South Sudan

Secondary Physics 4

Student's Book

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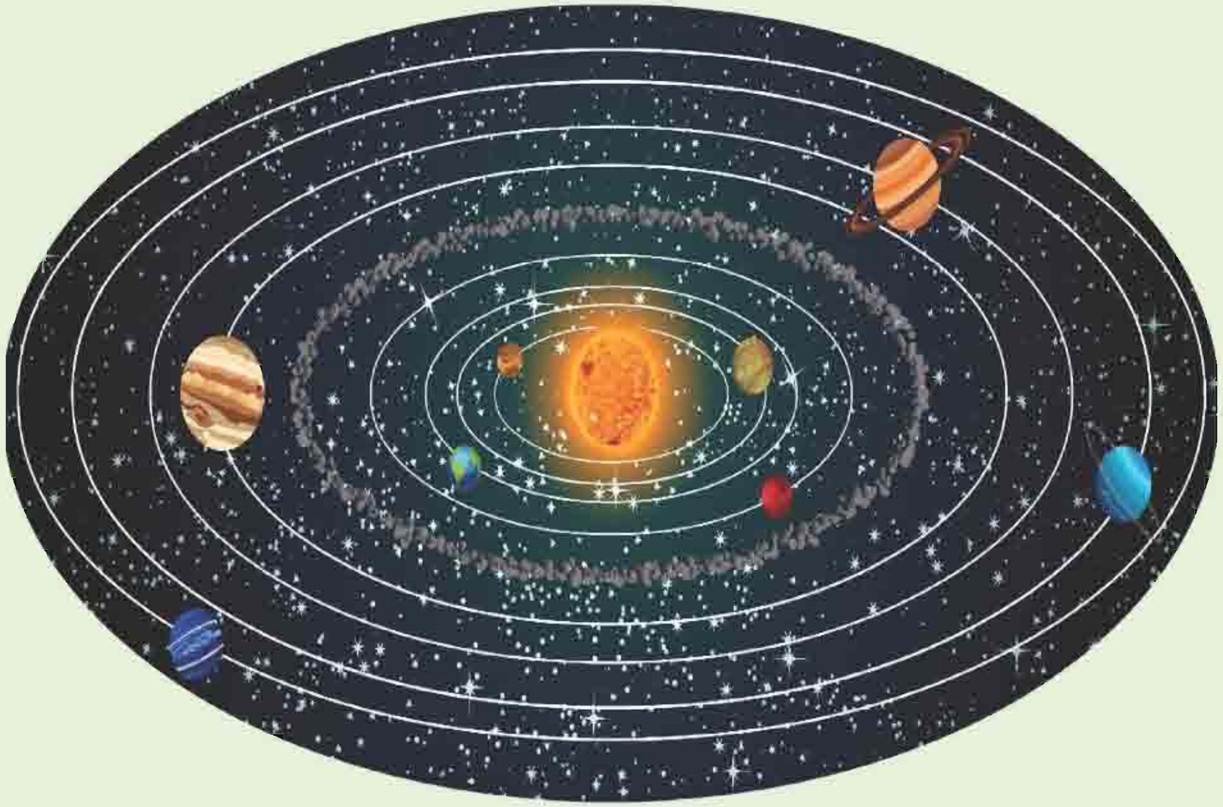
Secondary Physics Student's Book 4

South Sudan

THE REPUBLIC OF SOUTH SUDAN
MINISTRY OF GENERAL EDUCATION AND INSTRUCTION

Secondary Physics 4

Student's Book



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South Sudan

SECONDARY 4

Physics

Student's Book 4

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FOREWORD

I am delighted to present to you this textbook, which is developed by the Ministry of General Education and Instruction based on the new South Sudan National Curriculum. The National Curriculum is a learner-centered curriculum that aims to meet the needs and aspirations of the new nation. In particular, it aims to develop (a) Good citizens; (b) successful lifelong learners; (c) creative, active and productive individuals; and (d) Environmentally responsible members of our society. This textbook, like many others, has been designed to contribute to achievement of these noble aims. It has been revised thoroughly by our Subject Panels, is deemed to be fit for the purpose and has been recommended to me for approval. Therefore, I hereby grant my approval. This textbook shall be used to facilitate learning for learners in all schools of the Republic of South Sudan, except international schools, with effect from 4th February, 2019.

I am deeply grateful to the staff of the Ministry of General Education and Instruction, especially Mr Michael Lopuke Lotyam Longolio, the Undersecretary of the Ministry, the staff of the Curriculum Development Centre, under the supervision of Mr Omot Okony Olok, the Director General for Quality Assurance and Standards, the Subject Panelists, the Curriculum Foundation (UK), under the able leadership of Dr Brian Male, for providing professional guidance throughout the process of the development of National Curriculum and school textbooks for the Republic of South Sudan since 2013. I wish to thank UNICEF South Sudan for managing the project funded by the Global Partnership in Education so well and funding the development of the National Curriculum and the new textbooks. I am equally grateful for the support provided by Mr Tony Calderbank, the former Country Director of the British Council, South Sudan; Sir Richard Arden, Senior Education Advisor of DfID, South Sudan. I thank Longhorn and Mountain Top publishers in Kenya for working closely with the Ministry, the Subject Panels, UNICEF and the Curriculum Foundation UK to write the new textbooks. Finally, I thank the former Ministers of Education, Hon. Joseph Ukel Abango and Hon. Dr John Gai Nyuot Yoh, for supporting me, in my previous role as the Undersecretary of the Ministry, to lead the Technical Committee to develop and complete the consultations on the new National Curriculum Framework by 29 November 2013.

The Ministry of General Education and Instruction, Republic of South Sudan, is most grateful to all these key stakeholders for their overwhelming support to the design and development of this historic South Sudan National Curriculum. This historic reform in South Sudan's education system is intended to benefit the people of South Sudan, especially the children and youth and the future generations. It shall enhance the quality of education in the country to promote peace, justice, liberty and prosperity for all. I urge all Teachers to put this textbook to good use.

May God bless South Sudan. May He help our Teachers to inspire, educate and transform the lives of all the children and youth of South Sudan.

Deng Deng Hoc Yai, (Hon.)

Minister of General Education and Instruction, Republic of South Sudan

CONTENTS

UNIT 1 Periodic Motion

Topics in the unit

Topic 1: Circular Motion

Topic 2: Simple Harmonic Motion

Key inquiry question

- How do we apply simple harmonic motion in our daily activities?
- Why does the acceleration of simple harmonics tend towards the centre?
- Why does water in a bucket being whirled in a vertical circle not get poured down?
- Why does a person running in a circular path tend to fall towards the center of the circle?
- Why a stone being whirled in a circular motion fly along the tangent when released?

Learning outcomes

Knowledge and understanding

- Understand momentum, circular and harmonic motion.

Skills

- Carry out practical investigations on uniform circular motion.
- Investigate types of forces, such as centripetal and centrifugal associated with whirling a tied object.
- Compare simple harmonic motion with uniform circular motion.
- Investigate the free oscillation of a simple pendulum.
- Derive mathematical expressions that relate period, frequency and angular frequency.
- Investigate simple harmonic motion.
- Compare simple harmonic motion with uniform circular motion.

Attitude and value

- Appreciate the impact of momentum.

TOPIC 1 Circular motion

Topic outline

- Illustrating circular motion
- Angular displacement and angular velocity
- Circular motion and centripetal force
- Centripetal acceleration
- Applications of circular motion

Introduction

You may have observed the following phenomena:

1. An athlete running in a circular path leans inwards towards the centre.
2. A bucket of water is swung round in a circle without water spilling out.
3. As children play on a merry-go-round, the machine rotates fast making a circular motion.

These and many other similar effects are as a result of motion of bodies in a circular path. You will understand the physics behind these observations after going through this unit, where we shall consider the motion of particles describing a circular path either in a horizontal or vertical circle.

1.1 Illustrating circular motion

The following activities 1.1 to 1.3 illustrate some cases of circular motion.

Activities 1.1: **Motion of drops of water on a rotating umbrella**

Work as a whole class activity.

Materials

- An umbrella
- Water

Steps

- Take an umbrella, wet its cloth with water. With the umbrella open and its handle horizontal, rotate the handle in a circular manner, as shown in Fig. 1.1.

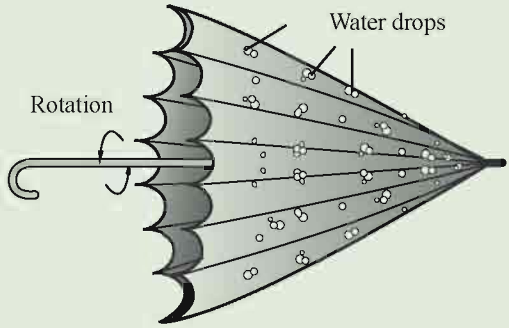


Fig. 1.1: An umbrella rotated in a circular motion

- Rotate the handle faster and watch the motion of the umbrella and the drops of water on the cloth of the umbrella. What happens to the drops of water? Why?

You should have observed that initially the water drops move in a circular path with the cloth of the umbrella. The force of adhesion between the drops of water and the cloth makes the cloth and the drops of water to move together in a circular path. As the speed of the handle increases, the adhesive force of the drops of water *'gives up'* and the drops of water break off from the cloth and fly off.

Activities 1.2: **Motion of a rotating mass attached to a spring balance**

Work in groups.

Materials

- Disc, peg, spring balance, 100 g mass.

Steps

1. Take a disc with a smooth surface and mount it horizontally, with a peg through its centre, so that it can be rotated about a vertical axis. Attach one end of the string to the peg and the other end to a spring balance.

   Place the spring balance along the radius of the disc. Attach a mass (100 g) to the other end of the spring balance using a string as shown in Fig. 1.2.

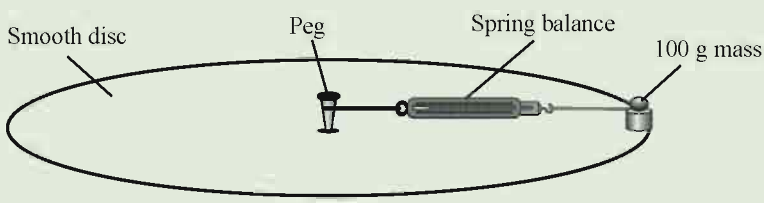


Fig. 1.2: A disc in a circular motion

2. Rotate the disc, observe and explain what happens to the reading of the spring balance. What happens to the mass? Describe the force acting on the mass.

You should have observed that the mass moves outwards and the string tightens. The spring balance reads the force exerted by the string on the mass. When the speed increases, the reading increases. The balance reading is a measure of the force directed towards the centre.

Activity 1.3: **Motion of a rotating ball attached to a string**

Work in groups.

Materials

- A small ball
- A string

Steps

1. Tie a small ball to one end of a string. Grip the free end of the string with one hand and rotate it in a circular manner, above the head, so that the ball moves in a horizontal circle (Fig. 1.3 (a)).

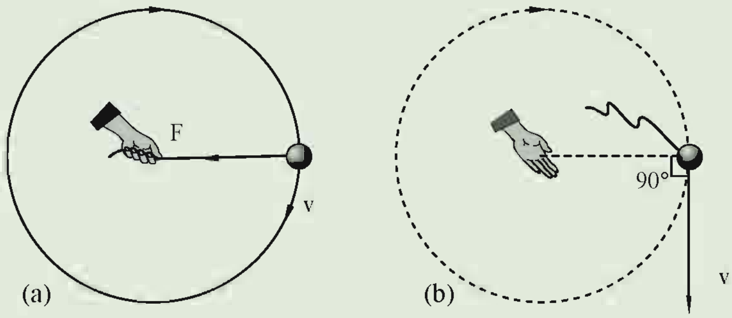


Fig. 1.3: Rotating ball attached to a string

Precaution: Make sure that the ball is tied securely to the string and the area around you is free.

2. Rotate the hand faster and then release the string. What happens to the ball as the string is released? Explain.

You should have observed that as the hand is rotated faster, the ball moves in a circular path with a higher speed, along with the hand. The pull of the hand on the string provides a force directed towards the centre and the ball is kept in a circular path of constant radius. When the string is released, suddenly there is no tension in the string and the ball having uniform velocity flies off along the tangent to the circle, at the point of release (Fig. 1.3(b)).

Activities 1.1 to 1.3 illustrate the motion of a body in a circle of certain radius. If the radius sweeps equal angles in each second, then the angular velocity of the body is uniform and the body is said to execute *uniform circular motion*.

There are two types of circular motion:

(a) Uniform circular motion – Is the motion of a body moving in a circular path at constant speed. Thus, its velocity changes due to change in direction only.

(b) Non-uniform motion – Is the motion of a body moving in a circular path at changing speed. Thus, its velocity changes due to change in speed and direction.

1.2 Terms used to describe circular motion

Activity 1.4: **To identify the terms used to describe circular motion**

Work individually.

