In a neutral atom, the number of electrons equals the number of protons and they are arranged within the shells, or **energy levels**. If electrons are lost or gained by the atom, it takes on a positive or negative charge and is then known as an ion.

- The atomic number is the number of protons in the nucleus of an atom.
- An ion is an atom that has gained or lost electrons and has an overall electric charge.

The **mass number** tells us the total number of protons and neutrons in the nucleus.

This can vary even between atoms of the same element. Most hydrogen atoms, for example, have a mass number of 1 and have no neutrons. A small number of hydrogen atoms, however, have either one or two neutrons and have mass numbers of 2 and 3, respectively. When this happens we say that they are **isotopes** of the same element.

Isotopes are atoms of the same element that have different numbers of neutrons and therefore different mass numbers.

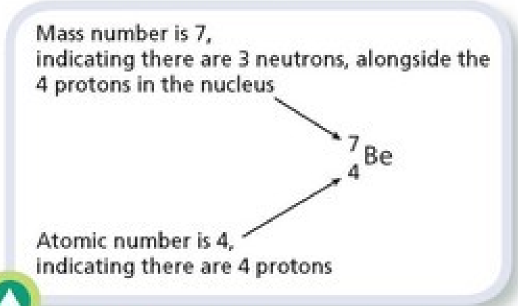


Figure 10.6 *Mass number and atomic number*

Atomic spectra

In Module 9 you learnt about X-ray machines. You saw how the anode absorbs energy from the electrons that strike it and then, a short period later, emits this energy in the form of X-rays. However, we did not consider how that is done. How is the kinetic energy of the electron converted into electromagnetic radiation?

The Rutherford–Bohr model of the atom allowed that to be explained, and in doing so showed how electromagnetic radiation is usually created. It also created the valuable scientific technique of spectroscopy, which is very useful in identifying the materials in a sample.

One subtlety of the arrangement of electrons in the atom that is often not discussed, is that not all the shells, or energy levels, are the same. The energy levels close to the nucleus contain electrons with less energy than those further out, and the quantity of energy held by electrons in each level is very precise and fixed by nature.

- Energy levels are the fixed values of energy that an electron can hold within an atom.
- Lower energy levels are close to the nucleus; higher energy levels are further away from the nucleus.

If an electron in a low-energy level gains energy, it instantly moves to the appropriate outer level. This movement is known as a **quantum leap**.

When an electron moves to an outer level, it leaves a gap in a lower level. After some time – usually a very short period of time – it falls back down to the lower level. When it does so, it has to shed the extra energy it had briefly contained. This energy is emitted as electromagnetic radiation.

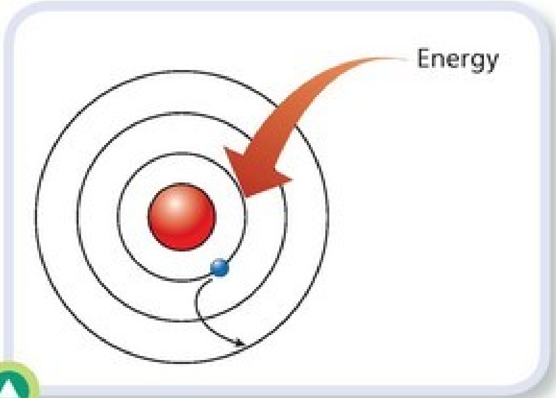


Figure 10.7 *The electron gains energy and jumps to a higher energy level*

We know from the electromagnetic spectrum that there are many different forms of electromagnetic radiation.

The spectrum ranges from the low-energy, low-frequency extreme of the waves used for radio and TV signals, up to the high-frequency, high-energy gamma rays. Essentially, the low-energy parts of the spectrum are created when an electron moves between two energy levels that are close together. As the gap between the energy levels is small, the energy emitted is low.

When an electron jumps from a very high level to a much lower one, the amount of energy released is very large, and in that instance a high-energy, high-frequency wave is created, such as an X-ray.

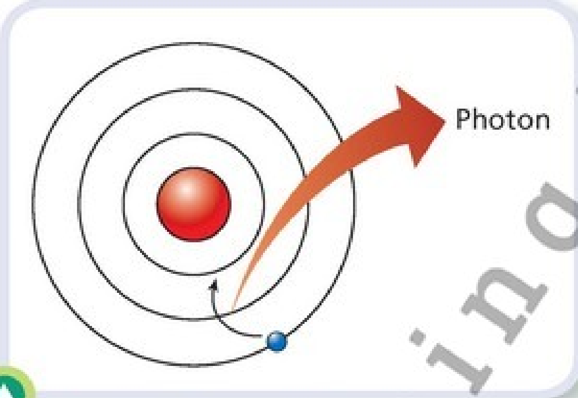


Figure 10.8 *The electron falls to a lower energy level, emitting electromagnetic radiation as a photon*

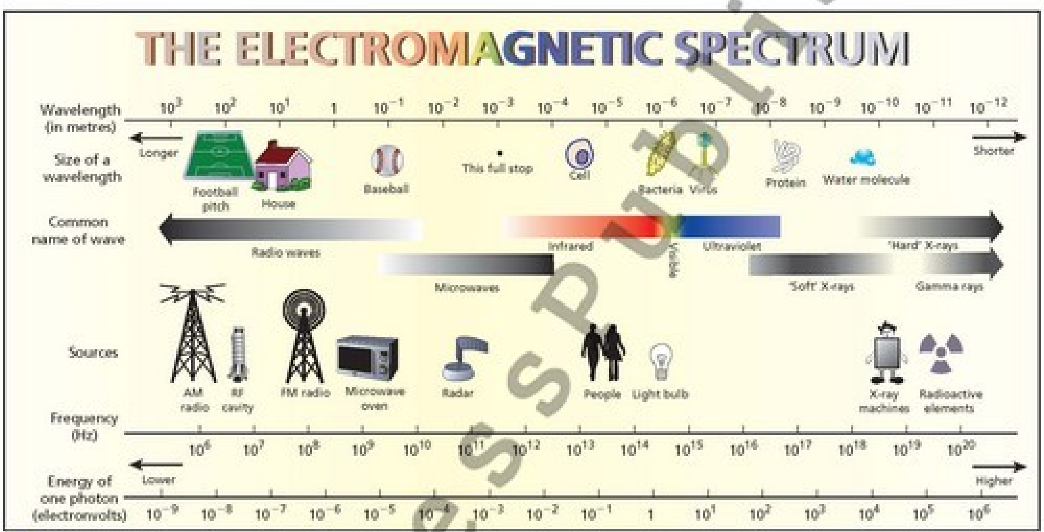


Figure 10.9 *The electromagnetic spectrum*

When a current flows through a conventional light bulb, the metal in the filament becomes very hot. This heat energy is distributed throughout the metal, and some of it will come to individual electrons, which move to a range of higher levels. When these electrons begin to fall down again to the lower levels, many waves are created, corresponding to all the colours of the spectrum of white light. This is why the bulb gives out light.

Figure 10.10 *The movement of electrons between energy levels creates the light in this bulb*

Spectroscopy

Figure 10.11 *The emission spectrum of hydrogen*

Every material when given additional energy, through heat, an electric current or any other means, gives out a range of colours of light. Because the arrangement of electrons is different for every element, each material creates a specific mix of colours. If we examine the light being emitted by a material when this happens, using a spectrometer, we can identify the elements contained within it in Figures 10.11 to 10.13. This is known as **spectroscopy**. It is, in a way, a form of atomic fingerprinting. To properly distinguish between the spectra of different elements, a sample under study first has to be turned into a gas – most solids and liquids create what we call continuous spectra, which contain all colours.

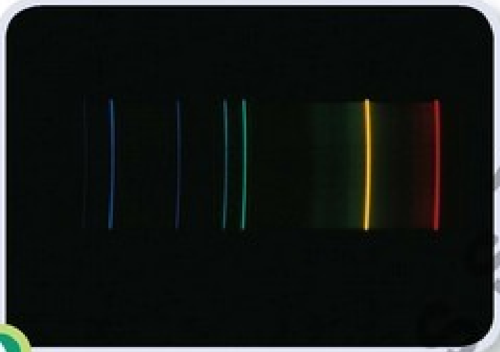


Figure 10.12 *The emission spectrum of helium*

Figure 10.13 *The emission spectrum of cadmium*

Q Understanding U6

10.5 Define the terms 'atomic number' and 'mass number'.

10.6 What are isotopes?

10.7 State the number of protons and neutrons in each of these neutral atoms:

(a) $^{35}_{17}Cl$ (b) $^{207}_{82}Pb$

10.8 State how many protons and neutrons there are in each of these isotopes of carbon:

(a) $^{14}_{6}C$ (b) $^{12}_{6}C$ (c) $^{13}_{6}C$

10.9 The spectra for an atomic element is shown in Figure 10.14. By comparing it to Figures 10.11 to 10.13 state which element you think it is.

Figure 10.14

Radioactivity

All of the protons in an atom are found inside the nucleus. The radius of the nucleus is about 10^{-15}m, so this means that there is a very large build-up of charge inside a very small space. As all of the protons have the same positive charge, and as each one of them will therefore be repelled by all of the other protons in the nucleus, it is clear that there is a large force trying to break the nucleus apart.

The reason that nuclei generally do not break apart is because of the presence of the **strong nuclear force.** This is a very strong attractive force, with a very short range, that all the particles in the nucleus feel for each other. As long as the total attractive force created in this way is greater than the repulsive force between the protons, the nucleus will stay intact.

For many nuclei, though, this is not the case: the repulsive force becomes greater than the attractive force and the nucleus disintegrates. When it disintegrates, firing particles out at high speed, we say that it is **radioactive**.

This happens in particular for larger nuclei, and indeed all the elements in the periodic table with atomic numbers over 83 are to some extent radioactive.

When a nucleus disintegrates, or decays, it emits particular types of particles and/or electromagnetic radiation. These are labelled after the first three letters in the Greek alphabet. They are known as alpha (α) particles, beta (β) particles and gamma (γ) rays.

Did you know?

Radioactivity is the spontaneous disintegration of an unstable atomic nucleus accompanied by the emission of one or more types of radiation.

Alpha particles

Alpha particles were used by Rutherford in the gold foil experiment. At that time all he knew was that they were small, fast moving and positively charged. Because of the knowledge that was gained from that experiment, it was eventually determined that each alpha particle consists of two protons and two neutrons. This is the same as the nucleus of the helium atom, and for this reason in nuclear physics the same symbol is often used for both: ${}^{4}_{2}He$. The Greek letter **α** can also be used.

One element that is known to emit alpha particles is uranium. From looking at its atomic and mass number (see **Figure 10.15**), you can see that this element has 92 protons and 146 neutrons. However, once it has fired out an alpha particle, which consists of two protons and two neutrons, the uranium nucleus is left with 90 protons and 144 neutrons.