Materials

- Geometrical set
- Optical pin
- Scissors
- Manilla paper

Steps

1. Research from references books the meaning of the terms angular displacement, angular velocity and frequency.
2. On a manilla paper, draw accurately a circle centre O of radius 7 cm and in it a sector of OMN with ∠MON = 30°.

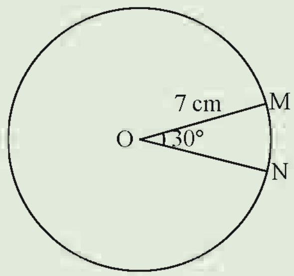


Fig. 1.4

3. Using the relevant formula, determine the length of arc MN.
4. Using arc length MN and radius OM, determine the value of ∠MON in radians.
5. Cut out the circle from the manilla paper and fix some plasticine at point M. Fix a pin through centre O and rotate the cut out vertically with the pin as the axel.
6. Suppose during the rotation the point M takes 0.4 s to move through distance MN; determine
   (a) Linear velocity of the plasticine ball (v).
   (b) Angular velocity of the plasticine ball (ω).
   (c) Frequency of rotation of the cut out (f).
7. Derive the mathematical expressions relating
   (a) linear velocity and angular velocity.
   (b) angular velocity and frequency.

1.2.1 Angular displacement

Consider a particle moving along a circular path. As the particle moves along the arc of the circle from A to B (Fig. 1.5), the line OA (radius r) joining the particle to the centre of the circle sweeps through an angle θ.

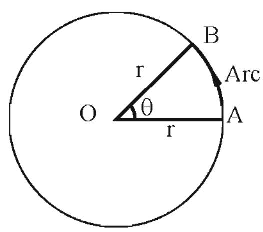


Fig. 1.5: Angular displacement

The angle swept is called *angular displacement*. It is measured in *radians*.

In Fig. 1.6(a), the length of the arc AB is equal to the radius r of the circle. The angle subtended by this arc at the centre of the circle is equal to *one radian*.

One radian is the angle subtended at the centre of a circle by an arc of length equal to the radius of the circle.

If the length of the arc is 2 times the radius, then the angular displacement is 2 radians. For the whole circle, the length of the arc is its circumference, i.e ($2\pi r$). The angular displacement is therefore 2π radians (Fig. 1.6(b)).

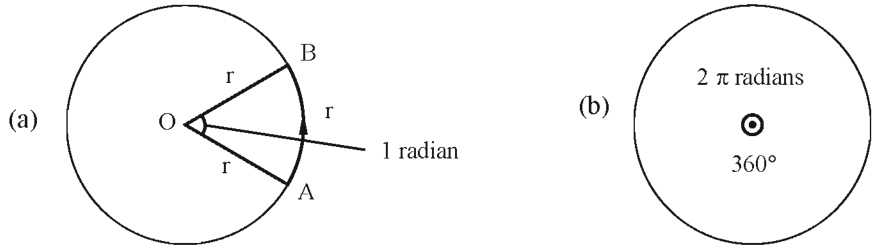


Fig. 1.6: The radian measure

Note: radians is also denoted as rad or ^{c}

The angle at the centre of a circle is 2π radians. It is also equal to 360°. Therefore, 2π radians = 360°

From this, we see that,

$$1 \text{ radian} = \frac{360°}{2\pi} = 57.3°$$

If the angle at the centre of a circle is 1 radian, then the length of the arc is r units. If the angle at the centre is θ radians (Fig. 1.7), the length s of the arc AB of the circle is given by

$$s = \frac{r}{1 \text{ rad}} \times \theta \text{ rad} = r\theta$$

Arc length $s = r\theta$

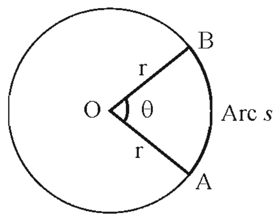


Fig. 1.7: Arc length s

Example 1.1

The radius of a particle moving along a circular path sweeps through an angle of 60° at the centre of the circle. Calculate the angular displacement of the particle in radians.

Solution

$$360° = 2\pi \text{ rad} \Rightarrow 1° = \frac{2\pi}{360°} \text{ rad}$$

$$\text{Hence, } 60° = \frac{2\pi}{360°} \times 60° = \frac{\pi}{3} \text{ radians}$$

Angular displacement of the particle = $\frac{\pi}{3}$ radians or 1.05 rad.

1.2.2 Angular velocity

A body moving from point A to point B in a *straight line* (Fig. 1.8) has *linear velocity*.

Fig. 1.8: Linear velocity

Linear velocity (v) is defined as the rate of change of linear displacement.

$$\text{Linear velocity } v = \frac{\text{linear displacement}}{\text{time}} = \frac{x}{t}$$

Consider a particle moving along a circular path covering an arc of length AB in a time, t (Fig. 1.9). The angular displacement of the radius OA is in the same time t. Such a body is said to have has angular velocity (ω).

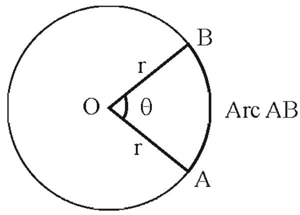


Fig. 1.9: Angular velocity

Angular velocity is defined as *the rate of change of angular displacement*.

$$\text{Angular velocity } \omega = \frac{\text{angular displacement}}{\text{time}} = \frac{\theta}{t}$$

It is expressed in radians per second (rad/s).

1.2.3 Relationship between angular velocity and frequency

For one complete cycle, $\theta = 360° = 2\pi$ radians and the time taken

$t = T$, (referred to as the periodic time).

$$\text{Hence } \omega = \frac{\theta}{t} = \frac{2\pi}{T}$$

Since the frequency of revolution $f = \frac{1}{T}$, we get $\omega = \frac{2\pi}{T} = 2\pi f$.

Therefore, angular velocity $\omega = 2\pi f$

1.2.4 Relationship between the angular velocity and the linear velocity

We have seen that when a body is whirled round it moves with an angular velocity (ω). However, when the string is released suddenly when is no tension and the ball flies off along a tangential velocity or with a linear velocity (v).

We have seen that the arc length, $s = r\,\theta$.

Dividing both sides by t, we get, $\frac{s}{t} = \frac{r\theta}{t}$.

But $\frac{s}{t}$ is the linear velocity or tangetial velocity, v of the rotating particle and $\frac{\theta}{t}$ is its angular velocity.

$\therefore$ linear speed, v = radius(r) × angular velocity (ω)

$$\therefore \quad v = r\omega$$

Example 1.2

Fig. 1.10 shows the motion of the second hand of a clock. Calculate its angular velocity.

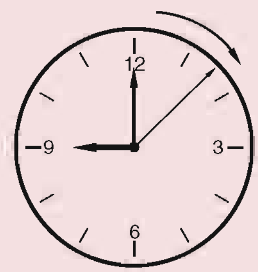


Fig. 1.10: Motion of the second hand of a clock

Solution

Angular velocity, $\omega = \frac{\theta}{t}$

The tip of a second hand takes 60 seconds to make one complete revolution i.e. 2π rad. Therefore,

$$\omega = \frac{2\pi}{60} = 0.105 \text{ rad/s}$$

Example 1.3

A bicycle wheel makes 300 revolutions per minute (rpm). Calculate the angular velocity of the wheel.

Solution

The wheel makes 300 revolutions in 1 minute. Therefore in each second the wheel makes $\frac{300}{60}$ = 5 revolutions.

1 revolution = 2π rad

5 revolutions = $5 \times 2\pi$ rad = 10π rad

$$\omega = \frac{\theta}{t} = \frac{2\pi\pi}{T} = \frac{10\pi\pi}{1} = 31.4 \text{ rad/s}$$

The angular velocity of the wheel is 31.4 rad/s.

Example 1.4

Calculate the angular velocity of the earth when it is rotating about its own axis. (Time period of the earth about its own axis = 24 hours).

Solution

The earth takes 24 hours to rotate once about its own axis. Hence the angular velocity (ω) is given by,

$$\omega = \frac{\theta}{t} = \frac{2\pi\pi}{(24 \times 60 \times 60)} = \frac{2\pi}{86\,400 \text{ s}}$$

$$= 7.3 \times 10^{-5} \text{ rad/s}$$

Example 1.5

A ball tied to a string is rotated at uniform speed in a circle of radius 10 cm. It takes 1.5 s to describe an arc of length 6 cm. Calculate its

(a) tangential velocity. (b) angular velocity (c) periodic time.

Solution

(a) Linear speed, $v = \frac{x}{t} = \frac{6}{1.5} = 4.0$ cm/s

(b) Since linear speed, v = ω r, angular velocity, $\omega = \frac{v}{r} = \frac{4.0}{10} = 0.4$ rad/s

(c) $\omega = \frac{2\pi\pi}{T}$, hence $T = \frac{2\pi\pi}{\omega} = \frac{2\pi\pi}{0.4} = 15.7$ s

Exercise 1.1

1. Define angular displacement and state its SI units.
2. (a) Define the radian measure.
   (b) Convert the following angles into radian measure:
   (i) 40° (ii) 270° (iii) 540°
3. The radius of a circle is 6 m. Calculate the length of the arc of the circle, if the angle subtended by the arc, at the centre is (a) 180° (b) 60°
4. Calculate the angular velocity of the minute hand of a wrist watch.

5. What do you understand by the term angular velocity? Deduce the relationship between the linear velocity and angular velocity.
6. A fly wheel is rotating at 10 revolutions in every 2 seconds. Calculate its angular velocity.
7. A particle revolves at 2 Hz in a circle of radius 2 m. Calculate its
   (a) angular speed. (b) linear velocity.
8. The wheel of a car of radius 20 cm is rotating at a frequency of 20 Hz. Calculate the linear speed of the car.

1.3 Centripetal force and acceleration

Sir Isaac Newton noted that the motion in a straight line is a common phenomenon and that deviations from this type of motion are caused by a force pulling the body out of the line. When the force acts on the body from a fixed point, then the body describes a circular motion. The following experiments will help us to understand the factors that determine the magnitude of this force.

Activity 1.5: **To investigate the relationship between the force (F) and the speed of revolution (v) of a body undergoing circular motion**

Work in groups.

Materials

- A glass or plastic tube
- A string 1.5 m long
- A paper clip
- A crocodile clip
- A mass

Steps

1. Obtain a glass or plastic tube of length 15 cm and about 1 cm in diameter (e.g. casing of a biro pen). Tie a body of mass m to the end of a thick string of length 1.5 m. Pass the free end of the string down through the tube and attach a hanger of known mass m.
2. Attach a long paper clip or a crocodile clip to the vertical portion of the string which can act as an indicator to keep the radius of the circular path constant and to check that the motion is steady (Fig. 1.11).

   Precaution: Make sure that mass m is tied securely to the string and the area around you is clear of other students and other things.

3. Adjust the position of the paper clip so that the radius of the circular path is 1 m, i.e. the length of the horizontal portion of the string is 1 m. Grip the tube with one hand and swing the hand above the head, so that mass m moves in a horizontal circle of radius 1 m. (Fig. 1.11)

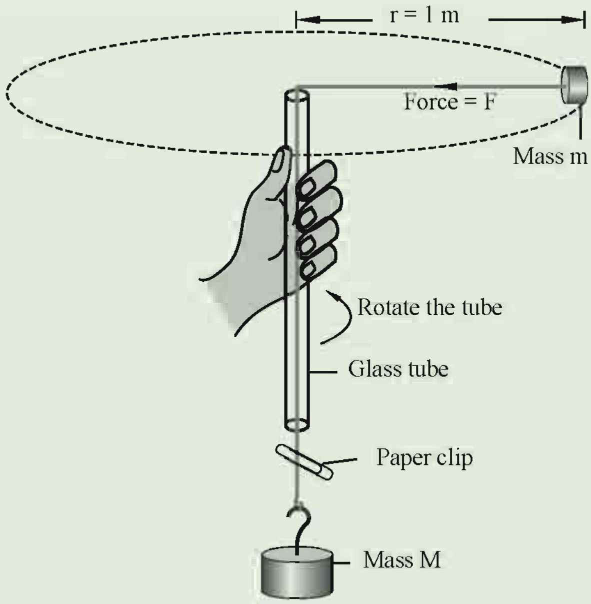


Fig. 1.11: A mass moving in a horizontal circle

4. Note the number of revolutions made by the mass *m* in a certain time. Calculate the frequency of revolutions *f*, i.e. the number of revolutions made by mass *m* in 1 second.

   Determine the periodic time $T(= 1/f)$. Calculate the linear speed (v) of revolution of the mass *m* from the equation, $v = 2\pi r/T$.

5. Keeping the mass *m* constant and the radius of the circular path as 1 m, add slotted masses M to the hanger and rotate the tube faster each time. Determine the frequency of revolutions and the corresponding speed, *v* of mass *m*. Record your observations in a table (Table 1.1).

Table 1.1

Mass of the hanger and the slotted masses (*M*) (kg)	Number of revolutions made in time *t* (N)	Frequency (*f*) $f = \frac{N}{t}$ (Hz)	*T*(s)	Speed v (r = 1 m)

6. Deduce the relationship between masses *M* in the hanger and the speed of revolution *v* of the mass (*m*).

The tension developed in the string due to the force of gravity on the hanger and the slotted masses (*Mg*) provides the horizontal force (*F*) needed to keep mass *m* in a circular path.

It is observed that when the frequency is doubled (i.e. time period is halved) the speed of revolution (v) of mass m is doubled and the force F needed to maintain the same radius as before is *4 times* more. Similarly the force needed is 9 times more, when the speed is trippled (increased 3 times). As the weight of the hanging masses (Mg) provides the required force F for circular motion, it can be concluded that: *The force F required to keep the body in a circular path of constant radius is directly proportional to the square of the speed of revolution*. Hence

$$F \alpha v^2$$

Activity 1.6: **To investigate the relationship between the force (F) and the radius (r) of the circular path**

Work in groups.

In this activity, you will design and carry out an investigation on the relationship between centripetal force (F) and the radius (r) of a circular path.

Instructions

1. Use the set up for Activity 1.5.
2. Identify the quantities to vary and those you will keep constant.
3. Write down the procedure.
4. Carry out the investigations, recording your data in Table 1.2.

Table 1.2

Mass of the hanger and the slotted mass M (kg)								
Radius r (m)								

5. Analyse the data.
6. Determine and write down the relationship between the values of mass M and radius r.

It is seen that when the mass (M) is doubled, the radius of the circular path is halved. i.e. the mass required to keep mass (M) in a circular path of radius $r/2$ is $2M$. Similarly when the mass is $3M$, the radius is $r/3$ and so on. From this experiment it can be concluded that

The force F needed to keep a body in circular motion is *inversely proportional to the radius r of the circular path, when the speed of revolution of the body is constant*. Hence

$$F \alpha \frac{1}{r}$$

Activity 1.7: **To investigate the relationship between the force (F) and mass m of a body undergoing circular motion**

Work in groups.

Materials

- Four 20 g masses
- 1.5 m long string
- A glass tube

Steps

1. Attach a known mass m to the string and repeat Activity 1.5 when the radius of the circular path is 1 m. Find the number of revolutions made by mass m in a certain time and determine the frequency of revolution.
2. Tie two identical masses (mass $2m$) securely to the end of the string and at the same time add one slotted mass M to the hanger so that the total hanging mass is $2M$.
3. Repeat the above experiment, keeping the radius of the circular path constant ($1m$), and determine the frequency of revolution of the mass m. Increase the number of identical masses (m) tied to the string and each time add one more identical slotted mass M to the hanger.
4. Repeat the experiment to maintain the same radius as before and determine the frequency of revolution each time. Record your observations in a table (Table 1.3).

Table 1.3

Mass attached to the string m (kg)	Mass of the hanger and the slotted masses M (kg)	Number of revolutions made in time t (N) (s)	Frequency (f) $f = \frac{N}{t}$ (Hz)

5. Deduce the relationship between mass m of the body, the hanging masses M, and the frequency of revolution of the mass m.

It is seen that as mass m of the body undergoing circular motion increases, the hanging mass M also increases in the same ratio and the frequency of revolution of the mass m is the same each time. From this experiment, it can be concluded that

The force F required to keep a body in circular motion is directly proportional to the mass undergoing circular motion. Hence

$$F \propto m$$

From Activities 1.5, 1.6 and 1.7 we can conclude that the force (F) required to keep a body in a circular path depends upon three factors namely the speed of revolution of the body (v), the radius of the circular path (r) and the mass of the body undergoing circular motion (m) or

$$F \propto v^2, \quad F \propto \frac{1}{r} \quad \text{and} \quad F \propto m.$$

1.3.1 Centripetal force

In Activities 1.5, 1.6 and 1.7, an external force acts towards the centre of the circle and keeps the body of mass m at a fixed distance from the centre i.e. the force constrains the body in motion to move in a circular path. This force is called *centripetal force* (Fig. 1.12. Centripetal is a Greek word meaning 'seeking centre'. So this force is also called *the centre seeking force*.

The activities also showed that centripetal force $F \propto v^2$, $F \propto \frac{1}{r}$ and $F \propto m$, which when combined together gives:

$F = \frac{Kmv^2}{r}$ where k is the constant of proportionality

Experiments show that $K = 1$

Centripetal force $F = \frac{mv^2}{r}$ where,

m is the mass of the object

v is the linear speed along the circular path in m/s

r is the radius of the circular path

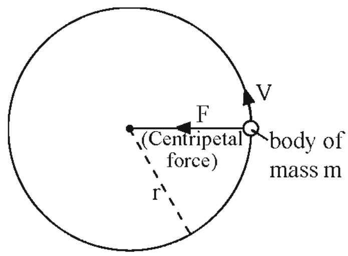


Fig. 1.12: Centripetal force

1.3.2 Centripetal force in terms of angular velocity

From experiments, centripetal force, F is given by; $F = \frac{mv^2}{r}$

But v = rω. where ω is angular velocity. Substituting for $F = \frac{mv^2}{r}$

$$F = \frac{m(r\omega)^2}{r} = \frac{mr^2\omega^2}{r} = mr\omega^2$$

$$F = mr\omega^2$$

What happens when the centripetal force fails?

In Activity 1.1, the force of adhesion between the water drops and the cloth of the umbrella provides the centripetal force. When the wheel of the bicycle or the umbrella starts moving at higher speeds, the centripetal force acting towards the centre of the circle increases. Since the adhesive force is small, it is not able to provide the required centripetal force and the mud particles or the water molecules fly off along the tangent.

Similarly in Activity 1.3, the hand exerts a pull and provides the centripetal force necessary to keep the ball in a circular orbit. The moment the string is released, the centripetal force on the ball ceases to act. If there is no centripetal force, then there can be no circular motion. But the ball has a velocity (v) along the tangent to the circle and hence flies off along the tangent, as shown in Fig. 1.3(b). For any circular motion, there should be a centripetal force towards the centre of the circle, provided by an external agent.

1.3.3 Centripetal acceleration

When a body executes uniform circular motion, though the speed is uniform, its direction of motion is continuously changing. The direction of motion of the body at a point P is along the tangent drawn at P. When the body is at Q, it is along the tangent drawn at Q and so on, as shown in Fig. 1.13.

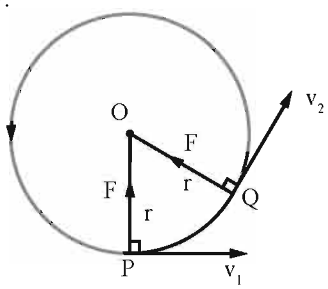


Fig. 1.13: Centripetal acceleration

Speed is a scalar quantity with magnitude only, whereas velocity is a vector quantity with both magnitude and direction. For a body in uniform circular motion, the linear velocity changes continuously since its direction changes continously in as much as its magnitude is constant. Change of velocity with time is the acceleration and so during circular motion, the body is accelerating due to continous change in direction though the speed remains uniform.

$$\text{Acceleration} = \frac{\text{change in velocity}}{\text{time taken}} = \frac{v_2 - v_1}{t}$$

From Newton's second law,

$$F = ma$$

But centripetal force,

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

Therefore the centripetal acceleration, a, of a body towards the centre is given by

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

where $v_2 = v_1 = v$ (in magnitude) and r is the radius of the circular path. This acceleration is called *the centripetal acceleration* and is different from the usual linear acceleration. The centripetal acceleration acts towards the centre of the circle and is at 90° to the tangent at each point of motion.

Therefore, $a = \omega^2 r$

Example 1.6

A 5 kg mass moves at uniform speed of 18 m/s in a circular path of radius 0.5 m. Calculate the centripetal force acting on the mass.

Solution

Centripetal force, $F = m\frac{v^2}{r}$

$= 5 \times \frac{18^2}{0.5}$

$= 3\ 240$ N

Example 1.7

A car of mass 1 200 kg has to make a circular turn of radius 30 m. If it is moving with a uniform speed of 10 m/s, calculate the centripetal force acting on the car.

Solution

Centripetal force, $F = m\frac{v^2}{r}$

$= \frac{1\ 200 \times 10^2}{30}$

$= 4\ 000$ N

Exercise 1.2

(Take $g = 10$ m/s^2, where necessary)

1. Define centripetal force and write the equation for centripetal force.
2. A student makes the following statement "A body moving with uniform speed is accelerating." Under what conditions this is true?
3. A satellite orbits the earth once every 4 hours. Calculate
   (a) the angular velocity of the satellite,
   (b) the centripetal acceleration of the satellite, if the radius of the satellite's orbit is 12 800 km,
   (c) the linear speed of the satellite.
4. A giant wheel of radius 20 m is rotating about its axis at a frequency of 5 Hz. Find
   (a) the angular velocity in radian/second,
   (b) the linear speed of a point on the rim of the wheel,
   (c) the centripetal acceleration at the edge of the wheel.

5. An artificial earth satellite of mass 8 000 kg describes a circular orbit close to the earth's surface in 90 minutes. Calculate the acceleration of the satellite and centripetal force, if the radius of the earth is 6 400 km.

6. A particle of mass 6 kg revolves at 2 Hz in a circular path of radius 2 m. Calculate its

   (a) linear speed

   (b) centripetal acceleration

   (c) angular velocity

   (d) centripetal force

1.4 Applications of uniform circular motion

1. A car negotiating a circular path on a level horizontal road

When a car is going round a circular path on a horizontal road, the centripetal force required for circular motion is provided by the frictional force F, between the tyres and the road (Fig. 1.14).

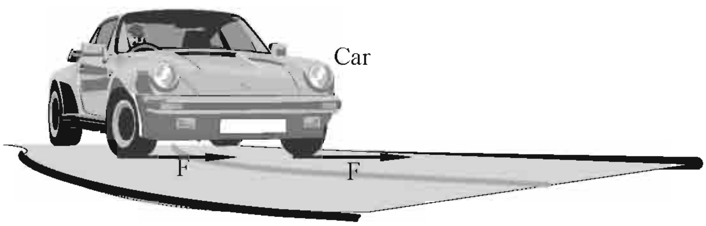


Fig. 1.14: A car going round a curve on a level road.

Centripetal force F = mv^2/r, where m is the mass of the car, v is its uniform speed and r is the radius of the circular path taken by the car. Hence

$$v_{max} = \sqrt{F \times \frac{r}{m}}$$

This is the maximum safe speed for the motorist not to skid off the track.

2. Banked tracks

In order that a motorist does not fully depend on the frictional force between the tyres and the road, circular paths are given a small *banking angle*, i.e. the outer edge of the road is raised a little above the inner side so that the track is sloping towards the centre of the curve. Fig. 1.15 shows a part of the contact force R (the normal reaction force) acting towards the centre of the circle providing the required centripetal force.

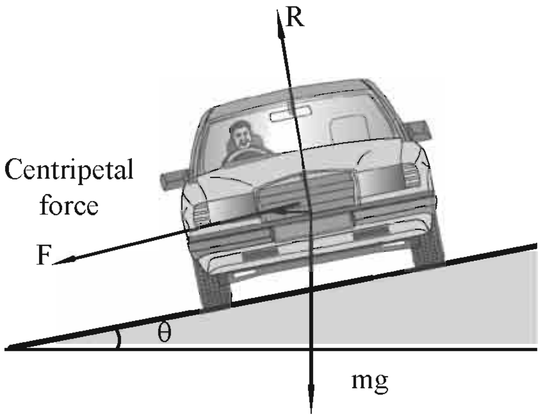


Fig. 1.15: Car on a banked road

3. Leaning inward of a cyclist

A cyclist going round a curve leans inwards to provide the necessary centripetal force, so as to be able to go along the curved track. Just like car on a banked track, a part of the contact force or the reaction force provides the required centripetal force acting towards the centre of the track, as shown in Fig. 1.16.

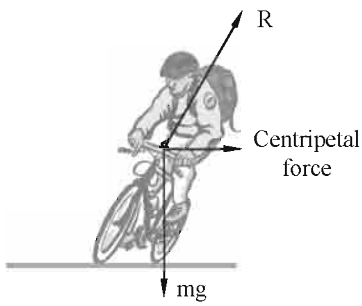


Fig. 1.16: A cyclist leans inwards when going round a curved track

4. An aircraft taking a circular turn

When an aircraft takes a turn in a horizontal plane, it must make a correct banking angle in mid air as shown in Fig. 1.17, in order to successfully negotiate the curved path.

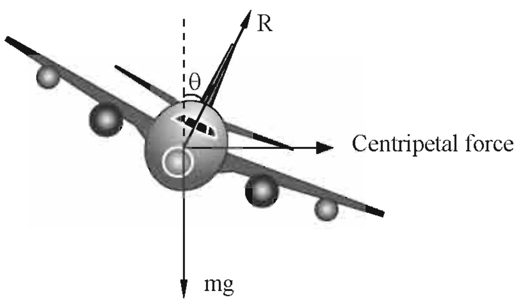


Fig. 1.17: An aircraft tilted inwards while taking a circular turn

5. *Conical pendulum*

Consider a simple pendulum held in the hand, with the bob of the pendulum hanging freely. If the hand is swung in a circular pattern, the bob of the pendulum starts revolving in a horizontal circle of radius *r*, as shown in Fig. 1.18.