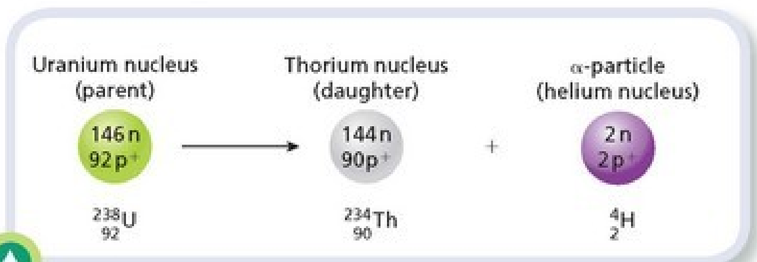


Figure 10.15 *The alpha decay of uranium*

The atomic number, or number of protons, is what defines an element. If the number of protons changes, everything else relating to that element's chemistry (chemical bonds, melting and boiling points, and so on) changes too. In fact, it becomes a different element. So when uranium loses two protons, the nucleus left behind is now the nucleus of a thorium atom – because thorium is the element with an atomic number of 90.

We say that uranium is the **parent nucleus**, and thorium is the **daughter nucleus**. When one element changes to another in this way, we call it **transmutation**. We write the equation for this as:

$$^{238}_{92}U \rightarrow ^{234}_{90}Th + ^{4}_{2}He$$

Note that this forms a balanced equation: the mass number beforehand is 238, and afterwards the total is still 238 (234 + 4). Similarly, the atomic number is 92 on the left and the total of the atomic numbers on the right is also 92.

This is always the case and is related to the fact that, in all nuclear reactions, the total electric charge is always conserved: the total electric charge beforehand is always equal to the total electric charge afterwards.

- An alpha particle is a radioactive particle that consists of two protons and two neutrons.
- The emission of an alpha particle reduces the atomic number by 2 and the mass number by 4.

Beta decay

Beta particles are actually electrons. They are emitted from a nucleus when a neutron decays into a proton and an electron. We often see in Physics: what **can** happen, **will**, at some stage, happen.

The neutron is very slightly larger than a proton: the difference is often ignored, but it is just large enough for an electron to be formed alongside a proton when a neutron decays. Also, the total charge on a neutron is zero, and the total charge of an electron and proton together is also zero (as the positive charge on the proton is cancelled by the negative electron). This shows us that it possible to make a proton and an electron from a neutron.

This new electron is formed inside the nucleus of the atom, not in the shells or energy levels where electrons are generally found. This is not **stable**, meaning that it cannot survive in that state, and the electron is fired out from the nucleus at very high speed. That is the beta particle.

We write the equation for beta decay like this:

$$^{1}_{0}n \rightarrow ^{1}_{1}p + ^{0}_{-1}e$$

Note that, as a beta particle actually is an electron travelling at high speed, we use the same symbol for the electron and the beta particle: $^{0}_{-1}e$. The Greek letter **β** can also be used.

One example of a nucleus that undergoes beta decay is carbon-14, a radioactive isotope of carbon:

$$^{14}_{6}C \rightarrow ^{14}_{7}N + ^{0}_{-1}e$$

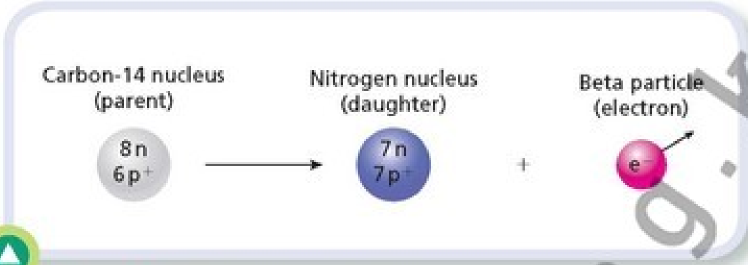


Figure 10.16 *The beta decay of carbon-14*

Note how the atomic number actually goes up, as a new proton has been formed. The mass number remains unchanged, however, as the extra proton is balanced by the loss of a neutron.

- A beta particle is a radioactive particle that consists of an electron emitted at high speed from the nucleus of an atom.
- The emission of a beta particle increases the atomic number by 1 and leaves the mass number unchanged.

Gamma rays

Gamma rays are very high-energy, high-frequency electromagnetic radiation.

We have already talked about how there are competing forces inside the nucleus: the repulsion between all the positively charged protons and the attraction between all of the particles in the nucleus that comes from the strong nuclear force. The presence of all these competing forces means that there is a lot of energy confined within the tiny space of the nucleus. Exactly how much energy is in there varies, depending on how the protons and neutrons are arranged. Some arrangements require more energy than others.

As the protons and neutrons move and shift position inside the nucleus, arrangements are sometimes found that require less energy than before. When this happens, the excess energy, no longer required by the nucleus, is released. As it is a large amount of energy, it emerges as a high-energy electromagnetic wave: the gamma ray (γ-ray).

The emission of gamma rays does not involve the transmutation of elements, as there is no change in the total number of protons and neutrons.

Ionising and Penetrating ability

All radioactivity has the ability to **ionise** the materials through which it passes. This means that it causes the atoms there to lose or gain electrons and to become charged. This property of radioactivity is why it can be so dangerous to us, by damaging the DNA and other key structures within the cells of our body. Very large exposures cause severe illness, which is often fatal, but even relatively small exposures increase the risk of cancer developing at some point in the future.

- A gamma ray is a form of radioactivity and consists of high-energy electromagnetic radiation emitted by the nucleus of an atom.
- The emission of gamma rays has no effect on atomic or mass numbers.

R2 R3 R4

Activity 10.1

Question

How can we demonstrate the ionising ability of radioactivity?

Equipment needed

Electroscope | Tongs | Radioactive material

Safety

- Take extreme care and follow all safety precautions when handling the material in this activity.

Conducting the activity

1. Charge an electroscope, so that the leaves diverge.
2. Using a pair of tongs, hold a source of radioactive material close to the electroscope and observe what happens.
3. Note your observations.

Q U6 R5

10.10 What did you observe when holding a source of radioactive material close to the electroscope?

10.11 How can you explain this observation?

Alpha particles

Alpha particles are the most ionising form of radioactivity. Because of their relatively large size, they are unlikely to travel far without colliding with some atoms or molecules. When an alpha particle does collide with an atom, the high kinetic energy of the particle is sufficient to remove an electron from that atom, thus ionising it.

At the same time, and also due to their relatively large mass, alpha particles are not very penetrating. They rarely travel more than 2–3 cm through air without colliding with atoms or molecules and therefore losing their energy. Once they have slowed down they soon acquire some electrons and become benign helium atoms.

The penetrating power of alpha particles is so poor that a single sheet of paper is usually enough to block their movement.

Beta particles

Beta particles are much smaller than alpha particles. As an electron, they have a mass of about $\frac{1}{2000}$ that of a proton, or $\frac{1}{8000}$ that of an alpha particle. As such, they are more likely to travel through air, or any material, for a greater distance before they collide with another atom or molecule. Beta particles typically can travel through about 30 cm of air, and need something such as a thin sheet of aluminium to be blocked.

Although their range is greater than that of alpha particles, their ionising power is correspondingly a little less.

Gamma rays

Gamma rays are the highest-frequency, and highest-energy, form of electromagnetic radiation. As such, they contain sufficient energy to ionise any material they pass through. That ionising ability is less than those of the other forms of radioactivity, but it is still a great danger to us in large doses, and the danger is increased by the great penetrating power of the rays: like other forms of electromagnetic radiation, they can travel enormous distances. They can effectively pass through any quantity of air, but they can be blocked by thick sheets of very dense material such as lead.

The gamma ray is emitted when the protons and neutrons within a nucleus are rearranged in a manner that reduces the total energy required to hold the nucleus intact. The energy no longer required becomes the gamma ray. These rays are usually emitted alongside either alpha or beta particles.

Research R2 Research R3 Research R4 Portfolio 76

Activity 10.2

Question

How can we demonstrate the penetrating power of radioactivity?

Equipment needed

Radioactive sources Geiger-Muller tube Speaker Tongs

Safety

- Take extreme care and follow all safety precautions when handling materials in this activity.

Conducting the activity

1. Take a number of radioactive sources and set them up as shown in Figure 10.17. This has to be done while respecting all safety procedures.

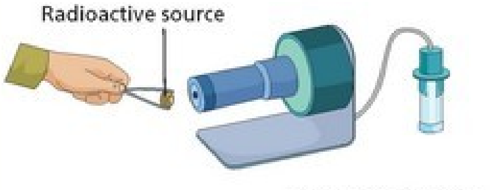


Figure 10.17 *Checking for radioactivity*

2. Hold an alpha source in front of, and close to, the detector, as shown. Move it slowly back and note how quickly the count falls.
3. Hold a beta source in front of the detector and note how the reading falls as the source is moved away from the detector.

4. Hold a gamma source in front of the detector and note how the reading falls as the source is moved away from the detector.
5. Hold each source in turn close to the detector and insert various barriers between it and the detector. Note what thickness of barriers and of what material is needed to eliminate the reading for each source.

Q U6 R4 R5

10.12 Complete the results summary table below.

Table 10.1

Particles	Nature	Change	Range	Ionising ability	Penetrating ability
α-Particle	Helium nucleus				
β-Particles	Electron				
γ-Rays	EM radiation				

Detectors: Geiger–Müller tube

The most common piece of equipment used to detect the presence of radioactivity is the **Geiger–Müller tube** – often referred to as a Geiger counter – named after its designers. It consists of a metal cylinder containing a mixture of argon and bromine at low pressure. An electric circuit is connected to the tube, as shown in Figure 10.19, with a gap between the positive and negative electrodes.

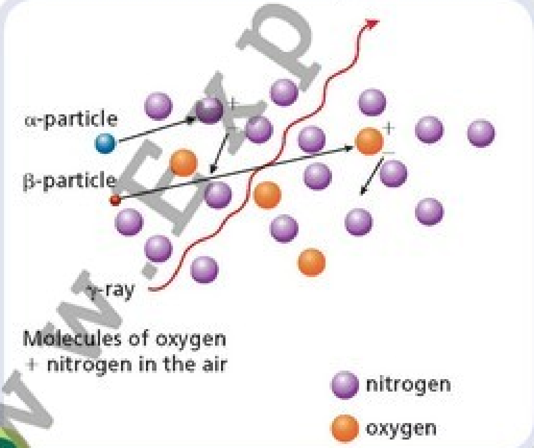


Figure 10.18 *The relatively large alpha particles have the least penetrating power but the greatest ionising ability. The gamma rays are the opposite, with relatively low ionising ability but very significant penetrating ability*

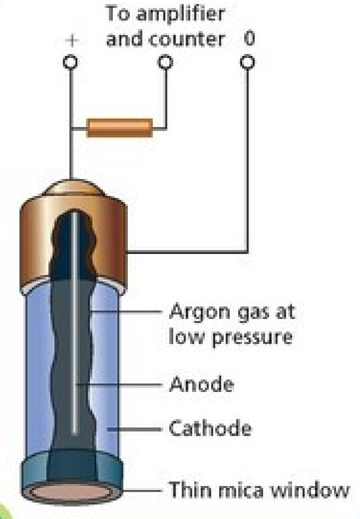


Figure 10.19 *A Geiger–Müller tube*

The gap between the electrodes means that generally no current can flow through the circuit. When ionising radiation enters the tube, however, it creates a number of ions, or charged particles. These move quickly to the two electrodes and briefly allow a current to flow.

The more often a current flows in this way, the greater the quantity of radioactivity in the area. Sometimes the current flows through a simple counter and sometimes through a speaker: those with speakers are often used in situations where people work with radioactive material and are left in a room where there might be a danger of a leak. The more often you hear the speaker 'click' the higher the radioactivity, and workers quickly become accustomed to the sound of background radiation, and know when the level has dangerously increased.