If the speed of the bob is increased gradually, the radius of the circle in which the bob revolves also increases.

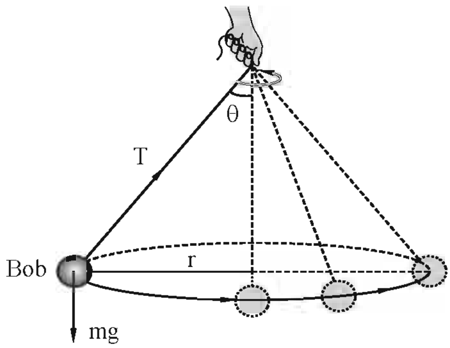


Fig. 1.18: A conical pendulum

At any stage, part of the tension T developed in the string provides the required centripetal force for the bob to execute circular motion. If the speed of the bob is increased gradually, at a certain maximum value, the string may break. If the string breaks, then the tension developed in the string is not able to provide the required centripetal force. At this critical stage, the string becomes horizontal and the maximum tension in the string, $T = m\dfrac{v^2}{r}$.

6. *Centrifuge*

Centrifuge is a device that separates liquids of different densities or solids suspended in liquids. The mixture is poured into a tube in the centrifuge, which is then rotated at a high speed in a horizontal circle, either mechanically or with the help of a motor. The tube is initially in the vertical position and takes up the horizontal position when the centrifuge starts working, as shown in Fig. 1.19. The matter of low density moves inwards towards the centre of rotation. On stopping the rotation, the tubes returns to the vertical position with less dense matter at the top.

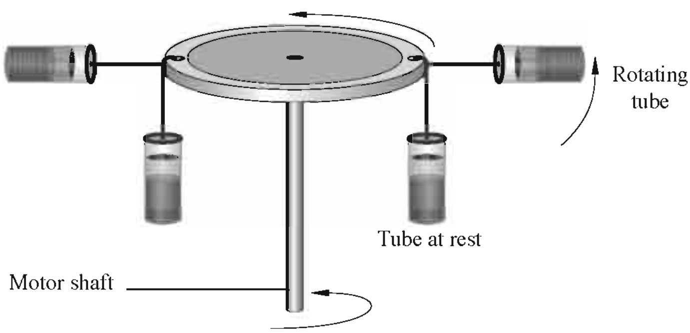


Fig. 1.19: Centrifuge

It is worthwhile to note that though the angular velocity of each part of the tube is the same, the linear speeds are different due to different radii for matters of different densities (masses).

In a cream separator, when the milk is churned rapidly, cream being lighter comes towards the top of the tube and can be removed. In the same manner when blood is rotated at a high speed in a centrifuge, red blood cells and the blood fluid are separated. Viruses and germs in the blood fluid can be separated in a similar manner. Very high speed centrifuges called *ultra-centrifuges* have been developed which can be rotated at more than a million rotations per minute and are extremely useful in medical researches. *Such researches include the study of viruses such as HIV which causes AIDS*.

⚠ Embrace people suffering from HIV and AIDS. AIDS is not a curse!

1.5 Motion in a vertical circle

Activity 1.8: **Demonstrating motion in a vertical circle**

Work in groups.

Materials

- A 10 g mass
- String

Steps

1. Tie the mass with a string and whirl it (a vertical circle slowly then faster).
2. Indicate all the forces acting on the mass and their directors at positions A, B and C as it rotates (Fig. 1.20).

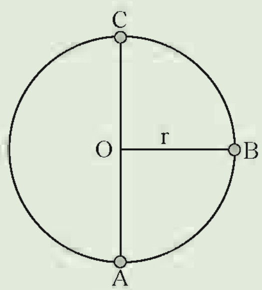


Fig. 1.20

3. Derive the expressions of tension in the string at positions A and B. In which position is the string more likely to break? Explain why?
4. Describe two applications of motion in a vertical circle.

Consider a ball whirled in a vertical circle by applying a tension through the string tied to it (Fig. 1.21).

At position A the tension in the string T_A, should provide the centripetal force as well as the force to balance the weight mg, of the ball.

Tension at A, $T_A = m \frac{v_A^2}{r} + mg$

where v_A is the speed of the ball at A and r is the radius of the circle.

At B, the tension in the string T_B provides just the centripetal force

$$T_B = m \frac{v_B^2}{r}$$

where v_B is the speed of the ball at B.

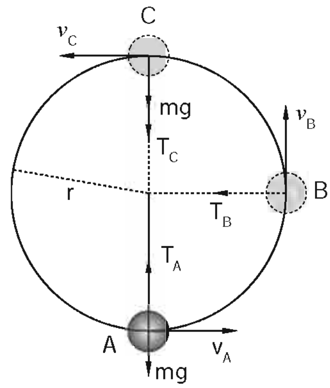


Fig.1.21: A ball whirling in a vertical circle.

At the topmost point C, the tension in the string T_C and the force of gravity mg acting on the ball must provide the centripetal force.

$$T_C = m \frac{v_C^2}{r} - mg$$

where v_C is the speed of the ball at C.

As long as the centripetal force mv_c^2/r is greater than or equal to mg, the ball will stay in the circular path at C and the string will not get slack in this position. If $mv_c^2/r = mg$, then the tension T_c will just become zero. Now

$m\, v_c^2/r = mg$ or $v_c^2 = gr$. Hence $v_c = \sqrt{gr}$. This speed $v_c = \sqrt{gr}$ is the *critical speed*, for the ball to stay in the circular path at C. If the speed at C is less than $\sqrt{gr}$, the string will get slack and the ball will not reach the topmost position of the circle.

Tension is least at C and greatest at A. Therefore the string is most likely to break at point A.

Applications of motion in a vertical circle

1. In a circus, an acrobat rides a motor cycle and makes a loop along a circular track in a vertical plane, as shown in Fig. 1.22. The critical speed at the topmost point C is $\sqrt{gr}$. This means that the motor cycle will stay in the tracks as long as the centripetal force mv^2/r is greater than or equal to mg, the total weight of the motor cycle and the acrobat.

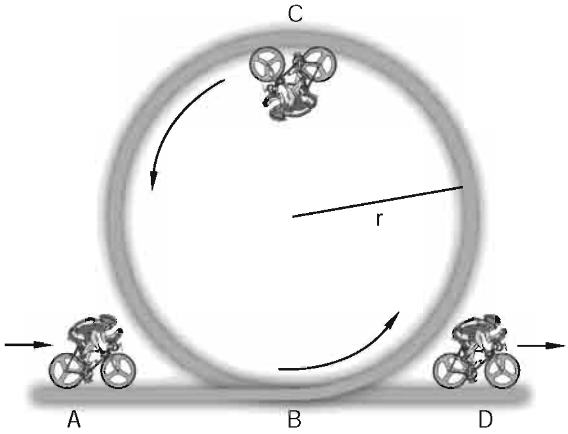


Fig. 1.22: A motor cyclist looping a vertical circle

2. A bucket of water can be swung round in a vertical circle without spilling water. The water in the bucket will stay in the track as long as the centripetal force is greater than or equal to the total weight of water and the bucket.

Example 1.8

Calculate the minimum speed with which the ball, suspended by a string of length, l (Fig. 1.23), should be projected from point A, so that it is just able to reach the topmost point in the circle.

Solution

Radius of the circle r = length of the string, l

For circular motion, the critical speed at C is given by, $v_C = \sqrt{gr}$.

By the law of conservation of energy, kinetic energy at A should be equal to the sum of the kinetic energy and the gravitational potential energy at C. i.e

$$K.E_A = (K.E + G.P.E)_C$$

$$\frac{1}{2}mv_A^2 = \frac{1}{2}mv_C^2 + mgh$$

Substituting for $v_C^2 = gr$ and $h = 2r$

$$\frac{1}{2}mv_A^2 = \frac{1}{2}m(gr) + mg(2r)$$

$$\frac{1}{2}v_A^2 = \frac{1}{2}gr + 2gr$$

$$\sqrt{v_A^2} = \sqrt{gr + 4gr} = \sqrt{5gr}$$

$$v_A = \sqrt{5gr} .$$

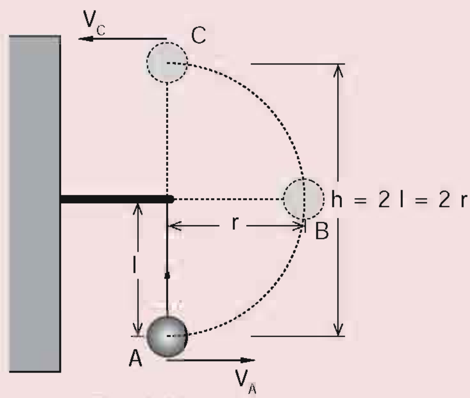


Fig. 1.23

3. *Drying machine*

Wet clothes are rotated in a cylindrical drum containing a lot of perforations. Initially the wet clothes move in a circular motion along with the drum. As the speed of the drum increases, the adhesive force of the water in the clothes 'gives up' and water breaks off from the clothes and flies off through the perforations.

Exercise 1.3

1. Explain the following statements:
   (a) A cyclist going round a curve leans inwards towards the centre.
   (b) Curved tracks are usually banked.
   (c) A pilot who is not fastened to the seat in an aircraft can "loop the loop" without falling downwards at the top of the circular loop.
2. Describe the action of a centrifuge.
3. A body of mass 400 g tied to a string, is rotated in a horizontal circle of radius 1.2 m at 2 Hz. Calculate the tension developed in the string.
4. Table 1.4 gives the values of the centripetal force F acting on a body of mass m, for different speeds v in an orbit of radius 20 cm.

Table 1.4

F(N)	8	32		128
v(m/s)	4	8	12	

   (a) Copy and complete the table. Show how you arrived at your answers.
   (b) Calculate the mass of the body.

Topic Summary

- Angular displacement of a particle is the angle swept through by the radius joining the particle to the centre of the circle.
- Angular displacement is measured in radians.
- A radian is the angle subtended at the centre of a circle by an arc length equal to the radius of a circle.
- 2π radians = 360°
- Length l of an arc of a circle is equal to $r\theta$, where θ is in the radian measure.
- Angular velocity is the rate of change of angular displacement. It is measured in radians per second.
- For a body in circular motion angular velocity, $\omega = \frac{2\pi}{T} = 2\pi f$

- Linear speed (v) = radius (r) × angular velocity (ω) i.e. $v = \omega r$
- For a body in circular motion, there should be a force acting towards the centre along the radius of the circle.
- Centripetal force is the force which acts towards the centre of a circle keeping a body in a circular path.
- Centripetal force, $F = m\frac{V^2}{r} = mr\omega^2$
- Centripetal acceleration $a = \frac{V^2}{r} = r\omega^2$
- Centrifuges, drying machines for clothes, banking of circular tracks, conical pendulums, are a few examples of applications of circular motion.

Topic Test 1

(Take $g = 10\ m/s^2$, where necessary)

1. Define centripetal force.
2. A satellite of mass 20 000 kg at a speed of 200 m/s orbits the earth once. Calculate
   (a) the centripetal acceleration of the satellite, if the radius of the satellite's orbit is 12 800 km,
   (b) the centripetal force.
3. A giant wheel of radius 20 m and mass of 3 500 g is rotating about its axis at a speed of 5 m/s. Find the
   (a) centripetal acceleration,
   (b) centripetal force acting towards the centre.
4. An artificial earth satellite describes a circular orbit close to the earth's surface with a speed of 111.1 m/s. Calculate the centripetal acceleration of the satellite, if the radius of the earth is 6 400 km.
5. A particle of mass 0.65 kg revolves in a circular path of radius 2 m with a speed of 30 m/s. Calculate its
   (a) centripetal acceleration.
   (b) centripetal force.
6. A car of mass 1.2 tonnes is moving on a circular section of a bridge of radius 25 m with a speed of 12 m/s. Calculate the centripetal force that make the car not to skid over this bridge.

7. A string with a breaking force of 3 000 N, has a mass of 600 g attached to one end and is whirled in a horizontal circle of radius 2 m. Calculate the maximum speed that will keep the string tout.

8. Explain the following statements:

   (a) A cyclist going round a curve leans inwards towards the centre.

   (b) Curved tracks are usually banked.

   (c) A pilot who is not fastened to the seat in an aircraft can "loop the loop" without falling downwards at the top of the circular loop.

9. Describe the action of a centrifuge.

10. Table 1.5 the values of the centripetal force F and the radius r, when a body of mass 500 g is undergoing circular motion with a constant speed.

Table 1.5

r (cm)	40	20	16	8	
F (N)	5	10		25	50

   (a) Copy and complete the table. Show how you arrived at your answers.

   (b) Calculate the uniform speed of the body.

   (c) Calculate the centripetal acceleration if r = 16.

11. A car of mass 1 200 kg is travelling round a bend on a road at a constant speed of 12 m/s. The radius of the circular path of the car is 20 m, as shown in Fig. 1.24.

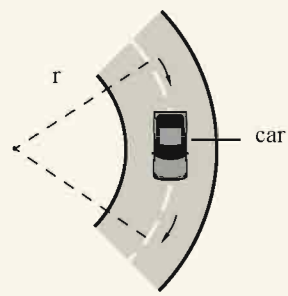


Fig. 1.24: A car moving at a bend

   (a) Explain, why, although the speed of the car is constant, it is accelerating.

   (b) Copy and complete the diagram to show the direction of the velocity and the acceleration of the car.

   (c) Calculate the centripetal force on the car.

12. Table 1.6 gives the centripetal force F acting on a body moving in a circle of radius 1 m, for the different speeds v of the body.

Table 1.6

Force F(N)	0.40	1.60	3.60	6.40	10.0	14.4
Speed v(m/s)	1.0	2.0	3.0	4.0	5.0	6.0

Draw a suitable graph to determine the mass of the body executing circular motion.

13. A car of mass 1 000 kg is negotiating a circular path of radius 20 m on a level horizontal road, where the frictional force between the tyres and the road is 7 200 N. Calculate the maximum speed with which the motorist can travel, so as not to skid.

14. A metal ball of mass 10 kg is rotated horizontally by means of a rope 4 m long. If its linear speed is 20 m/s, find the force that will snap the rope.

TOPIC 2 Simple Harmonic motion

Topic outline

- Definition of simple harmonic motion
- Terms used to describe simple harmonic motion
- Equation of simple harmonic motion
- Simple harmonic motion for a simple pendulum
- Simple harmonic motion oscillators
- Energy changes in simple harmonic motion
- Damped oscillations

Introduction

In secondary 2, we performed activities involving a simple pendulum oscillating and a marble rolling in a curved dish to investigate the law of conversation of mechanical energy. The objects oscillated between two highest points repeated until they came to rest. But what really causes this kind of motion and how can its various aspects be described and determined? In this unit, we use the same setups to analyse this motion.

2.1 Definition of simple harmonic motion

Activity 2.1: **To describe simple harmonic motion**

Work in groups.

Materials

- Clamp and stand
- pendulum bob
- string

Steps

1. Tie the pendulum bob with the string and suspend it on the clamp as shown in Fig. 2.1.

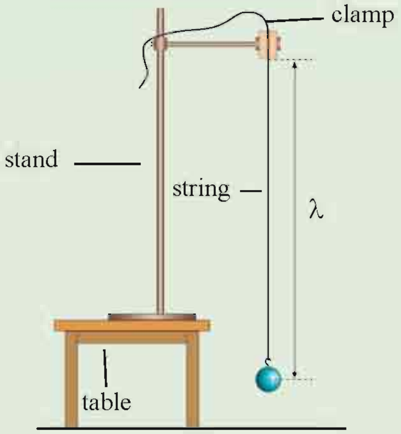


Fig. 2.1: Set-up for a simple pendulum

2. Displace the pendulum slightly from its rest position to a point A and release it to swing freely as shown in figure 2.2.

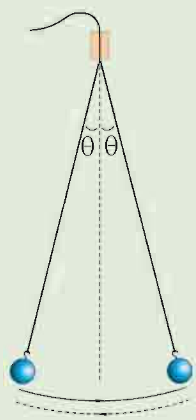


Fig. 2.2: Swinging pendulum

(a) Describe the motion of the pendulum.

(b) Explain why the pendulum swings past the resting position.

3. Compare the subsequent oscillations .

(a) Why does the displacement keep on reducing?

(b) Describe in terms of direction the force that is making the pendulum swing.

(c) How does the force in (b) vary with displacement of pendulum?

Simple harmonic is repetitive motion back and forth through an equilibrium position such that the maximum displacement on one side of this position is equal to the maximum displacement on the other side.

Consider a marble displaced from the bottom most point B (equilibrium position) in a concave dish to a maximum height at point B (figure 2.3)

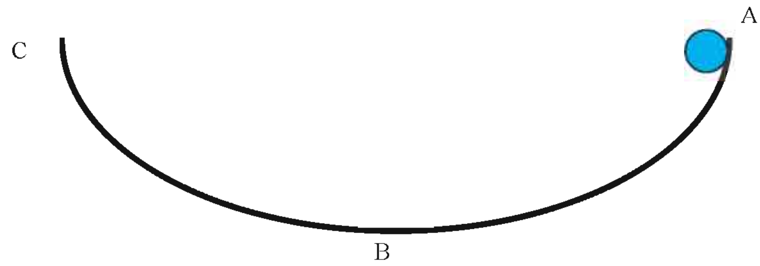


Fig. 2.3

When the marble is released, a restoring force makes it roll back to B.

At B, the momentum of the ball make the marble oscillate to the other side of B. Immediately the marble rolls past B (equilibrium position), a restoring force is generated that acts to restore the ball back to B. The marble hence keeps on decelerating up to point C; which is the maximum displacement on the other side of B. Point A and C are at the same level. Thus, the restoring force makes the marble keep on oscillating to equal displacements on the opposite sides of B.

However, the displacements from B keep on decreasing due to the external forces like friction and so does the restoring force.

Therefore, *the restoring force responsible for simple harmonic motion is directly porportional to the displacement (x) and always act in a direction opposite to that of displacement.*

This is known as the force law of simple harmonic motion and is mathematically represented as

$F \alpha x$

$F = -kx$ …… *(i)*

But from Newton's 2nd law

$F = ma$ ……… *(ii)*

Equating equations (i) and (ii), we get

$ma = -kx$ … *(iii)*

$$a = -\frac{kx}{m}$$

Since $\frac{k}{m}$ *is a constant, then*

$a \alpha -x$ …… *(iv)*

Thus, acceleration is directly proportional to displacement from the equilibrium point and is always directed towards that point. The negative signs in equations (i) and (iv) indicates that force and the acceleration act towards the equilibrium position.

2.2 Terms used to describe simple harmonic motion

Activity 2.2: **To explain terms used to describe oscillations.**

Work in pairs

Steps

Look at the graph of an oscillation shown in Fig. 2.4.

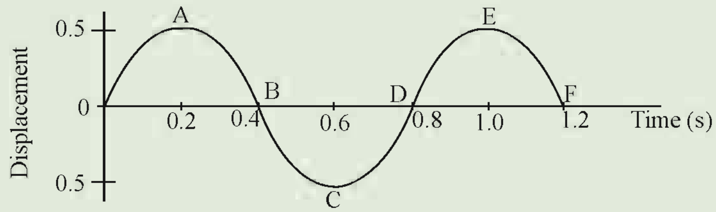


Fig. 2.4 Displacement- time graph fro an oscillation

1. Use the letters shown to identify one complete oscillation.
2. Define the following terms and determine their values for the oscillation shown in figure 2.4.
   (i) Period
   (ii) Frequency
   (iii) Velocity
   (iv) Amplitude

Period (T)

This is the time taken by an object or particle to undergo one complete oscillation. It is the time interval between two positions of the particle that are in phase i.e. in these two positions, the particle is moving at the same speed in the same direction.

For example, the periodic time for a pendulum is the time interval between the two maximum positions of the pendulum on the same sides of the rest position, or also the time taken for the pendulum to move from rest position to maximum on side, back to the mean position and then to the maximum position on the other side then back to the mean position.

Frequency, (f)

This is the number of oscillations made in one second. $f = \frac{\text{Number of cycles}}{\text{Time taken (s)}}$.

Since the period is the time taken for one oscillation, the frequency is expressed in terms of period as follows:

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

This SI unit of frequency is hertz (Hz).

Linear displacement (x)

The is the distance moved by a particle from the mean position in a particular direction

Amplitude

This is the maximum displacement of the particle from its resting (mean) position.

Linear velocity (v)

This is the rate of change of linear displacement. Its SI unit is m/s.

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

Linear acceleration (a)

This is the rate of change of linear velocity of that particle with time. Its SI unit is m/s^2

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

Angular displacement (θ)

This is the angle (in radians) moved by an object.

In one complete oscillation, angular displacement is

$$\theta = 360° = 2\pi \text{ radians}$$

Angular velocity (ω)

This is the rate of charge of angular displacement.

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

For one complete oscillation, $\theta = 2\pi$ and $t = T$(period)

Thus $\omega = \frac{2\pi}{T} = 2\pi f$ (simple $\frac{1}{T} = f$)

Figure 2.5 shows the displacement-time graph for an oscillation.

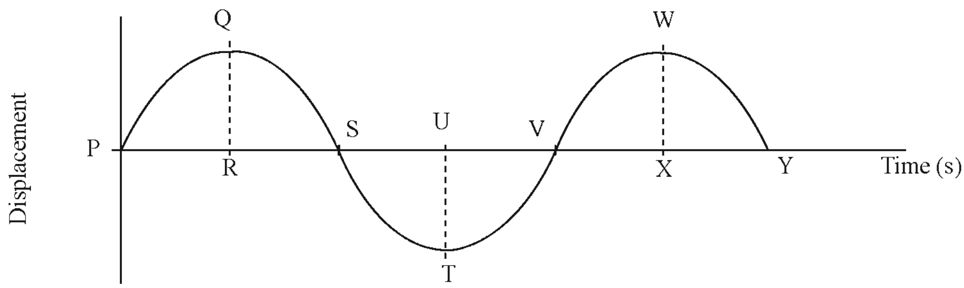


Fig. 2.5

- PQSTV or QSTVW or STVWY is one oscillation
- RQ = UT = WX is amplitude
- Time interval PV = QW = SY is period
- The graph is sinusoidal (in the shape of sine wave) hence is represented by the equation.
- Displacement $x = A \sin \theta$

  but $\theta = \omega t$

  $x = A \sin \omega t$ where A is the amplitude

2.3 Equation of simple harmonic motion

The equation of simple harmonic motion is derived from the conditions necessary for this kind of motion to occur.

Activity 2.3: **To research on differentiation of trigonometric functions**

Work in groups.

Materials

- Reference books
- Internet

Steps

1. Research from reference books on how to find the first and second derivatives of the following trigonometric equations.
   (a) $y = \sin \theta$

(b) $y = \sin a\theta$ where a is constant

(c) $y = b \sin a\theta$ where a and b are constant

2. Given that the displacement of an object is given by $x = A \sin \omega t$ where A and t are constants, find an expression for the velocity and acceleration of the object.
3. Present your findings to the rest of the class.

We have already learnt that linear velocity is the rate of change of linear displacement.

$$v = \frac{dx}{dt}$$

$$v = \frac{d(A \sin \omega t)}{dt}$$

$v = A\omega \cos \omega t$ .... (i)

But, $\sin^2 \omega t + \cos^2 \omega t = 1$ (one of the trigonometric identities)

Then, $\cos \omega t = \pm \sqrt{1 - \sin^2 \omega t}$ .... (ii)

Substituting (ii) in (i) and simplifying:

$v = \pm\omega\sqrt{A^2 - A^2\sin^2 \omega t}$ .... (iv)

Substituting $x = A \sin \omega t$ in (iv) gives

$v = \pm \omega \sqrt{A^2 - x^2}$ .... (v)

We can infer from equation (v) that the maximum linear velocity occurs when the displacement (x) of the body is zero. The velocity is zero when displacement is maximum (i.e., when displacement = amplitude).

We can obtain an expression for linear acceleration as follows:

$a = \frac{dv}{dt}$ .... (vi)

$d = \frac{d(A\omega \sin \omega t)}{dt}$ .... (vii)

$a = -\omega^2 A \sin wt$

$= -\omega^2 x$ .... (viii)

From equation (viii) we can infer that, maximum acceleration occurs when displacement x is maximum i.e. when displacement is = equal to amplitude A.

$a_{max} = -\omega^2 A$ .... (ix)

We ca also obtain an expression for acceleration as follows.

$$a = \frac{d}{dt}\left(\frac{dx}{dt}\right)$$

$$a = \frac{d^2x}{dt^2} \text{ ...... (x)}$$

Equating (ix) and (x) gives;

$$\frac{d^2x}{dt^2} = -\omega^2 x$$

$$\frac{d^2x}{dt^2} + \omega^2 x = 0 \text{ ...... (xi)}$$

Equation (xi) is known as the differential equation of simple harmonic equation. Its suitable solution is given by;

$$x = A\sin(\omega t + \Phi)$$

Where x is the displacement, A is the amplitude and Φ (phi) is arbitrary phase angle shift to cater for all starting points for the oscillation.