Research R2 Research R3 Research R4 Portfolio 77

Activity 10.3

Question

How can we measure background radiation?

Equipment needed

A Geiger counter

Speaker

Safety

- Take care not to drop or damage the equipment.

Method

1. Switch on a Geiger counter.
2. Note the number of clicks on the speaker (or flashes of an LED) over 5 minutes.

Communicating C2 Research R4

10.13 How many clicks did you measure per minute?

10.14 Research how this compares to the average radiation you are exposed to during an X-ray.

Health effects

We have already seen how ionising radiation is dangerous to us. By damaging the cells within the body it can cause radiation sickness – which is often fatal – or, over a longer period, cancer. Even in relatively small doses it can cause burns, comparable to sunburn.

Figure 10.20 *A scientist measuring the radiation levels in a forest contaminated following the Chernobyl nuclear disaster*

The same properties can be used to help us, however. Just as healthy cells can be damaged by radioactivity, so can cancerous cells. One of the most effective treatments for cancer is to expose a tumour to radioactivity. In doing so, it is important to limit the damage to healthy tissue. One way of doing this is to focus several separate beams of radioactivity onto a damaged area. Each beam is of too low a dose to cause damage, but where they meet up, at a tumour, the dose is sufficient to attack the cancer cells.

It is important to remember that, despite the association between radioactivity and modern technology, radioactivity is a natural phenomenon. One naturally occurring material that can be very dangerous to us is radon.

In what is known as a decay series, any uranium present in the Earth will decay into thorium, emitting an alpha particle. The thorium thus created is also radioactive and decays into radium. This usually happens deep in the Earth and is of little concern to us.

However, the radium then emits an alpha particle and yields radon as a daughter nucleus, and that is of interest to us because it is a gas. As it is a gas, the radon is able to seep up through the Earth and escape into the atmosphere.

There is nothing we can do about the presence of radon in the atmosphere, but it is important to avoid any build-up of radon gas in homes and workplaces, because radon is also radioactive. It is estimated that 9% of lung cancer deaths every year are due to overexposure to radon.

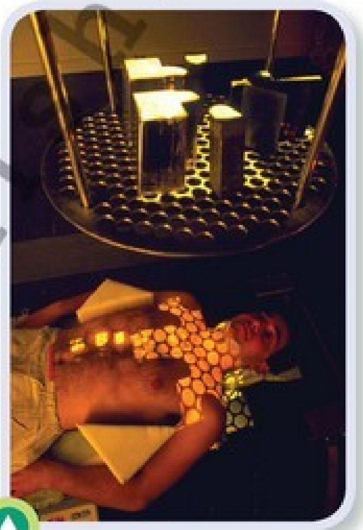


Figure 10.21 *A patient undergoing radiotherapy for Hodgkin lymphoma – a form of cancer*

Sample question 1

Copy and complete the following equations:

(a) ${}^{226}_{88}Ra \rightarrow$ ________ $+ {}^{4}_{2}He$ (b) ${}^{14}_{6}C \rightarrow$ ________ $+ {}^{0}_{-1}e$

Answer:

(a) An alpha particle reduces the mass number by 4 and the atomic number by 2, therefore: ${}^{226}_{88}Ra \rightarrow {}^{222}_{86}Rn + {}^{4}_{2}He$

The element is identified as radon by checking which element has atomic number 86.

(b) A beta particle increases the atomic number by 1 and leaves the mass number unaffected, therefore: ${}^{14}_{6}C \rightarrow {}^{14}_{7}N + {}^{0}_{-1}e$

Radioactivity

Radioactivity, like the photoelectric effect and X-rays, was discovered largely by accident. In February 1896, French physicist Antoine Henri Becquerel (1852–1908) was working on photography. He was hoping to carry out an experiment that involved taking photographs of uranium but – with the basic camera equipment of the time – needed sunlight to do so. The day was cloudy, so he put his equipment away, hoping for more luck a few days later.

When he returned to the experiment he found that the photographic film, although wrapped in black paper, had already been exposed. The only explanation for this was that some radiation was emanating from the nearby uranium.

Also in France, the husband and wife team of Pierre Curie (1859–1906) and Marie Curie (1867–1934) carried out similar experiments and found several other elements with similar properties. In particular they isolated the elements polonium and radium for the first time.

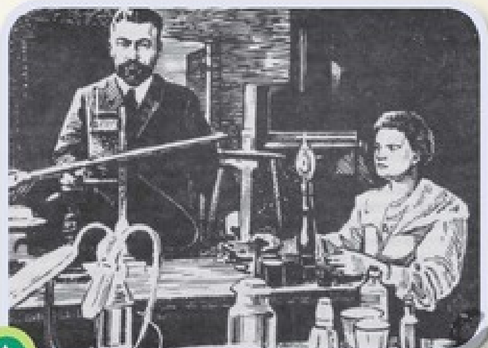


Figure 10.22 *Pierre and Marie Curie in their laboratory*

Figure 10.23 *Advertisement for Tho-Radia, a radioactive facial cream. In 1933, when the advert was produced, radioactivity was still considered beneficial to health*

Initially people were very excited by radioactivity, and many believed that exposure to it would have great health benefits. It was only slowly that its dangers became apparent. In fact the notebooks used by Marie Curie during her experiments are themselves so radioactive that they can only be handled with protective equipment.

Becquerel and the Curies were awarded the Nobel Prize in Physics for their discoveries. Marie Curie went on to receive a second prize in Chemistry for her work, her work, as did her daughter Irène Joliot-Curie (1897–1956), several years later.

Q Understanding U6 Society S2

10.15 What is radioactivity?

(a) An alpha particle **(b)** A beta particle **(c)** A gamma ray.

10.16 Comparing alpha particles, beta particles and gamma rays, what is the approximate range of each through air?

10.17 (a) Name a commonly used device that acts as a detector for radioactivity.

(b) Draw a diagram of this device and briefly explain how it operates.

10.18 When a beta particle is emitted, what is the effect on the atomic and mass numbers?

10.19 In this equation representing the decay of uranium through the emission of an alpha particle, which is the parent nucleus and which is the daughter nucleus?

$^{238}_{92}U \rightarrow ^{234}_{90}Th + ^{4}_{2}He$

10.20 Copy and complete the following equations:

(a) $^{226}_{88}Ra \rightarrow ^{222}_{86}Rn +$ ________

(b) $^{1}_{0}n \rightarrow$ ________ $+ ^{0}_{-1}e$

(c) $^{220}_{86}Rn \rightarrow$ ________ $+ ^{4}_{2}He$

10.21 In a number of steps, $^{232}_{90}Th$ decays to become $^{220}_{86}Rn$.

(a) State how many alpha and beta particles were likely to be released in the process. Explain your answer.

(b) What is the particular significance of radon in terms of the health effects of radioactivity?

Conservation laws

All radioactive decays obey the basic laws and principles of physics. This means that in every decay, the following will be obeyed:

- The principle of conservation of electric charge
- The principle of conservation of momentum
- The principle of conservation of mass–energy.

The conservation of energy is something you will have heard about before, but here it is stated as the conservation of mass–energy. This reference to mass is not a change in the law, but it is included because in this area of study we have to take into account that mass is itself a form of energy.

$E = mc^2$

Albert Einstein (1879–1955) was the first to notice that mass is a form of energy. You do not have to study the process by which he discovered this, but it arose out of his study of relativity.

Einstein built his special theory of relativity on the premise that the speed of light in a vacuum is fixed. Arising out of this, he showed that there must therefore be some odd behaviour in nature when objects travel at high speed. Among these are that the passage of time varies depending on how fast you are travelling, as does the measurement of length. A lot of Einstein's conclusions about this can seem bizarre when first encountered, but they are all now well-established. Among the more unusual aspects of the theory is that the faster an object travels, the heavier it becomes. When a particle travels close to the speed of light it requires near infinite quantities of energy to gain any more speed and, for this reason, can never travel faster than light.

Einstein published all of this in one of his famous papers in 1905. After the paper was published he continued to look at his maths. He re-worked the algebra relating to matters such as the principle of conservation of momentum and noticed that when he did so, there was often one new mathematical term included in expressions for energy: mc^2. He wondered what the physical meaning of this term was and eventually deduced that it represented the energy within a particle due to what we call the rest mass, the mass of a particle when it is not moving at all.

Einstein wrote a short letter outlining these findings, and it was published later that year. It introduced to the world what would become his most famous equation:

$$E = m c^2$$

The implication of this equation is that mass is in itself a form of energy. In many areas of study, this can be ignored, as whatever energy is present in the form of mass does not change. But when studying radioactivity this is not the case. The mass of subatomic particles is not fixed. It varies slightly depending on the arrangement of particles, and although this variation is usually very small, any change in mass releases very large quantities of energy and must be taken into account. This is why we refer to mass-energy.

Because of the extremely small values involved when we are considering the mass of particles such as protons, neutrons and electrons, masses are often given in atomic mass units, or **u**.

When using the formula $E = mc^2$, however, we need to work with the standard unit for the mass, the kilogram.

$$1u = 1.6605402 \times 10^{-27} \text{ kg}$$

It is rarely necessary to work to seven decimal places, but it is often necessary to work with at least four, given the very small variations in mass that occur. You have to look at the accuracy of the information given to you when making a decision.

Sample question 2

How much energy is contained within a mass of 1 kg, according to the equation $E = m c^2$?

Answer:

$$E = m c^2$$
$$= (1)\,(3 \times 10^8)^2$$
$$= 9 \times 10^{16} \text{ J}$$

Sample question 3

If 4 MeV of energy is converted from mass in a nuclear reaction, how much mass has been lost?

Answer:

$$4\text{ MeV} = (4 \times 10^{6})(1.602 \times 10^{-19})$$
$$= 6.4 \times 10^{-13}\text{ J}$$
$$E = mc^2$$
$$m = \frac{E}{c^2}$$
$$= \frac{(6.4 \times 10^{-13})}{(3 \times 10^{8})^2}$$
$$= 7.12 \times 10^{-30}\text{ kg}$$

Sample question 4

In a nuclear reaction, a proton collides with a lithium nucleus according to this equation:

${}^{1}_{1}p + {}^{7}_{3}Li \rightarrow 2\,{}^{4}_{2}He$ + energy

Referring to the formulae find:

(a) the total mass before the reaction

(b) the total mass after the reaction

(c) the energy released.

Answer:

(a) Mass of proton = 1.6726×10^{-27} kg

Mass of lithium nucleus = $(7.016)(1.6605 \times 10^{-27}) = 1.165 \times 10^{-26}$ kg

Total mass before = 1.3323×10^{-26} kg

(b) Total mass after $= (2)(6.6447 \times 10^{-27})$ kg

$= 1.3289 \times 10^{-26}$ kg

(c) Mass lost = 3.36×10^{-29} kg

Energy released: $E = mc^2$

$= (3.36 \times 10^{-29})(2.9979 \times 10^{8})^2$

$= 3.02 \times 10^{-12}$ J

Q U6 S2

10.22 In the equation $E = mc^2$, what do each of the symbols E, m and c represent?

10.23 What conservation laws are followed in nuclear reactions?

10.24 If 2×10^{-27} kg of mass is converted into other forms of energy during a nuclear reaction, how much energy is released?

10.25 The Sun loses about 4 million tonnes of mass each second through the conversion of mass into other forms of energy. How much energy is being released in this way?

10.26 Carbon-14 with an atomic mass of 14.003742 u, emits a beta particle of mass 9.109×10^{-31} kg and is converted into nitrogen with an atomic mass of 14.0030749 u. How much energy is released?

10.27 In a famous experiment, Rutherford bombarded nitrogen atoms with alpha particles and found that oxygen was created, according to this equation:

$^{14}_{7}N + ^{4}_{2}He \rightarrow ^{17}_{8}O + ^{1}_{1}H$

(a) Find the total mass before the reaction and the total mass afterwards.

(b) If energy were released in this reaction, where would it come from?

Law of radioactive decay

Radioactive decays are genuinely random events. If you could isolate an individual atom of, say, radium, you could say with some certainty that at some point in the future it would decay with the emission of an alpha particle. However, there is no process by which you could, with any accuracy, predict when that might happen.

This randomness does not prevent us from analysing radioactivity with maths, however. The reality is that you will not be able to isolate an individual atom or radium or any other element. Even a microscopic sample would contain many billions of atoms, and the large numbers involved allow us to make use of statistics.

The most basic way of looking at this is to say that the larger a sample of a radioactive material is, the more radioactive it is going to be. This is essentially the **law of radioactive decay**:

> The law of radioactive decay states that the number of disintegrations per second is proportional to the number of nuclei present (N).

This can be represented mathematically as:

$$A \propto N$$

where:
A = activity of the sample
N = number of atomic nuclei in the sample

As always, when two measurements are proportional we can say that one is a constant times the other. This introduces the idea of the **decay constant** (λ).

$$A = \lambda N$$

The decay constant is constant for a particular material but varies from one element, or isotope, to another. In basic terms, the higher the value of the decay constant, the more radioactive an isotope is going to be.

We can measure activity in two ways. We can count the number of particles emitted by a sample every second. For each particle emitted, remember that a nucleus of the parent element has been lost, so we can alternatively count the rate at which parent nuclei are lost. In either case, the unit we use is the **becquerel** (Bq).

One becquerel (1 Bq) is the decay of one atomic nucleus per second.

The half-life

Another mathematical approach to radioactivity is to look at what we call the **half-life**. Just as we can say that the larger the number of nuclei in a sample, the more active it is, we can say that as the number of nuclei falls, so does the activity of the sample.

- The half-life of an element is the time taken for half of the nuclei in any given sample to decay.

  OR
- The half-life of an element is the time taken for the activity of any given sample to decrease to half its original value.

The half-life is related to the decay constant by the formula:

$$T_{1/2} = \frac{\ln 2}{\lambda}$$

Did you know?

The quantity ln2 is the natural log of 2. Logs (logarithms) are an area you might have studied in maths, but here the value is always a constant. A quick check on your calculator will show you that the value is always the same: 0.693.

Sample question 5

A detector records 1200 counts per minute when the activity of a radioactive sample is first measured. Six minutes later the activity has fallen to 150 counts per minute. Calculate the half-life of the sample.

Answer:

Initially: activity = 1200

After 1 x $T_{1/2}$ activity = 600

After 2 x $T_{1/2}$ activity = 300

After 3 x $T_{1/2}$ activity = 150

$\Rightarrow$ 3 x $T_{1/2}$ = 360 s (6 minutes)

$\Rightarrow$ $T_{1/2}$ = 120 s

Q Understanding U6

10.28 State the law of radioactive decay.

10.29 What is the unit in which we measure radioactivity? Define this unit.

10.30 A detector records 240 counts per minute when the activity of a radioactive sample is first measured. Six minutes later the activity has fallen to 30 counts per minute. Calculate the half-life of the sample.

10.31 The number of atomic nuclei present in a sample of radioactive material is found to be 4.6×10^{15}. After a number of weeks, it has fallen to 5.75×10^{14}. How many half-lives have passed?

10.32 The isotope of hydrogen known as tritium, ${}^{3}_{1}H$, has a half-life of 12.33 years.

(a) What is the half-life in seconds?

(b) What is its decay constant in s^{-1}?

10.33 A sample of radium-226 has an activity of 4×10^{4} Bq. This isotope has a half-life of 1600 years.

(a) How many atoms are present in the sample?

(b) What would you expect the activity of 5×10^{20} atoms of this isotope to be?

Nuclear fission

We have looked at how many nuclei, particularly large nuclei, are unstable, and how this leads to them decaying, accompanied by the release of small radioactive particles. There is another way that instability can affect a nucleus, however: it can cause the nucleus to split into two new nuclei. When this happens it is known as **nuclear fission**.

> Nuclear fission is the breaking up of a large nucleus into two smaller nuclei of similar size, with the release of energy.

There are a number of nuclei that can undergo fission. The first one studied was the most common isotope of uranium, uranium-238. Some nuclear reactors make use of the element plutonium. However, we will focus on the most common fuel used in the nuclear industry and the element most likely to undergo fission – a rare isotope of uranium, uranium-235.

The fission of uranium-235

The most plentiful isotope of uranium is uranium-238 (${}^{238}_{92}U$). From its atomic and mass numbers, we can see that atoms of this isotope have 92 protons and 146 neutrons. Less than 1% of all uranium is a rarer isotope, uranium-235, which has only 143 neutrons.

If the nucleus of a uranium-235 atom is struck by a neutron, that neutron can actually become embedded, briefly, in the nucleus. This means that the number of neutrons has risen to 144, which, for reasons related to the delicate balance of forces with an atomic nucleus, is a very unstable arrangement. Accordingly, the nucleus disintegrates almost immediately and splits into two new, smaller nuclei.

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In a typical scenario, the nuclei of the elements barium and krypton are formed, and three neutrons are released:

$$ {}^{1}_{0}n + {}^{235}_{92}U \rightarrow {}^{141}_{56}Ba + {}^{92}_{36}Kr + 3{}^{1}_{0}n $$

This is a typical outcome of the fission of uranium-235, but it is not the only possible outcome. The elements formed can sometimes be either slightly larger or smaller, and the number of neutrons released can also vary. We will use this reaction, though, as an example with which to study fission in more detail.

In all situations in which fission occurs, a large quantity of energy is released at the same time. This is due to the fact that, although the total number of protons and neutrons has not changed, the mass of these subatomic particles is reduced, and according to the equation **$E = mc^2$**, this releases energy.

Chain reaction

You might have noticed in the above reaction that the fission of the uranium begins when a nucleus is struck by a neutron, and it results in the release of three neutrons. It is clear that some – or all – of these neutrons may go on to strike the nuclei of other nearby atoms and cause them to undergo fission, too. When a reaction is sustained by its own products in this way, it is called a **chain reaction**.

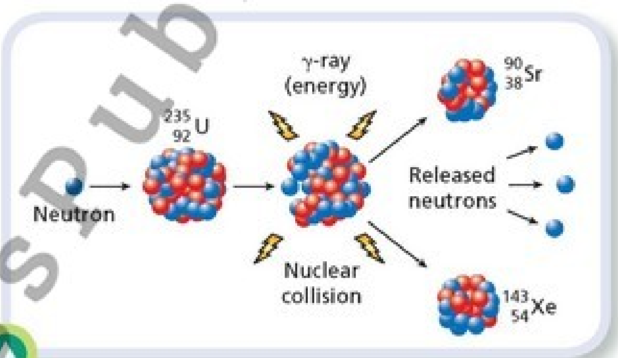


Figure 10.24 *One example of the fission of uranium-235*

The reaction could carry on through a few steps in this way and then die out. That would happen if all the released neutrons were to escape from the uranium sample without striking the nucleus of another atom.

When you remember how tiny the nucleus is when compared even with the size of an atom, you can see that this is very likely to be the case for small samples.

It can also be the case, though, that every neutron released goes on to create fission in another nucleus (see Figure 10.25). When this happens, the rate at which

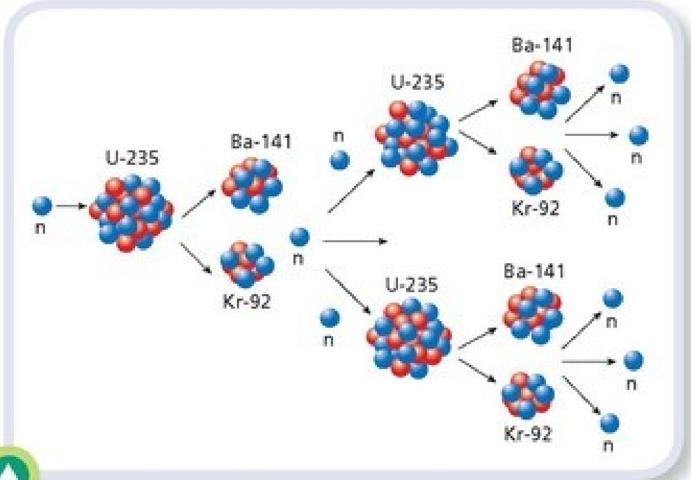


Figure 10.25 *A chain reaction in sample of uranium-235*

energy is released grows at an enormous rate. The release of enormous quantities of energy in a very short period of time is essentially what constitutes an explosion, and what we are talking about here is, therefore, a **nuclear explosion**.

Whether the reaction will grow to an explosion or die out is determined by the size of the sample. Basically, if the sample is large enough, the neutrons cannot escape without striking a nucleus and an explosion occurs. The size of the sample required for the reaction to inevitably grow in this way is known as the **critical mass**.

If a sample of fissile material is less then the critical mass, nuclear fission will quickly die out. If the sample is larger than the critical mass, the reaction will escalate.

The critical mass of uranium-235 is about 10 kg. Because uranium is a very dense material, a mass of 10 kg is only about the size of a tennis ball.

Nuclear weaponry

Nuclear bombs were used in warfare only at the end of the Second World War, when the Japanese cities of Hiroshima and Nagasaki were bombed by the United States.

In such bombs, two small amounts of fissile material are kept apart until the bomb is detonated. At that point a small, conventional, explosion pushes the two pieces together. It is then above the critical mass. A neutron source then causes the material to undergo an escalating chain reaction and a nuclear explosion follows.

It is worth noting that the nuclear explosion involved in a bomb of this type is not strictly a radioactive event – fission is not radioactivity. However, one of the things that makes the use of these weapons so terrible is that the by-products of the explosion, such as the isotopes of barium and krypton created from uranium-235, are radioactive. Due to the nature of a nuclear explosion, they are also spread out over a large area and will linger in the atmosphere for an extended period.

Figure 10.26 *The city of Hiroshima after being bombed in 1945. About 70 000 people died instantly, with tens of thousands more dying in the aftermath*

Those people not affected by the original explosion, as enormous as it is, may be affected by the radioactive by-products.

Fission reactor

In order to generate electricity from nuclear energy, it is necessary to sustain a chain reaction over many years, without letting it escalate and become an explosion. This is the chief aim of a **nuclear reactor** (see Figure 10.27).