Example 2.1

A simple pendulum has an amplitude of 80 cm and a period of 4.0 s. Calculate the maximum

(a) velocity

(b) acceleration

Solution

(a) $v = \pm\,\omega\sqrt{A^2 - x^2}$

At v_{max}, $x = 0$

$$v_{max} = \omega\sqrt{A^2 - 0} = \omega A$$

$$= 2\pi f A = \frac{2\pi}{T} A$$

$$= \frac{2 \times 3.14 \times 0.8}{4} = 1.256 \text{ m/s}$$

(b) $a = -\omega^2 x$

at a_{max}, $x = A$

$$a_{max} = -\omega^2 A = (\frac{2\pi}{T})^2 A = -\frac{4\pi^2 A}{T^2}$$

$$d_{max} = \frac{4\pi^2 A}{T^2} = \frac{4 \times 3.14^2 \times 0.8}{4^2} = 1.97 \text{ m/s}^2$$

Example 2.2

The displacement (x) in metres of an object executing simple harmonic motion is given by $x = 5\sin(6\pi t + \frac{\pi}{2})$. Determine the:

(a) amplitude

(b) frequency

(c) velocity as it passes through mean position

Solution

(a) Comparing the equation $x = 5\sin(6\pi t + \frac{\pi}{2})$ with the general equation of simple harmonic motion i.e. $x = A\sin(\omega t + \Phi)$

We get,

$A = 5$ m, $\omega = 6\pi$ and $\Phi = \frac{\pi}{2}$

(b) $f = \frac{\omega}{2\pi} = \frac{6\pi}{2\pi} = 3\text{Hz}$

(c) $v = \frac{dx}{dt} = \frac{d}{dt}(5\sin(6\pi t - \frac{\pi}{2}) = 30\pi\cos(6\pi t + \frac{\pi}{2})$

At t = 0; $v = 30\pi\cos(\frac{\pi}{2}) = 94.21$ m/s

Example 2.3

A particle executing simple harmonic motion has velocities 8 cm/s and 5 cm/s at distances 4 cm and 6 cm respectively from mean position. Find its

(a) the amplitude

(b) the period

(c) velocity as it passes through the equilibrium position.

Solution

(a) We are given: $v_1 = 8$ cm/s, $x_1 = 5$ cm, $v_2 = 4$ cm/s, $x_2 = 6$ cm

We know $v_1 = \pm\omega\sqrt{A^2 - x_1^2}$ and $v_2 = \pm\omega\sqrt{A^2 - x_2^2}$

Hence: $8 = \pm\omega\sqrt{A^2 - 4^2}$ .... (i)

$5 = \pm\omega\sqrt{A^2 - 6^2}$ .... (ii)

Dividing equations (ii) by (i)

$$\frac{8}{5} = \frac{\sqrt{A^2 - 16}}{\sqrt{A^2 - 36}}$$

Squaring both sides we get

$$\frac{64}{25} = \frac{A^2 - 16}{A^2 - 36}$$

Solving by cross multiplication we get

A = 7 cm

(b) Let us find the angular velocity at a linear velocity of 8 cm/s and displacement 4 cm. Both cases give the same value of angular velocity w.

$$V_1 = \omega \sqrt{A^2 - x_1^{\ 2}}$$

$$8 = \omega \sqrt{7^2 - 4^2}$$

$$\omega = 1.4 \text{ rads}^{-1}$$

$$T = \frac{2\pi}{\omega} = \frac{2\pi}{1.4} = 4.49 \text{ s}$$

(c) As the mean position, the velocity is maximum

$$v_{max} = \omega A = 4.49 \times 7 = 31.43 \text{ cm/s}$$

Exercise 2.1

1. Define simple harmonic motion and describe three examples.
2. Explain the following terms as applied in simple harmonic motion.
   (a) period
   (b) linear velocity
   (c) angular velocity
   (d) amplitude
3. A particle is undergoing simple harmonic motion with a frequency of 4 Hz and an amplitude of 6 cm. Determine
   (a) Its displacement in the one cycle.

(b) Its maximum velocity. Where does this velocity occur?

(c) Maximum acceleration of the particle. where does this occur.

4. An oscillator takes 15 s to complete 6 complete oscillations. Find:

(a) the period of its motion.

(b) Its frequency in Hz.

(c) angular velocity in rads/s

5. The displacement of (x) in metres of a particle at t = 0.3 s is given by

$x = 4\sin(4\pi t + \frac{\pi}{2})$

Determine the

(a) frequency and period of the oscillation.

(b) amplitude of the oscillation.

(c) phase constant.

(d) displacement of the particle at t = 0.3 s.

(e) maximum velocity of the particle.

6. Figure 2.6 is the displacement-time graph for an object undergoing simple harmonic motion

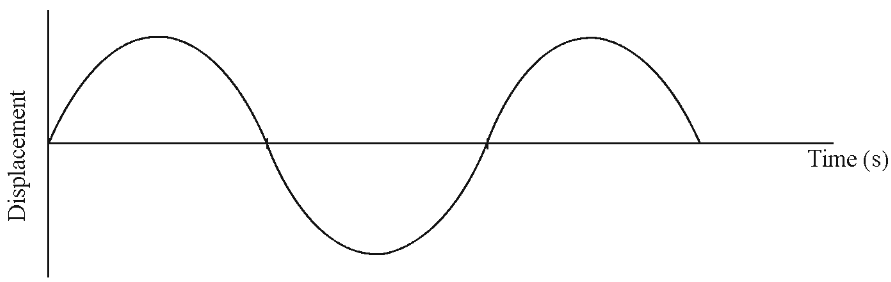


Fig. 2.6

On the same graph, sketch the

(a) velocity-time graph

(b) Force-time graph for the motion

7. A particle is undergoing simple harmonic motion. The amplitude of the oscillation is 12 cm and the angular frequency is 0.18 rad/s. At the mean position, its velocity is 0.98 cm/s. Determine the

(a) equations representing the displacement and velocity of the motion.

(b) the maximum velocity of the particle.

2.4 Simple harmonic oscillating systems

These are systems that undergo simple harmonic motion. We will analyse the motion of a simple pendulum, a spring mass system and a conical pendulum.

2.4.1 A simple pendulum

Activity 2.4: To analyse the simple harmonic motion of a simple pendum

Work in groups

Materials

- Pendulum bob
- string
- clamp and stand.

Steps

Part 1

1. Set up the same apparatus as you used in Activity 2.1.
2. Displace the bob through a very small angle θ and let it go. Describe the motion the pendulum makes.
3. Identify and show on Fig. 2.7 all the forces acting on the pendulum bob at position B and their directions.

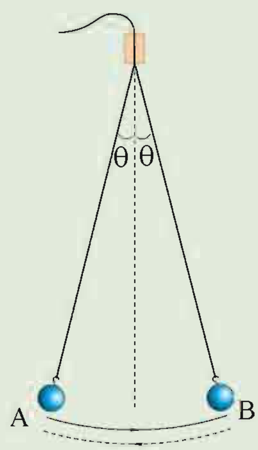


Fig. 2.7

4. Write down the mathematical expression relating the force restoring the pendulum bob and the other forces acting on it at B. Manipulate this equation arithmetically to derive an expression for periodic time of the pendulum.
5. Present your findings to the rest of the class.

Part 2

6. Repeat step 2 and use a stop-watch to time 20 oscillations (complete cycles) of the pendulum.
7. Repeat the activity a second time and calculate the average time for 20 oscillations.
8. Repeat the process for at least six different lengths.
9. Record your results in a table (see Table 2.1).

Table 2.1

Length, l (m)	Time for 20 oscillations (s)		Average time t for 20 oscillations (s)	Periodic time T (s)	T^2 (s^2)
	trial 1 t_1	trial 2 t_2	$t = \frac{t_1 + t_2}{2}$	$T = \frac{t}{20}$	
0.60					
0.70					
0.80					
0.90					
1.00					
1.10					

10. Draw a graph of T^2 against L (line of best fit). Determine the gradient of the graph.
11. Use the following equation and the gradient of the graph to determine the acceleration due to gravity.

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

A simple pendulum consists of a small bob of mass m suspended from a fixed support using a light inextensible string of length L (Fig. 2.8). This system is in equilibrium when the string is vertical and the bob is not moving.

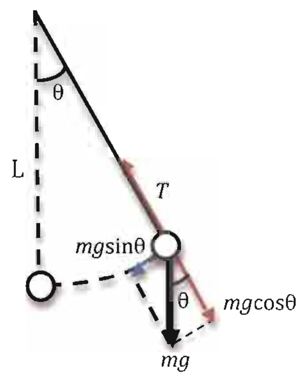


Fig. 2.8: A simple pendulum

When the bob is displaced through a small angle θ and released, it oscillates along a circular arc of length *s* whose centre is the fixed suspension point on the support.

The forces acting on bob when it is released are:

- Its weight (*mg*) vertically downwards.
- Tension (T) in the string acting towards the suspension point.
- *Mg cosθ* – the component of weight that balances the tension.
  i.e. $T = mg\cos\theta$ are equal but opposite in direction.
- *Mg sinθ* – the force that restores the bob to the mean position. It acts in the direction along the arc.

The resulting force (*mgsinθ*) produces an acceleration a on the bob according to Newtons 2nd law.

$$F = ma = -mg\sin\theta$$

$$A = -g\sin\theta \text{ ……………… } (i)$$

For small angular displacement, $\sin\theta \approx \theta$

Therefore $a = -g\theta$ where θ is angular displacement

But $\theta = \frac{\text{arc length}}{\text{radius}} = \frac{s}{l}$

$$A = -g\frac{s}{l} \text{ ……………… } (ii)$$

We earlier saw that $a = -\omega^2 x$ where x is linear displacement. In this case $x = s$.

Hence $a = -\omega^2 s$ …………… (iiii)

Substituting (iii) in (ii) we get

$$-\omega^2 s = -\frac{gs}{l}$$

Simplifying we get

$$\omega^2 = \frac{g}{L} \text{ …… } (iv)$$

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

Substituting for ω in (iv) we get

$$\left(\frac{2\pi}{T}\right)^2 = \frac{g}{L}$$

Finding square root both sides

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

Making T the subject gives

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

The equation shows that the periodic time of a simple pendulum depends on

- Length of the spring
- Acceleration due to gravity

Other factors that affect the period are:

- The angle through which the pendulum is displaced.
- Air resistance.

Example 2.4

A simple pendulum of length 90 cm is set to oscillate freely. Determine the:

(a) periodic time of the motion ($g = 10\ m/s^2$).

(b) frequency of the oscillation.

Solution

(a)
$$T = 2\pi\sqrt{\frac{L}{g}}$$
$$= 2\pi\sqrt{\frac{0.9}{10}}$$
$$= 1.884\ s$$

(b)
$$f = \frac{1}{T}$$
$$= \frac{1}{1.884\ s}$$
$$= 0.53\ Hz$$

Example 2.5

A swing is suspended with two 2.5 m long chains. (Take $g = 9.8\ m/s^2$)

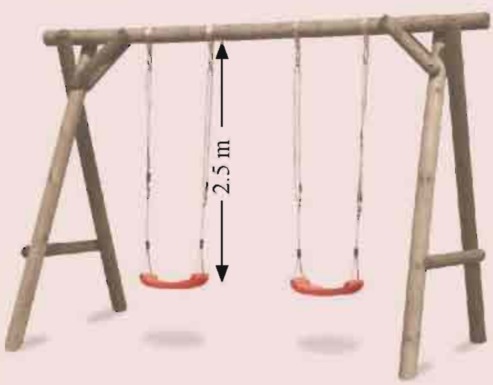


Fig. 2.9: Swing

(a) What is the period of its oscillation?

(b) What is the frequency of the motion?

Solution

(a) $T = 2\pi\sqrt{\frac{L}{g}}$

$= 2\pi\sqrt{\frac{2.5}{9.8}}$

$= 3.17\ s$

(b) $f = \frac{1}{T}$

$= \frac{1}{3.17\ s}$

$= 0.318\ Hz$

2.4.2 Mass suspended from a coiled spring

Activity 2.5: **To determine the value for acceleration due to gravity, g, using a spiral spring**

Materials

2 retort stands, clamps and bosses, a spiral spring, a 100 g mass in a hanger of mass 100 g (total mass 200 g), a stopwatch, an optical pin fitted at the bottom of the spring with Blu-tack or sellotape to act as a pointer, a half metre or a metre rule.

Steps

Part 1

1. Set up the apparatus as shown in Fig. 2.10. Note and record the position of the pointer on the metre rule. This is the initial reading.

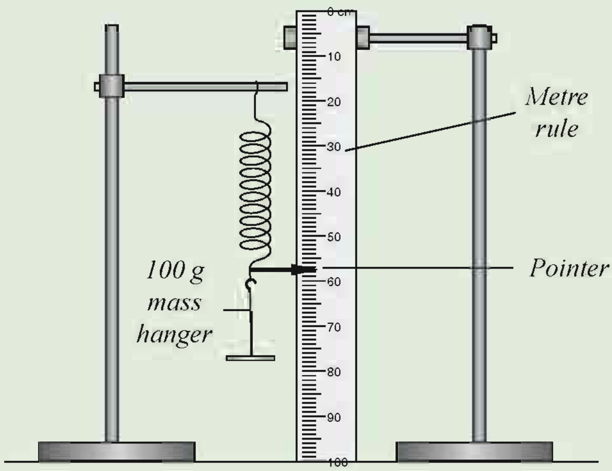


Fig. 2.10

2. Displace the mass slightly downwards and release it. Describe the motion of mass.

3. Given that the weight of the mass is mg and is equal to stretching force (F = ke) in the spring i.e. ke = mg, derive an expression for the periodic time of the oscillating mass. (You can make reference to the internet for more hints.