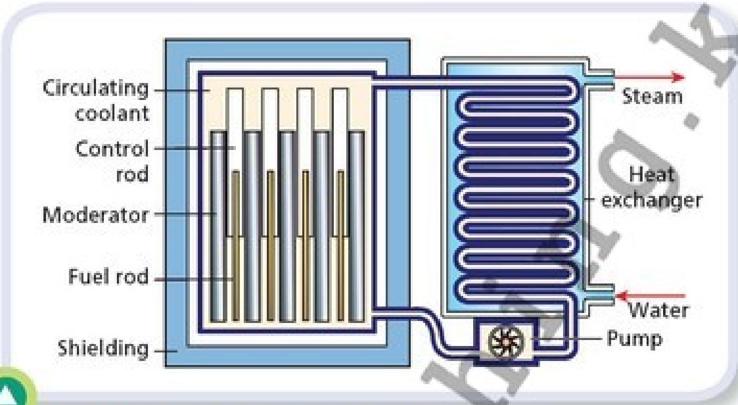


Figure 10.27 *The key features of a nuclear reactor*

Uranium-235 is very rare, and difficult to separate from uranium-238. But a chain reaction can be sustained if the percentage of uranium-235 is significantly increased. This is known as **enriched uranium** and is the material usually used in **fuel rods**.

The **control rods** are often made from cadmium, which is a dense material capable of absorbing any neutrons that pass through it. If the reaction is slowing down and there is a danger that it might die out, the control rods can be lifted: more neutrons pass from fuel rod to fuel rod, and the reaction should begin to speed up again.

If, by contrast, the reaction looks like it might be escalating and there is a fear that there could be an explosion, the control rods are lowered; they absorb more neutrons and the reaction slows down.

This may sound like a precarious balancing act, and we all know that it can go wrong, but with a well-designed system the movements in the rods are very slight and all extremes are avoided.

The energy continuously released in the reactor is absorbed by the **coolant**, which is then used to boil water. The jets of steam thus created can turn a turbine and generate an electric current.

The **moderators** are another key part of the design. Any neutrons moving at very high speed are more likely to be absorbed by uranium-238 than they are to create fission in a uranium-235 atom. For this reason, to increase the efficiency of the reactor, the neutrons are slowed down as they pass between fuel rods. They emerge at, or close to, the best speeds for the creation of fission.

Environmental issues

The use of nuclear reactors to generate electricity has long been controversial. As always, in any argument worth having, the issue is not at all straightforward and can be looked at from many points of view.

Arguments **for** nuclear power:

- Nuclear **fission does not release carbon dioxide** to the atmosphere, as the burning of fossils fuels does, and therefore does not add to global warming.
- Because of the enormous amounts of energy released in a reactor a **small number of reactors are needed** to run the electricity system for a whole country.

Arguments **against** nuclear power:

- The **likelihood of nuclear accidents** may be small, but they have happened and may happen again.
- The **mining process** for uranium is extremely dirty, and does cause the release of carbon dioxide.
- The **removal and storage of radioactive waste material** is extremely problematic: where and how can we store such dangerous materials without endangering ourselves or future generations, is an important issue.

Krypton

Krypton is a real element with atomic number 36. It is a colourless gas at ordinary temperatures but if cooled to less than –160°C, it can form a white crystalline powder. Kryptonite, however, is fictional. The word 'kryptonite', if it followed standard practice, would be a compound in which krypton was chemically combined with oxygen – but krypton is a noble gas and forms almost no compounds, and it is not known to bond with oxygen in any situation.

Figure 10.28

Did you know?

Kryptonite is fictional. Krypton, however, is real, usually a colourless gas, and does not damage superheroes.

Nuclear fusion

In the previous section we learnt about nuclear fission – the splitting up of a large nucleus to form two smaller nuclei, with the release of energy. Now we will look at the opposite of this: the joining together of two small nuclei to form a larger nucleus, with the release of energy. When this happens it is called **nuclear fusion**.

Nuclear fusion occurs when two small atomic nuclei join together to form a larger nucleus, accompanied by the release of large amounts of energy.

Nuclear fusion is the reaction that has been going on in our Sun, and other stars, for billions of years, and not only is it responsible for the vast quantities of energy we receive from the Sun, but it is also the process by which most of the atoms in the universe have been manufactured.

There are many examples of nuclear fusion, but a typical reaction is shown in Figure 10.29. Because the isotopes of hydrogen were among the first formed, they were initially given separate names: hydrogen-2 is usually referred to as deuterium, and hydrogen-3 is tritium. In this reaction, two deuterium nuclei fuse together to form an isotope of helium:

$$^{2}_{1}H + ^{2}_{1}H \rightarrow ^{3}_{2}He + ^{1}_{0}n + \text{energy}$$

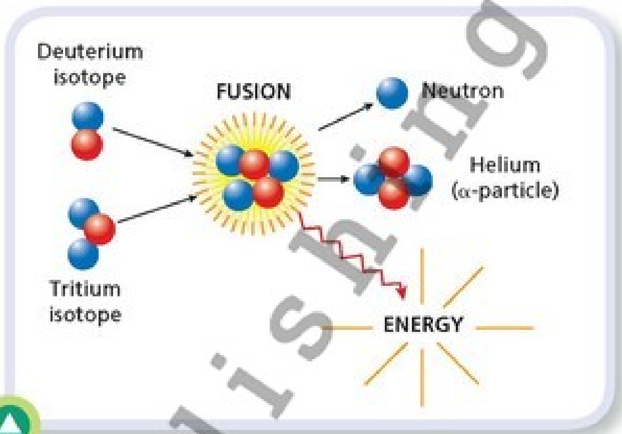


Figure 10.29 *Another example of fusion, creating helium*

Again, the energy that is released comes from the fact the total mass of the deuterium atoms beforehand is slightly greater than that of the helium and neutron afterwards. The 'missing' mass is released as other forms of energy – usually heat, which appears in the form of the fast movement of the particles involved (see Figure 10.29).

Energy source

As a source of energy, nuclear fusion would offer several very real advantages over almost every other source.

- **The fuel that is required is plentiful.** The two main isotopes of hydrogen that are used – deuterium and tritium – form only a small percentage of all the hydrogen in the world, but there is such an abundance of hydrogen that this is really no problem. Without any strain on our resources we could easily produce multiples of the Earth's energy requirements for centuries.
- **There are no dangerous waste products.** Most fusion reactions produce helium. This is not only a safe product, but it is actually a useful one. Supplies of helium are beginning to be stretched. This is worrying because although we could probably all do without so many party balloons, helium is also required for important technologies such as MRI scanners in hospitals.
- **A large amount of energy can be released without worsening the problems of climate change.**
- **There is no danger of nuclear fusion developing into a runaway chain reaction** as can happen with fission. Instead the reaction tends to proceed in a way that compares with an ordinary fire: as long as it is supplied with sufficient fuel and maintained at high temperature, the reaction will continue.

Despite these advantages, we do not yet use nuclear fusion for the production of electricity. The reason for this is that the reaction only takes place at extremely high temperatures. The deuterium–deuterium fusion shown above, for example, requires temperatures of 4×10^8 K (about 400 000 000 K) before it will begin.

These temperatures are considerably hotter than those found in the Sun, but creating them is not the problem. This has been done in nuclear explosions, and can be done in a controlled way using lasers. The problem is with where we would carry out the reaction.

We can dream of a scenario in which we simply fill a box with deuterium and heat it up to hundreds of millions of degrees until the fusion is initiated, but the sad reality is that we do not currently have any material with which to build the box: no material would survive those temperatures in solid form.

There are plans to create a fusion reactor by essentially suspending the fuel in mid-air using magnetic fields. However, the engineering required to do so is not at all straightforward. Various international groups of scientists have been working on it for decades but have not yet achieved any real success.

Why such high temperatures?

So why are such high temperatures required for fusion to occur? Remember that nuclear fusion is not just the joining together of two atoms. That happens all the time when chemical bonding takes place. Instead in fusion, the **nuclei** of two atoms have to come together to form one new nucleus.

The nucleus of an atom is where we find the protons, and all nuclei therefore have a positive charge. This means that any two nuclei are repelled from each other by an electrostatic force that follows Coulomb's law. Coulomb's law tells us that the closer the two nuclei come to each other, the greater the force pushing them apart. This force is large enough that, in ordinary situations, two nuclei would never join together.

You have learnt that the higher the temperature at which a gas is held, the faster the individual atoms within that gas move. When we reach the point at which the deuterium gas is held at 400 000 000 K, the individual atoms are moving fast enough that their nuclei overcome the repulsive forces between them and come close enough that the attraction created by the strong nuclear force takes over.

In other words, the **heat supplies sufficient energy to overcome the coulomb repulsion** between the nuclei.

Nuclear fusion actually takes place in the Sun at a slightly lower temperature. This is because the gases in the Sun are at extremely high pressures – much higher than we could ever hope to replicate on Earth.

Figure 10.30 *Nuclear fusion powers the Sun*

Sample question 6

During a nuclear explosion, 8×10^{15} J of energy were released. How much mass do you think would have been lost to release this quantity of energy?

Answer:

$$E = mc^2$$

$$m = \frac{E}{c^2}$$

$$= \frac{(8 \text{ x } 10^{15})}{(3 \text{ x } 10^{8})^2}$$

$$= 0.089 \text{ kg}$$

Sample question 7

Calculate the energy released in the following fusion reaction:

$${}^{2}_{1}H + {}^{2}_{1}H \rightarrow {}^{3}_{2}He + {}^{1}_{0}n$$

Answer:

Mass before $= 2 \text{ x } 2.014$ u

$= (2)(2.014)(1.6605 \text{ x } 10^{-27})$

$= 6.6885 \text{ x } 10^{-27}$ kg

Mass after $= (3.016)(1.6605 \text{ x } 10^{-27}) + 1.67493 \text{ x } 10^{-27}$

$= 6.683 \text{ x } 10^{-27}$ kg

Mass 'lost' $= 5.502 \text{ x } 10^{-30}$ kg

$E = mc^2$

$= (5.502 \text{ x } 10^{-30})(2.9979 \text{ x } 10^{8})^2$

$= 4.945 \text{ x } 10^{-13}$ J

Q Understanding U6 Communicating C3 Society S2

10.34 What is nuclear fission?

10.35 A coal-fired power station uses about two million times more fuel each year than an equivalent nuclear power plant. Explain why this might be so.

10.36 In a nuclear reactor, what is the purpose of the:

(a) control rods **(b)** moderators?

10.37 During the testing of a nuclear bomb, $1.8 \text{ x } 10^{15}$ J of energy were released. How much mass do you think would have been lost to release this quantity of energy?

10.38 What is nuclear fusion?

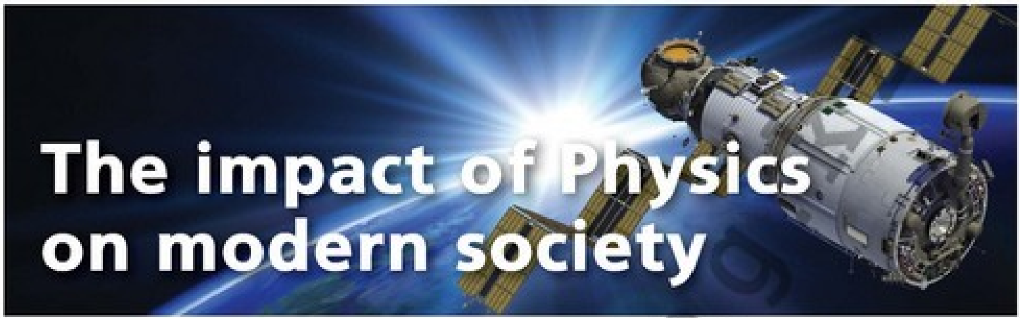
10.39 Why are very high temperatures required to initiate nuclear fusion reactions?

10.40 Give two benefits a nuclear fusion reactor would have over a fission reactor.

10.41 Calculate the energy released in the following fusion reaction:

$${}^{2}_{1}H + {}^{3}_{1}H \rightarrow {}^{4}_{2}He + {}^{1}_{0}n$$

MODULE 11



The impact of Physics on modern society

Learning outcomes

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

- Explain how developments in physics and astronomy have influenced society and the perspectives of mankind 9.8.1.1
- Evaluate the advantages of new technologies and consider their potential negative effects on the environment 9.8.1.3

Keywords

✔ navigation ✔ engineering ✔ shift ✔ harness ✔ foresee ✔ discovery ✔ natural phenomena ✔ application ✔ renewable ✔ non-renewable ✔ biomass ✔ geothermal ✔ solar ✔ fossil fuel

Physics and Astronomy

The study of physics and astronomy has since its beginning had an enormous impact on society and how mankind understands its place and role in the world. In ancient times, this involved looking at the night-sky and making theories about the stars and their impact on Earth and nature.

At times, new theories such as those of Copernicus, who first claimed that the Earth was not the centre of the universe, have brought about fundamental shifts in religious, scientific and philosophical thought. At other times, seemingly small discoveries have resulted in opening up whole new fields of scientific inquiry and in revolutionising technology. When Faraday succeeded in inducing electricity into a conductor using a magnet, he could not possibly have foreseen what his discovery would bring about.

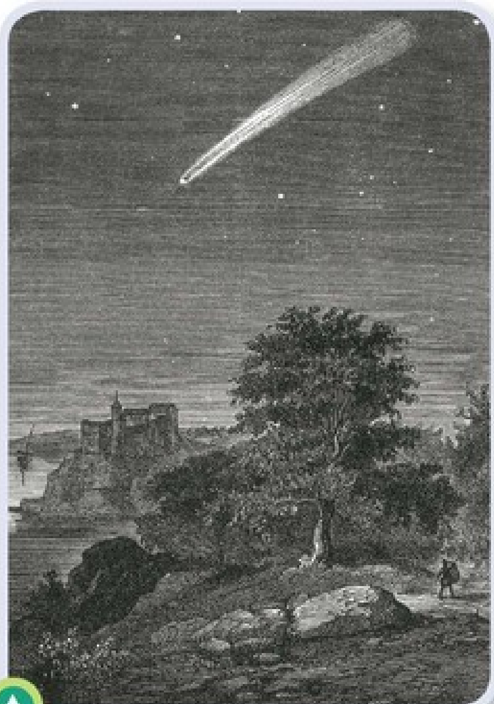


Figure 11.1 *The Great Comet of 1811*

Discovery and invention in the field of physics from ancient times to the modern day has been responsible for developments in navigation, systems of measurement, engineering and the ability of mankind to harness Earth's resources through technology. Discoveries in different branches of physics and their subsequent technological applications – especially over the past two hundred years- have fundamentally altered the way humans conduct every aspect of their daily lives: the means to hand for accessing media and information and communicating across distance, and the technologies available for performing everyday, industrial and scientific tasks. Below, we consider just some of the impacts of different discoveries in the different fields of physics that have shaped society in the last 150 years.

Q Society S2

11.1 Name three modern technologies that use Faraday's discovery of inducing electricity in a conductor using a magnet.

11.2 Without looking ahead in the module, can you predict which fields of physics we will consider as having had the greatest impact on modern life?

Nuclear Physics

The most iconic discovery from the last century that changed our understanding of the fabric of our world was the discovery by Rutherford and his team that atoms consist of tiny positively-charged nuclei orbited by negatively-charged electrons. Though this discovery led to the century-defining moment of the dropping of the atomic bomb, a whole range of positive technologies have developed from this discovery through advancements in medicine, energy and our ability to understand and monitor environmental systems. In hospitals a whole array of non-invasive (not involving surgery) equipment to scan and diagnose patients have developed through applications of nuclear science and technology such as X-rays, MRI scanners, ultrasound and CAT scans.

Figure 11.2
MRI scanner

Quantum mechanics

Understanding of principles like particle-wave duality (Module 10) has led to the development of the laser, the internet, personal computers and many other modern electronic inventions. The key component in modern electronic technologies is the semiconductor. Properties of semiconductor materials allow electronic signals within devices to be controlled far more effectively.

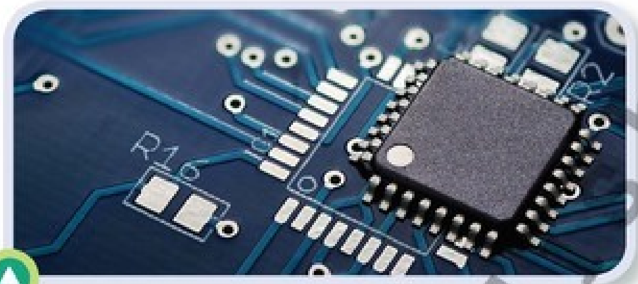


Figure 11.3 *Semiconductors in computer technology*

Geophysics and Meteorology

Advances in understanding in these areas of natural phenomena have made it possible to understand and better predict the weather and how to predict and develop reliable warning systems for natural disasters such as earthquakes, tsunamis, tornadoes, and hurricanes.

Figure 11.4 *Storms are becoming more regular in some parts of the world*

An example of this, is the development of the hurricane warning system. Warnings are now issued 36 hours before winds in an area develop to tropical-storm force to allow residents to take effective precautions. Once winds have reached tropical storm force, making preparations for a hurricane becomes much more difficult.

Electricity and Magnetism

Discoveries by physicists like Michael Faraday and Andre-Marie Ampere in the nineteenth century allowed electricity to be generated for practical purposes and led to the development of thousands of electrical devices that we see and use every day. Modern devices that contain electromagnets include speakers, computer hard drives, microphones, electric buzzers, electric motors and generators.

Figure 11.5 *An electric buzzer system*

Thermodynamics

The power turbine in power stations, the refrigerator and the car all work using heat engines developed using our understanding about the laws of thermodynamics. Linked to this area of physics are discoveries such as natural gas which is a source of energy for cooking, heating, electricity generation and much more, and the fuel cell which could potentially reduce our dependence on fossil fuels in the future.

Figure 11.6 *Hydrogen fuel cell*

Q Understanding U8

11.3 What generally accepted view did Copernicus challenge?

11.4 What did diagnosis before the invention of scanners linked to nuclear science often involve?

11.5 What is often described as the key component of modern electronics? Which field of modern physics did this develop from?

11.6 Explain the difference between a turbine and a generator.

Communicating C1 Communicating C2 Communicating C3

11.7 Research current uses of the fuel cell and its potential future benefits.

We have seen that physics as a science considers physical systems that range in size from subatomic particles to solar systems and stars. It is a broad field with many diverse areas that have contributed to shaping our understanding of the world and the technologies we use to function within it. A major part of the subject is understanding the forces and laws on which the interactions of matter and energy are based. In the final section of this module, we shall turn our attention to the human need for energy and how our choices in meeting this need can impact on the environment.

How do we use energy and where does it come from?

What are the forms of energy we use in our homes? Where does that energy come from?

We usually flick a light switch without any thought as to what source of energy produces the electricity in the light.

Figure 11.7 *Radiation from the Sun*

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In order to supply homes with energy, some source of fuel or resource must be changed or transformed to electrical energy.

There are two forms of resources available to us: non-renewable and renewable.

Q Communicating C2

11.8 List all the forms of energy that you can identify that are used in your home.

Non-renewable resources

Non-renewable resources are **limited resources** that will run out and we are unable to replace them. In common terms we call them the **fossil fuels**.

What are fossil fuels?

Fossil fuels are the remains of animals and plants from millions of years ago. The remains were squashed/compressed by earth over a long period of time producing the fossil fuel.

The main fossil fuels are:

- coal
- gas
- oil
- peat.

Figure 11.8 *Different forms of fossil fuel*

Fossil fuels have held energy in earth for millions of years. For example, coal can be mined and broken into nuggets of a suitable size for our fires.

We are using fossil fuels at a much greater rate than they can actually be produced. More than three-quarters of Earth's energy needs are met by the burning of fossil fuels.

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Q C2 Communicating

11.9 In pairs or groups explore:

(a) The advantages and disadvantages of the burning/combustion of fossil fuels.

(b) The advantages and disadvantages of the use of nuclear energy.

Renewable resources

Renewable resources can be replaced and will not run out in the short term.

Some examples of renewable resources and their uses are:

- **Wind power** – Turbines/windmills that turn and rotate in the wind, transforming some of the energy in the wind to electrical energy.
- **Water** – This is using the energy within moving or falling water and changing it to electrical energy. Examples of how this is done are hydroelectric stations.
- **Biomass** – The burning of fuel that comes from living things. An example is wood from trees. It is renewable only if the trees that are cut down are then replaced.
- **Geothermal** – This requires us to use the heat that is beneath the ground. Water is pumped underground and warmed from the heat in the rocks. This heat energy is generated and stored in the Earth.
- **Solar panels/tubes** – Solar panels heat water that runs through them. The energy source that supplies the heat is the light from the Sun.
- **Solar cells** – These cells are found in devices that transform light energy to electrical energy. An example is a solar-powered calculator.

The fastest-growing source of energy in the world is the wind turbine. One wind turbine, of sufficient size, can supply enough energy to provide all the energy needs to over 300 homes.

Figure 11.9 *Wind turbines convert wind energy to electrical energy*

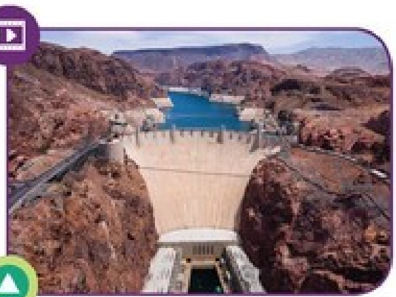

Figure 11.10 *Energy from falling water is converted to electrical energy*

Figure 11.11 *Biomass can be converted to electrical energy*

Figure 11.12 *Water at the Old Faithful geyser (in Yellowstone National Park in the United States) is heated underground by the rocks*

Figure 11.13 *Solar panels harness energy from the Sun*

Figure 11.14 *Some solar panels are small, like the one on this calculator. These smaller panels are called 'solar cells'*

Did you know?

Enough energy from the Sun falls on Earth every hour that we could power the entire Earth for a full year – if only we could work out how to trap or use it!

Communicating C6

11.10 Research the following areas and determine the effect, be it positive or negative, on the energy output of the following renewable sources of energy. Present your findings to the class.

Solar panels

(a) Can the presence of clouds or solid particles impact the energy output from the panels?

(b) Is the angle and direction in which a solar cell or panel is facing important? Explain your answer.

Wind turbines

(c) Does the number of blades or the length of the blades on a wind turbine affect the amount of energy being produced from that turbine?