Part 2

4. Add a 100 g mass to the hanger. Note and record the pointer reading on the metre rule. This is the final reading.

   Determine the elongation, *e*, produced in the spring by the 200 g mass.

   Initial reading of the pointer = ... cm.

   Final reading of the pointer = ... cm.

   Elongation, *e*, produced = ... cm.

   = ... m.

5. Now displace the 200 g mass vertically through a small displacement and release. Observe the vertical oscillations. When the oscillations are steady and even, find the time, *t*, for 20 oscillations and record your results in Table 2.2. Repeat the experiment and find the mean time taken for 20 oscillations. Determine the periodic time T. Enter your results in Table 20 and complete the table.

Table 2.2

Time, *t*, for 20 oscillations (s)				$T = \frac{t}{20}$ (s)	T^2 (s^2)
Trial 1	Trial 2	Trial 3	mean		

6. Find the value for the accelation due to gravity, *g*. Proceed as follows:

$$\text{Since } T = 2\pi\sqrt{\frac{e}{g}}$$

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

$$\therefore \quad g = 4\pi^2\left(\frac{e}{T^2}\right)$$

   Acceleration due to gravity, g = ... ms^{-2}.

For a spiral spring obeying Hooke's law, extension is directly proportional to the extending tension. As shown in Fig. 2.11 below, a mass m, attached at the end of a suspended spring exerts a force on it thereby causing an extension e on the spring.

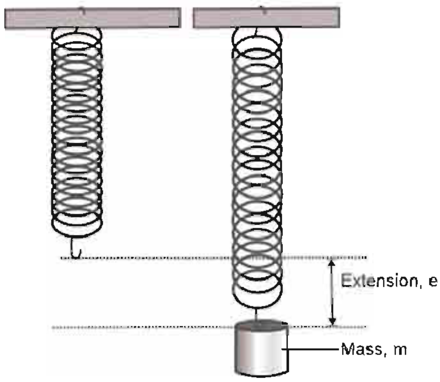


Fig. 2.11: Extension on a spiral spring

For a such spring that obeys hooke's law, the extension produced by a force F is directly proportional to the force.

$F \alpha e$

So that F = ke

The spring is maintained in equilibrium when the stretching tension overcomes the force due the attached mass.

Stretching tension = downward force

$ke = mg$ .... (i)

What if the mass is pulled further down a distance x below the equilibrium position as shown in Fig. 2.12?

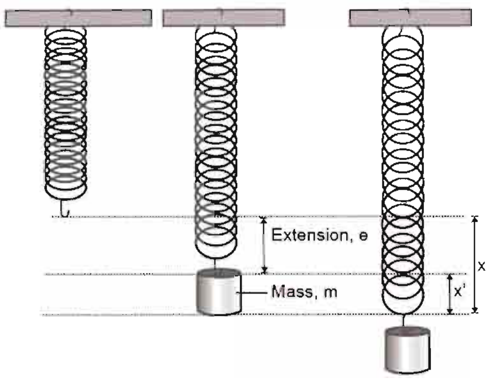


Fig. 2.12: Mass displaced by a stretching external force downwards

In this case, the stretching force is equal to the upward tension, which is given by k(x+e). The resultant force acting on the mass downwards is thus given by;

Resultant force = Downwards force – Upward force

$$F = mg - k(x + e)$$

According to Newton's law of motion, this resultant force, F= ma

Hence,

$$ma = mg - k(x + e)$$

$$ma = mg - kx - ke \quad \ldots\ldots\ldots\ldots\ldots\text{(ii)}$$

Substituting equation (i) into equation (ii),

$$ma = -kx$$

$$a = -\frac{k}{m}x \quad \ldots\ldots\ldots\ldots\ldots \text{(iii)}$$

Where k and m, the springs constant and the mass of the attached mass respectively are all constants. From this equation, it can be seen that the acceleration is directly proportional to the displacement and acts in opposite direction to extension. The spring thus executes simple harmonic motion.

As discussed earlier under the equation of simple harmonic motion (page 33), . Comparing this with equation (iii),

$$-\omega^2 x = -\frac{k}{m}x$$

$$k = m\omega^2$$

$$\omega = \sqrt{\frac{k}{m}} \qquad \Rightarrow \quad \text{but } \omega = \frac{2\pi}{T}$$

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

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

$$T = 2\pi\left(\frac{1}{\sqrt{\frac{k}{m}}}\right)$$

$$T = 2\pi\sqrt{\frac{m}{k}} \quad \ldots\ldots\ldots\ldots\ldots \text{(iv)}$$

From equation (i); ke = mg,

$$\frac{m}{k} = \frac{e}{g}$$

Hence,

$$T = 2\pi\sqrt{\frac{e}{g}} \quad \ldots\ldots\ldots\ldots\ldots \text{(v)}$$

Concluding from equations (iv) and (v), the periodic time of an oscillating mass attached to spring depends on the extension and the mass attached.

Example 2.6

A mass of 0.4 kg was hanged on a spring of spring constant k = 100 N/m. The spring was slightly displaced vertically and allowed to oscillaiate freely. What is the

(a) period of the oscillation of the mass?

(b) the frequency of the oscillation

Solution

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

$$= 2\pi\sqrt{\frac{0.4}{100}} = 0.4 \text{ s}$$

(b) The frequency of the oscillation

$$f = \frac{1}{T} = \frac{1}{0.4}$$

$$= 2.5 \text{ Hz}$$

Example 2.7

A mass of 1.5 kg is hanged on a spring and displaced downwards slightly. The spring oscillates vertically with a period of 2s. Determine the spring constant of the spring.

Solution

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

$$2 = 2\pi\sqrt{\frac{1.5}{k}}$$

Squaring both sides, we get

$$2^2 = 4\pi^2\,\frac{1.5}{k}$$

$$k = \frac{4\pi^2 \times 1.5}{4} = 14.8 \text{ N/m}$$

2.4.3 The compound pendulum

A rigid body oscillating in a vertical plane about a fixed horizontal axis that is passing through the body at a point that is not its centre of gravity (c) is called a *compound pendulum* or a rigid pendulum (Fig. 2.13).

The point on the body through which it is suspended on the horizontal axis is called the point of suspension (p). The distance between the point of suspension and the centre of gravity is called *the length of the compound pendulum (d).*

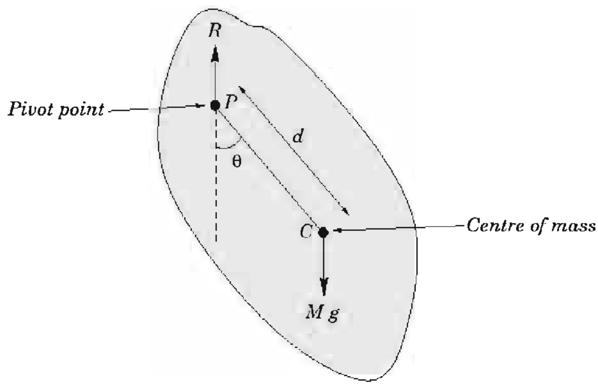


Fig. 2.13: A compound pendulum

The pendulum is in equilibrium when its centre of gravity rests vertically below the suspension point P.

Suppose the pendulum is displaced slightly such that its length l makes an angle θ to the vertical line through the suspension point vertical (Fig 2.11).

The forces acting on the pendulum in this case are:

- Its weight *(mg)* acting vertically downward at C.
- The reaction force $R = mg$ acting vertically up at the point of suspension.
- The restoring force $-mglsin\theta$ acting along the arc of rotation of the pendulum through C to restore it to the equilibrium position.

The restoring torque (T) is therefore $T = -mglsin\theta$ …… (ii)

For a small displacement θ, sin θ ≈ θ

Therefore, restoring torque is: $T = -mgl\theta$ ……(ii)

If I is the moment of inertia of the pendulum about the horizontal axis passing through P and $a = \frac{d\theta^2}{dt^t}$ is the angular acceleration, then the restoring torque is also given by:

$T = Ia = I\frac{d\theta^2}{dt^t}$ …… (iii)

Equating (ii) and (iii) we get

$I\,\frac{d\theta^2}{dt^t} = -mgl\theta$

$$\frac{d\theta^2}{dt^t} = \frac{-mgl\theta}{l}$$

But $$\frac{d\theta^2}{dt^t} = \omega^2 = (2\pi f)^2 = (\frac{2\pi}{T})^2$$

Therefore $$(\frac{2\pi}{T})^2 = \frac{-mgl\theta}{l}$$

When the amplitude is very small, we get that the period T is given by

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

Example 2.8

A rigid uniform rod of length 1.2 m is pivoted at one end and has moment of inertia of 1.6 kgm^2. If the rod has a mass of 2 kg, determine its period as it oscilate. (g = 10 m/s^2)

Solution

The centre of mass is at the centre of the rod i.e. $\frac{12}{2}$ m

$$T = 2\pi\sqrt{\frac{I}{mgl}}$$

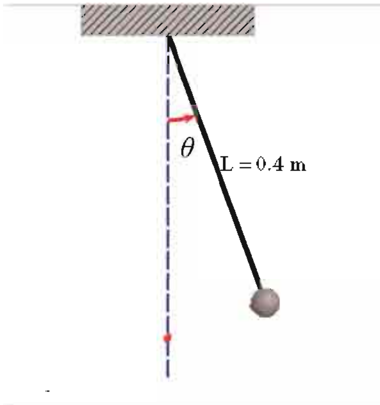
$$= 2\pi\sqrt{\frac{1.6}{2 \times 10 \times 0.6}} = 2.35$$

In case of forced oscillation, an external time dependent force is applied in the harmonic oscillation. This force will cause a change in period and amplitude.

Exercise 2.2

Take g = 10 m/s^2 in this exercise.

1. A mass *m* was hanged on a straight wire of length 0.4 m and let to swing freely as shown in Fig. 2.14.



Fig, 2.14

(a) Find the period of the mass motion.

(b) Determine the frequency of the motion.

2. A 2 kg mass was attached to a spring of constant 20 N/m. The mass was displaced to a point x = 2 cm. How much time does it take for the block to travel to x = 1 cm?
3. Give the meaning of simple harmonic motion.
4. Explain what will happen when two simple pendulums of different length are allowed to swing in a vacuum?
5. What is the period of oscillation of a mass of 100 kg on a spring with a constant k = 50 N/m? Hence, determine the frequency.

2.5 Kinetic and potential energy of an oscillating system

Kinetic energy is the form of energy possessed by a body in motion. The kinetic energy of a moving body is given by,

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

In an oscillating system, the velocity of the oscillating object is given by

$$V = \pm \omega \sqrt{A^2 - x^2}$$

Therefore,

$$KE = \frac{1}{2} m(\omega \sqrt{A^2 - x^2})^2$$

$$= \frac{1}{2} m\omega^2(A^2 - x^2)$$

$$KE = \frac{1}{2} m\omega^2 A^2 - \frac{1}{2} m\omega^2 x^2$$

For a body in oscillatory motion, potential energy is the work done against a force trying to restore the body. This work done against the force for a body being displaced by a distance, x is given by;

$$\text{Work done} = \text{Average force} \times \text{distance}$$

$$\text{Work done} = \frac{F + 0}{2} \times \text{distance}$$

$$= \frac{1}{2}Fx$$

Therefore,

$$PE = \frac{1}{2}Fx$$

But $F = ma$, while $a = -\omega^2 x$

The potential energy of an oscillating body is thus given by;

$$PE = \frac{1}{2}m\omega^2 x^2$$

2.6 Energy changes in simple harmonic motion

Activity 2.6 **To describe energy changes during simple energy during simple harmoni motion**

Work in groups.

In this activity, you will design and carry out an investigation into how potential and kinetic energy of a simple pendulum varies during simple harmonic motion.

Materials

- Pendulum bob
- String
- Clamp and stand

Instructions

1. Design the set up you will use in your investigation.
2. Identify the variable(s) you will keep constant and what you will vary.
3. Carry out the investigation and use it to answer the following questions:
   (a) Describe how PE and KE change as the pendulum moves from the lowest to highest point and then back.
   (b) At which point does the pendulum bob poses maximum? (i) PE (ii) KE
   (c) Negleting air resistance, how does the total mechanical energy (PE + KE) vary during one oscillation?

We notice that as the pendulum moves from a point of maximum displacement, to the lowest point, its speed increases. Beyond this point of equilibrium, it rises but in opposite direction with reducing speed.

At the highest point the pendulum appears momentadum at rest. See Fig. 2.15.