(d) Does the direction the wind turbine is facing affect its efficiency?

(e) What are the main disadvantages in using solar panels and wind turbines?

What are our current and future energy requirements?

We have become an **energy hungry society**. This means, per individual on Earth, we have a very high demand and requirement for energy.

Evidence of this is in a satellite image of Earth – look at all the light that can be seen from space coming from cities and people's homes in Figure 11.15.

Figure 11.15 *A satellite image of Europe shows up electric light from cities and towns*

Most of our current energy needs are met by burning fossil fuels. Fossil fuels, along with nuclear energy, supply 93% of the world's energy requirement. The remaining 7% comes from renewable energy sources.

Table 11.1 shows how much fossil fuel is used just to supply the world's electrical demands.

Table 11.1 Percentage of types of fuel used to supply the world's electrical demands

Energy type	% of world electrical supply	Energy type	% of world electrical supply
Coal	39	Oil	16
Gas	19	Hydro	7
Nuclear	17	Other	2

As economies and countries become more developed, the demand for energy increases dramatically.

A simple example of this is the number of cars that are currently on the world's roads. From a study done in 2014, there are now over one billion cars on the road, with the US having the highest number of cars and China having the second-highest.

Figure 11.16 *Traffic on a road in the USA*

In addition, the world's population is also expanding – and it is expected to reach about 10 billion people in the next fifty years – and so our energy demands will also increase.

Energy experts expect that by the time we reach 2030 the world energy demand will have increased by 55% compared to today.

Not only will we have to use renewable energy in greater and greater amounts, we will need to be more efficient about how we use our energy. Energy efficiency is essential as scientists believe that within the next 50 to 100 years our fossil fuels will run out, and once they are gone they are gone!

Did you know?

On average 15% of electricity used in the home is used by devices and equipment that are on standby.

Communicating C2

11.11 In pairs or groups, investigate all renewable energy forms that are being used in Kazakhstan. How efficient are they, and how expensive?

11.12 Does Kazakhstan have targets linked to specific dates for:

(a) a percentage of all energy being used in the country to come from renewable energy?

(b) a percentage total of transport that will have to be run on renewable energy sources?

Figure 11.17 *Renewable energy*

Figure 11.18 *Wind farm energy*

Did you know?

Scientists believe that it would take only one percent of the world's land area covered in solar panels to supply all of the world's present electrical needs.

We can no longer continue with our current dependency on fossil fuels. Nor can we continue to ignore how important it is for us to begin to use renewable energy in greater amounts.

Our future, in terms of energy, depends on what we do now and research and development in Physics that allows us to meet our future energy needs in a sustainable way.

Understanding U8 Communicating C2 Society S2

11.13 (a) In groups can you think of six different types of career linked to an understanding of physics where someone could contribute positively to helping society meet its need for energy.

(b) Rank your list in terms of most to least likely to benefit society in terms of the 'energy' question.

(c) Compare your list with other groups.

Glossary

A

acceleration

$Accelaration = \frac{Change\ in\ Velocity}{Time}$ or $a = \frac{v-u}{t}$ where a is acceleration, v is final velocity, u is initial velocity and t is time.

acceleration due to gravity In the absence of air resistance, objects near Earth's surface fall with constant acceleration due to gravity, $g = 9.8\ m\ s^{-2}$.

acoustics The study of all mechanical waves in gases, liquids, and solids including topics such as vibration, sound, ultrasound and infrasound.

aerial antenna The part of a radio or television system having any of various shapes, such as a dipole, Yagi, long-wire, or vertical aerial, by means of which radio waves are transmitted or received.

airbag The airbag is a vehicle safety device. It is a restraining device designed to inflate rapidly during an automobile collision. The airbag is designed to only inflate in moderate to severe frontal crashes.

air track A tube with a row of holes through which air is blown from an air blower. The air lifts a rider slightly off the track thus creating very low friction between the rider and the air track.

ammeter An instrument used to measure the size of an electric current.

angular displacement θ is the angle subtended at centre of a circle by an arc of equal length to the radius.

angular velocity ω is the rate of change of angular displacement with respect to time.

anode The electrode that is connected to the positive terminal of the power supply.

application The utilization of scientific principles in practical devices and systems.

audible Something audible can be heard.

average speed The distance travelled divided by the time taken to travel that distance (scalar).

B

biomass A renewable source of fuel to produce energy often used to mean plant based material, but biomass can equally apply to both animal and vegetable derived material.

boundary The portion of a fluid flowing past a body that is in the immediate vicinity of the body and that has a reduced flow due to the forces of adhesion and viscosity.

Boyle's law Boyle's law states that at constant temperature, the volume of a fixed mass of gas is inversely proportional to its pressure.

C

calorimeter A device used for measuring heat transfer.

capacitance Charge stored per unit of potential difference across a capacitor $C = Q/V$.

cathode The electrode that is connected to the negative terminal of the power supply.

celestial sphere In astronomy and navigation, the celestial sphere is an abstract sphere with a concentric radius to Earth. All objects in the sky can be conceived as being projected upon the inner surface of the celestial sphere, which may be centred on Earth or the observer.

centre of gravity The point on an object through which the entire weight of the object may be considered to act.

centripetal acceleration The rate of change of tangential velocity.

centripetal force A force which acts on a body moving in a circular path and is directed towards the centre around which the body is moving.

chain reaction A self-sustaining series of reactions. In a chain reaction in a uranium-based nuclear reactor, for example, a single neutron causes the nucleus of a uranium atom to undergo fission. In the process, two or three more neutrons are released.

charge carriers Particles that are free to move and carry electrical charge, e.g. electrons or ions.

collision The meeting of particles or of bodies in which each exerts a force upon the other, causing the exchange of energy or momentum.

conductor (electrical) A substance that allows electric charge to flow freely through it.

conductor (thermal) A substance that allows heat to transfer through it.

contact A contact force is any force that requires contact to occur. Molecular and quantum physics show that the electromagnetic force is the fundamental interaction responsible for contact forces.

cosmonaut A person trained to travel in spacecraft.

couple Two equal, opposite and parallel forces which create rotational force.

critical mass The smallest mass of a fissionable material that will sustain a nuclear chain reaction.

cross-sectional area The area that is exposed when an object is cut at right angles to its length.

current The flow of electric charge.

D

data-logger A device that collects and stores information. Information is usually transmitted to the data-logger from a motion sensor.

decay Radioactive decay is a process in which a nucleus undergoes spontaneous transformation into one or more different nuclei and simultaneously emits radiation, loses electrons, or undergoes fission.

deflect The change in an object's velocity as a consequence of contact (collision) with a surface or the influence of a field.

density Density is the mass of a body per unit volume.

displacement A vector quantity, the distance of an object from its initial position, in a given direction.

E

echo A reflection of sound that arrives at the listener with a delay after the direct sound. The delay is proportional to the distance of the reflecting surface from the source and the listener.

electric charge The amount or type of electrical force that something has. The protons in an atom have a positive charge, and the electrons have a negative charge.

electronvolt A unit of energy equal to the energy gained by an electron in passing from a point of low potential to a point one volt higher in potential: 1.60×10^{-19} joule.

emergent light ray A light ray that leaves a medium.

energy The ability to do work.

engineering science The study of the combined disciplines of physics, mathematics and engineering, particularly computer, nuclear, electrical, electronic, materials or mechanical engineering.

F

fluorescence The emission of light by a substance that has absorbed light or other electromagnetic radiation. It is a form of luminescence.

force Anything that causes the velocity of an object to change. Force = Mass × Acceleration.

fossil fuel A hydrocarbon fuel, such as petroleum, coal, or natural gas, derived from the accumulated remains of ancient plants and animals and used as fuel.

frequency The number of cycles (or oscillations) passing a point in one second. The most common unit of frequency is the hertz (Hz).

friction A force that opposes motion.

fuel rods Long tubes, often made of a zirconium alloy and containing uranium-oxide pellets, that are stacked in bundles of about 200 to provide the fuel in certain types of nuclear reactor.

G

gamma rays Electromagnetic radiation of the shortest wavelength and highest energy.

geostationary satellites Being or having an equatorial orbit at an altitude of about 22,300 miles (35,900 kilometres) requiring an angular velocity the same as that of the Earth, so that the position of a satellite in such an orbit is fixed with respect to the Earth.

geothermal energy Thermal energy generated and stored in the Earth. Earth's internal heat is thermal energy generated from radioactive decay and continual heat loss from Earth's formation.

gravitational field strength The force that a unit mass would experience at a specified point. Measured in metres per second or Newtons per kilogramme.

gravitational potential The energy that a unit mass would have at a specified point. Measured in Joules per kilogramme.

gravitational potential energy The energy an object has due to its relative position above the ground. Found by mass x gravity (or gravitational field strength) x height or force per unit mass at a set point in a gravitational field.

H

half-life The time required for a quantity to reduce to half its initial value. The term is commonly used in nuclear physics to describe how quickly unstable atoms undergo, or how long stable atoms survive, radioactive decay.

harmonics Frequencies that are multiples of a certain frequency, f.

heat capacity The heat energy needed to change its temperature by one kelvin (1 K).

heat transfer The non-mechanical transfer of energy from the environment to the system or from the system to the environment because of a temperature difference between the two.

I

impulse The product of average force and time of contact for a collision.

infrared waves Electromagnetic radiation of a particular wavelength or colour that are named 'infrared.' They are between 700 nm (nanometres) and 1 mm.

infrasound Sometimes referred to as low-frequency sound. Sound that is lower in frequency than 20 Hz or cycles per second, the "normal" limit of human hearing.

instantaneous acceleration The change of velocity over an instance of time.

instantaneous position Position of an object at a specific time.

instantaneous velocity The velocity of an object at any given instant (especially that of an accelerating object).

insulator (electrical) A substance that does not allow electric charge to flow through it easily.

insulator (thermal) A substance that does not allow heat to transfer through it easily.

interference Interference occurs when two waves meet and a new wave is formed. The displacement produced at any point by this wave is the algebraic sum of the displacements that each wave would produce on its own.

internal combustion An engine, such as an automotive gasoline piston engine or a diesel, in which fuel is burned within the engine proper rather than in an external furnace, as in a steam engine.

internal energy Sum of potential energy and kinetic energy with random motion.

inverse square laws The principle in physics that the effect of certain forces on an object varies by the inverse square of the distance between the object and the source of the force. The magnitude of light, sound, and gravity obey this law, as do other quantities.

ion An electrically charged atom or group of atoms formed by the loss or gain of one or more electrons.

ionise Any process by which electrically neutral atoms or molecules are converted to electrically charged atoms or molecules (ions). Ionisation is one of the principal ways that radiation, such as charged particles and X rays, transfers its energy to matter.

isotopes Different atoms of a chemical element in the periodic table all have the same number of protons, but may have a different number of neutrons in their nuclei. These different versions of the same element are called isotopes.

K

kilowatt-hour A unit of energy defined as 1000 watts for 3600 seconds, or kW x h (kWh).

kinetic energy The energy an object possesses due to its motion, given by KE = 0.5 x mass x velocity^2.

L

latitude The angular distance of a place north or south of the Earth's equator in degrees.

launch A rocket launch is the take-off phase of the flight of a rocket. Launches for orbital spaceflights, or launches into interplanetary space, are usually from a fixed location on the ground, but may also be from a floating platform or from an airplane.

laws of equilibrium The sum of the forces acting upwards must be equal to the sum of the forces acting downwards and the sum of the clockwise moments must be equal to the sum of the anticlockwise moments.

lightning conductor A metal strip terminating in a series of sharp points, usually attached to the highest part of a building, to discharge the electric field before it can reach a dangerous level and cause a lightning strike.

light dispersion The process of splitting white light into seven colours is called dispersion of light.

light gate A device with a light beam that goes across it. When an object passes through a light gate, a timer records the time that the light beam is interrupted by an object.

linear momentum A vector product of Mass and Velocity (= m x).

longitude The angular distance of a place east or west of the meridian at Greenwich, England. Zero degrees of longitude means you have to be either north or south of Greenwich.

longitudinal A wave that oscillates back and forth on an axis that is the same as the axis along which the wave propagates. Sound waves are longitudinal waves, since the air molecules are displaced forward and backward on the same axis along which the sound travels.

luminosity The total energy per unit time emitted by the object. Another term for luminosity is power. For example, the Sun's luminosity, or power output, is 3.8 x 10^{26} watts.

luminous The quantity of visible light that is emitted in unit time per unit solid angle. The unit for the quantity of light flowing from a source in any one second.

M

magnetic declination The angle that a compass needle makes with the direction of the geographical north pole at any given point on the Earth's surface.

magnetic flux density The force acting per unit current per unit length on a wire placed at right angles to the magnetic field.

magnification $Magnification = \frac{v}{u}$ or $\frac{h_i}{h_o}$.

magnified image An image that is larger than the object.

mass The amount of matter in any solid object or in any volume of liquid or gas. The acceleration of a body equals the force exerted on it divided by its mass – measured in kg.

meridian A (geographical) meridian (or line of longitude) is the half of an imaginary great circle on the Earth's surface, terminated by the North Pole and the South Pole, connecting points of equal longitude. Each meridian is perpendicular to all circles of latitude.

micrometer An instrument used to measure small distances accurately.

microwave A form of electromagnetic radiation with wavelengths ranging from one meter to one millimetre; with frequencies between 300 MHz (100 cm) and 300 GHz (0.1 cm).

moment of a force The force multiplied by the perpendicular distance between the force and the fulcrum.

momentum Momentum = Mass × Velocity

motion sensor A sensor detects the movement of an object and transmits this information to a data-logger and a computer.

multimeter An instrument that can be used to measure various electrical quantities, e.g. voltage, current or resistance.

N

natural phenomenon All phenomena that are not artificial.

navigation To move on, over, or through (water, air, or land) in a ship or aircraft. To ascertain or plot and control the course or position of (a ship, aircraft, and so on).

nebula A cloud of interstellar gas and dust.

newton balance An instrument that measures force (also known as a force-meter).

no parallax No parallax means that an observer will observe no relative motion between two objects.

non-renewable A natural resource such as coal, gas, or oil that, once consumed, cannot be replaced.

normal An imaginary line perpendicular to the surface.

nuclear fission Is either a nuclear reaction or a radioactive decay process in which the nucleus of an atom splits into smaller parts (lighter nuclei).

nuclear fusion A reaction in which two or more atomic nuclei come close enough to form one or more different atomic nuclei and subatomic particles (neutrons or protons). Fusion is the process that powers active or 'main sequence' stars, or other high magnitude stars.

O

orbit The path followed by an electron within an atom. The planets follow elliptical **orbits** around the sun.

origin (of a graph) (0,0) point on a graph.

oscillation The movement back and forth in a regular rhythm.

oscilloscope A laboratory instrument commonly used to display and analyse the waveform of electronic signals.

P

peak The highest point on a wave is called the peak. The lowest point is called the trough. The peak of a wave and the trough of a wave are always twice the wave's amplitude apart from each other.

period A period T is the time required for one complete cycle of vibration to pass a given point. As the frequency of a wave increases, the period of the wave decreases.

period of motion The period T of an object in circular motion is the time taken for the object to make one complete revolution.

periodic time (period) of a particle executing simple harmonic motion The time taken for one complete oscillation.

perpetual freefall The motion of an object where gravity is the only force acting upon it. A skydiver may be pulled towards Earth by gravity, but they are also affected by air resistance, a force opposing their downward movement.

piston A sliding piece moved by or moving against fluid pressure which usually consists of a short cylindrical body fitting within a cylindrical chamber or vessel along which it moves back and forth.

pitch The sensation of a frequency is commonly referred to as the pitch of a sound. A high pitch sound corresponds to a high frequency sound wave and a low pitch sound corresponds to a low frequency sound wave.

photoelectric effect The emission of electrons or other free carriers when light shines on a material. Electrons emitted in this manner can be called photo electrons.

photon A bundle of electromagnetic energy. It is the basic unit that makes up all light. The photon is sometimes referred to as a 'quantum' of electromagnetic energy.

Planck's constant Relates the energy in one quantum (photon) of electromagnetic radiation to the frequency of that radiation. In the International System of units (SI), the constant is equal to approximately 6.626176×10^{-34} joule-seconds.

power The rate at which work is done.

pressure Force per unit area. $P = \frac{F}{A}$ where P is pressure, F is force and A is area.

pressure gauge An instrument used to measure pressure.

prism A geometric solid whose bases are congruent polygons lying in parallel planes and whose sides are parallelograms. A solid of this type, often made of glass with triangular ends, is used to disperse light and break it up into a spectrum.

principle of conservation of momentum The principle of conservation of momentum states that in any interaction between two or more bodies, the total momentum of the bodies before the interaction is equal to the total momentum of the bodies after the interaction provided no external forces act on the system.

potential energy The energy possessed by an object because of its position relative to other objects, stresses within itself, its electric charge, or other factors.

Q

quanta Discrete bundles in which radiation and other forms of energy occur. For example, in the Bohr atom, light is sent out in quanta called photons.

R

radian A radian is the angle subtended at the centre of the circle when the arc length is equal in length to the radius.

radioactivity The particles which are emitted from nuclei as a result of nuclear instability.

red giant A star that is past its peak and has consumed its core's supply of hydrogen fuel. As a result, helium has built up in the core, hydrogen has fused in the outer shells, and the star has expanded into a red giant.

re-emit To give off (radiation or particles).

regenerative braking A form of braking in electric vehicles in which the loss of kinetic energy from braking is stored and then fed back later to provide power to the electric motor. The system uses regenerative braking to recharge the battery.

renewable energy Energy that is collected from renewable resources, which are naturally replenished on a human timescale, such as sunlight, wind, rain, tides, waves, and geothermal heat.

repel If two things repel each other, they push each other away with an electrical force; two positive charges repel each other.

resonance The transfer of energy between two objects of the same natural frequency.

rocket A rocket is a missile, spacecraft, aircraft or other vehicle that obtains thrust from a rocket engine. Rocket engine exhaust is formed entirely from propellant carried within the rocket before use.

S

scalar A quantity with magnitude but no direction.

seismograph An instrument designed to measure tremors of the Earth's surface.

simple harmonic motion A body is said to be moving with simple harmonic motion if its acceleration is directly proportional to its distance from a fixed point on its path and its acceleration is always directed towards that point.

simple pendulum A mass at the end of a string. For a small angle of swing, a simple pendulum can be considered to be undergoing simple harmonic motion.

sink To displace part of the volume of a supporting substance or object and become totally or partially submerged or enveloped.

solar energy The energy the Earth receives from the sun, primarily as visible light and other forms of electromagnetic radiation.

sonometer A device consisting of a hollow wooden box with a wire stretched between two movable bridges.

spark A spectrum formed from the light produced by an electric spark, characteristic of the gas or vapour through which the spark passes.

spectroscopy The study of the interaction between matter and electromagnetic radiation.

speed A scalar quantity, speed = distance / time.

stable In balance (sum of the forces and torques are equal to zero).

star A star is a type of astronomical object consisting of a luminous spheroid of plasma held together by its own gravity. The nearest star to Earth is the Sun.

T

temperature The measure of the hotness or coldness of a body.

thermal equilibrium Thermal equilibrium occurs when all parts of a system are at the same temperature.

thermionic emission An electrically charged particle or ion that is emitted by a heated conducting material. The electrons emitted from the cathodes of electron tubes (such as cathode ray tubes) are thermions.

thermometer An instrument used to measure temperature.

thermometric property A physical property that changes measurably with temperature.

threshold frequency The lowest frequency of electromagnetic radiation that will result in the emission of photoelectrons from a specified metal surface.

thrust A type of force due to an engine (usually forward force).

ticker timer and ticker tape A standard ticker timer has frequency of 50 Hz and makes 50 dots per second on ticker tape.

time interval An SI quantity, measured in seconds (s).

time zone A time zone is a region of the globe that observes a uniform standard time for legal, commercial, and social purposes.

torque/moment Moment = force x perpendicular distance from the pivot to the line of action of the force.

torque Torque = one of the forces x the distance between them.

transmitter An electronic device used in telecommunications to produce radio waves in order to transmit or send data with the aid of an antenna.

transmutation A change in the structure of atomic nuclei and hence may be induced by a nuclear reaction, such as neutron capture, or occur spontaneously by radioactive decay, such as alpha decay and beta decay.

transverse waves Characterised by particle motion being perpendicular to wave motion. Examples of these waves are: vibrations in strings, ripples on water surface and electromagnetic waves.

trough The opposite of a peak, so the minimum or lowest point in a cycle.

turning forces More than one force that if unbalanced will cause a rotation.

U

ultrasound frequency The number of ultrasound waves per second; medical ultrasound machines use waves with a frequency ranging between 2 and 15 MHz.

ultraviolet radiation That portion of the electromagnetic spectrum extending from the violet, or short-wavelength end of the visible light range to the X-ray region.

V

vacuum Space in which there is no matter or in which the pressure is so low that any particles in the space do not affect any processes being carried on there. It is a condition well below normal atmospheric pressure and is measured in units of pressure (the pascal).

vector A quantity with magnitude and direction.

velocity-time graph A motion graph which shows velocity against time for a given body.

velocity $Velocity = \frac{Displacement}{Time}$ or $v = \frac{s}{t}$ where v is velocity, s is displacement and t is time.

vibration Periodic back-and-forth motion of the particles of an elastic body or medium, commonly resulting when almost any physical system is displaced from its equilibrium condition and allowed to respond to the forces that tend to restore equilibrium.

volume A physical quantity representing how much 3D space an object occupies, measured in cubic metres (m^3).

W

wavelength The distance between any point on one cycle of a wave to the corresponding point on the next cycle of the wave.

wave-particle duality The exhibition of both wave-like and particle-like properties by a single entity. For example, electrons undergo diffraction and can interfere with each other as waves, but they also act as point-like masses and electric charges.

weight The weight of an object is the force of Earth's gravity acting on it. The gravitational force acting on a body is measured in newtons (N). Weight = mass x gravitational force.

white dwarf Compact stars with extremely high interior densities and are the most common end product in the evolution of stars.

Z

zenith An imaginary point directly "above" a particular location, on the imaginary celestial sphere. The zenith is the "highest" point on the celestial sphere.

zero error Zero error occurs when a measuring instrument registers a reading when there should be no reading.

GRADE 9

Physics

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