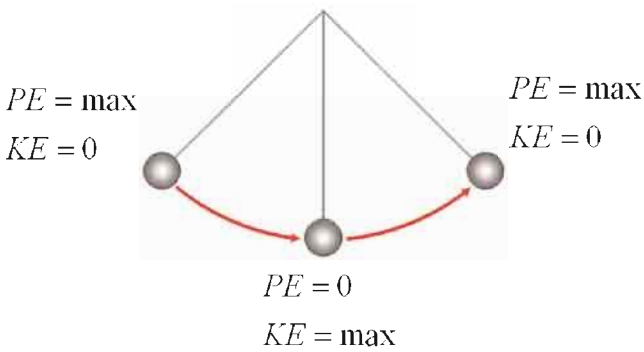


Fig. 2.15

At a point of maximum displacement, potential energy is maximum and is given by

$$P.E_{max} = mgh$$

At the lowest point, the pendulum has maximum kinetic energy and is given by

$$K.E_{max} = \frac{1}{2} mv^2$$

An expression for maximum velocity attained by the pendulum can be obtained as follows by the equation.

P.E lost = KE gained

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

$$V = \sqrt{2gh}$$

This velocity depends on the amplitude.

Fig. 2.16 is a graphical representation of the variations of PE and KE in the oscillation.

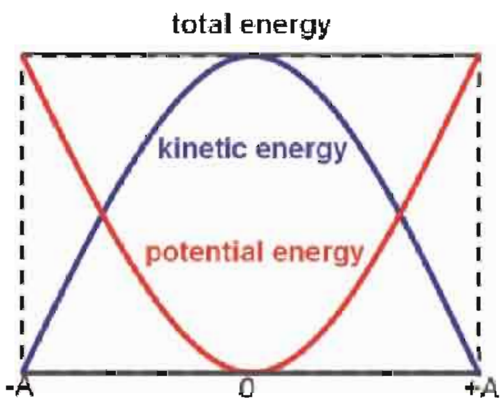


Fig. 2.16

The mechanical energy of a body in simple harmonic motion is conserved.

For pendulum

Mechanical energy (E) = P.E + K.E = constant.

$$= mgh + \frac{1}{2} mv^2$$

For a spring, kinetic energy (K.E) is due to the speed of the system.

$$K.E = \frac{1}{2} mv^2$$

Its the potential energy is due to restorating force in the spring.

$$P.E = \frac{1}{2} Kx^2$$

where K is spring constant.

x – is the maximum displacement

Therefore the total mechanical energy of a mass spring system in a simple harmonic motion is given by

$$E = \frac{1}{2} mv^2 + \frac{1}{2} kx^2$$

Generally, since simple harmonic motion is sinusoidal, we obtain other expressions of KE and PE as follows.

In the previous section, we saw that for a body in simple harmonic motion

$$KE = \frac{1}{2}m\omega^2A^2 - \frac{1}{2}m\omega^2x^2 \;\ldots\ldots\; (i)$$

$$PE = \frac{1}{2}m\omega^2x^2 \ldots\ldots\; (ii)$$

Displacement x = A sin ωt ……… (iii)

Total energy = KE + PE

$$E = \frac{1}{2}m\omega^2A^2 - \frac{1}{2}m\omega^2x^2 + \frac{1}{2}m\omega^2x^2$$

$$E = \frac{1}{2}m\omega^2A^2 \;\ldots\ldots\ldots\ldots\; (iv)$$

Alternatively

Substituting x = Asinωt in (i) gives.

$$KE = \frac{1}{2}m\omega^2A^2 - \frac{1}{2}m\omega^2A^2 \sin^2\omega t \;\ldots\ldots\; (v)$$

$$KE = \frac{1}{2}m\omega^2A^2(1 - sin^2\omega t) \qquad But\ 1 - sin2\ \omega t = cos^2\ \omega t$$

$$KE = \frac{1}{2}m\omega^2A^2cos^2\omega t$$

Similary, substituting x = A sin ωt in (ii) gives (vii)

$$PE = \frac{1}{2}m\omega^2A^2sin^2\omega t$$

The total energy of the sum of PE and KE at a point is given by the

E = sum of (v) and (vii) i.e.

E = KE + PE

$$= \frac{1}{2}m\omega^2A^2cos^2\omega t + \frac{1}{2}m\omega^2A^2sin^2\omega t$$

$$= \frac{1}{2}m\omega^2A^2\ (cos^2\omega t + sin^2\omega t)$$

$$E = \frac{1}{2}m\omega^2A^2 \quad \ldots\ldots\ldots\ (viii)$$

From the two equations, it can be seen that the total mechanical energy is constant. The energy is also independent of displace x of the body. The constant mechanical energy is an indication that the variation of potential energy and kinetic energy of an oscillating body is such a way that the total energy is conserved.

Example 2.9

A block of mass 500 g is attached to a light spring and set to oscillate on a frictionless horizontal air track. If the spring has a spring constant of 40 N/m while the amplitude of the motion is 5.0 cm, determine,

(a) The total energy of the system.

(b) The maximum velocity of the block.

(c) The velocity of the block at 3.0 cm.

(d) The kinetic energy and potential energy when the position of the block is 3.0 cm.

Solution

m = 500 g = 0.5 kg, k = 25N/m, A = 5.0 cm = 0.05 m

(a) $E = \frac{1}{2}m\omega^2A^2 \quad \Rightarrow m\omega^2x = F$

$$\Rightarrow k = \frac{F}{x} = m\omega^2$$

$$E = \frac{1}{2} kA^2$$

$$E = \frac{1}{2} \times 40 \times 0.05^2$$

$$= 0.05 \text{ J}$$

(b) Maximum velocity

At max velocity, PE = 0 while KE is max;

$$E_{max} = \frac{1}{2} mv^2$$

$$0.05 = \frac{1}{2} \times 0.5 \times v^2$$

$$v^2 = 0.0125$$

$$v = 0.112 \text{ m/s}$$

(c) The velocity of the block 3.0 m

$$V = \pm\sqrt{\frac{k}{m}(A^2 - x^2)}$$

$$V = \pm\sqrt{\frac{40}{0.5}(0.05^2 - 0.03^2)}$$

$$V = \pm 0.3578 \text{ m/s}$$

(d) $KE = \frac{1}{2} mv^2$

$$KE = \frac{1}{2} \times 0.5 \times 0.3578^2$$

$$= 0.032 \text{ J}$$

$$PE = \frac{1}{2} kx^2$$

$$KE = \frac{1}{2} \times 40 \times 0.03^2$$

$$= 0.018 \text{ J}$$

Example 2.10

A mass of 5 kg oscillating on a spring with force constant of 4 N/m passes through its equilibrium point with a velocity of 8m/s. What is the energy of system at this point?

Solution

$$K.E = \frac{1}{2} mv^2$$

$$= \frac{1}{2} \times 5 \times 8^2 = 160 \text{ J}$$

PE = 0

Exercise 2.3

1. A mass of 2 kg is attached to a spring of constant 20 N/m. It is displaced to a point x = 0.3 m when the spring is released, the mass moves to a point x = 0.2 m. what is the work done by restoring force.
2. A 3.6 kg block hunging on a spring causes stretches the spring by 10 cm.
   (a) What is the restoring force exerted on the block by the spring?
   (b) What is the springs constant?
   (c) What force is required to stretch this spring by 12.5 cm?
   (d) What is the period of the oscillation?
3. A 60 kg boy is bouncing on a spring scale spring constant of 1.6 X 106 Nm. If the amplitude of his bounce is 0.25 m,
   (a) What is the maximum velocity?
   (b) What is the maximum energy stored in the spring?
4. A 0.400 kg mass is vibrating in a system in which the restoring constant is 90 N/m; the amplitude of vibration is 0.200 m. Find the:
   (a) total energy of the system
   (b) maximum kinetic energy and maximum velocity
   (c) PE and KE when x= 0.100 m
   (d) maximum acceleration
   (e) equation of motion if x= A at t = 0
5. A 3.0-kg mass is attached to a spring with a spring constant of 98 N/m. The mass is resting on a frictionless horizontal plane as a horizontal force of 10.2 N is applied to the mass, and it is then released.
   (a) What is the amplitude of SHM?
   (b) What is its period?
   (c) What is the total energy of the SHM?

(d) What is the maximum velocity of the vibrating mass?

(e) What is the PE and KE of the mass when it is 4 cm from equilibrium position?

6. A pendulum bob consists of a 1.00 kg ball hung on a string 3m long.

(a) If it is drawn back 20 cm from equilibrium position and released, what is its period of motion?

(b) What will be its kinetic energy as it passes through the middle of its swing?

(c) What are its PE and KE for a displacement of 10 cm?

2.7 Damped oscillations

Activity 2.7: To observe damped oscillations

Materials

- Water in a large trough or pool
- A small stone

Steps

1. Let the water on the trough or pool settle.
2. Drop a small stone into the water at the centre of trough or pool. Observe the waves as they spread away from the source.
3. Observe the change in the amplitude of the waves with time. Explain what causes the change.

In an ideal situation, a mass on a spring or a simple pendulum would oscillate freely and continuously without stopping. Such motion is said to be undamped motion. However, due to external forces like friction, the amplitude decreases with time, gradually. The oscillation is said to be damped.

Therefore, damped oscillation is an oscillation in which the amplitude decreases with time. This depends on the friction, which is in itself proportional to the velocity of the oscillation.

Under damped is when an oscillating system returns to equilibrium point after some oscillating. For example, shocks in vehicles best example of under damped if they are in good condition and driven well on bumps.

When the system returns to the mean position slowly without oscillation, the oscillation is known as over damped oscillation.

Sometimes a system can return to the original position as fast as possible without oscillating. This is called critical damping of simple harmon motion.

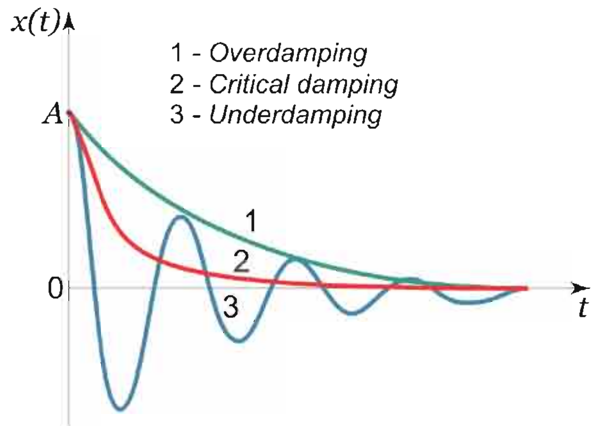


Fig.2.17: Damped oscillation

Applications of damped oscillations

Shock absorbers

Shock absorbers in vehicles are made with either springs or fluids.

In case the vehicle goes over a bump or pothole it is able to return to equilibrium through under damping. If the shocks are not in good conditions, the vehicle will experience critical damping which makes the occupant uncomfortable.

Topic Summary

- Simple harmonic motion is a periodic motion where the restoring force is directly proportionanl to the displacement.
- Amplitude is the maximum displacement of an object from the mean position.
- Period, T, is the time taken for one complete cycle.
- Period for mass-spring simple harmonic motion is given by

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

- Period for a simple pendulum of a simple harmonic motion is

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

- Total mechanical energy for a system in a simple harmonic motion is given by

$$E = \frac{1}{2}mv^2 + \frac{1}{2}kx^2$$

- Damped oscillation is an oscillation in which the amplitude decreases with time.
- Over damped oscillation is an oscillation when system returns to the mean position slowly without oscillating.
- Critical damping is when a system returns to the mean position very fast without oscillating.
- Underdamped is when a system returns to equilibrium point after some oscillation.

Topic Test 2

1. A 1.4 kg mass is attached to a horizontal spring on the top of a table. The mass is pulled 12 cm from the equilibrium position and released. It then undergoes simple harmonic motion making 2.2 oscillations each second. Determine:
   (a) the equation of motion
   (b) the spring constant
   (c) the total energy
   (d) the maximum acceleration of the mass (and indicate where this occurs)
   (e) the maximum velocity of the mass (and indicate where this occurs)
   (f) the acceleration of the mass when it is 7cm from the equilibrium position
   (g) the velocity of mass when it is 7cm from the equilibrium position
2. A spring is hanging freely from the ceiling. You attach an object to the end of the spring and let the object go. It falls down a distance 49 cm and comes back up to where it started. It continues to oscillate in simple harmonic motion going up and down a total distance of 49 cm from top to bottom. What is the period of the simple harmonic motion?
3. A 10 kg mass is attached to a rope that is 100 m long to form a huge pendulum. The mass is pulled aside so that it is 5 meters above its resting point.
   (a) How much potential energy (PE) does it have when it is 5 m above its resting point?

(b) When the pendulum is released how much kinetic energy (KE) will it have when it passes through its lowest point?

(c) How fast will it be moving when it passes through its lowest point?

(d) If it takes 2 seconds for the pendulum to reach its lowest point after it is released, when will it return to its initial position? What is this time called?

4. By what factor should the length of a simple pendulum be changed if the period of vibration were to be tripled?

5. A 5.00 kg block hung on a spring causes a 10.0 cm elongation of the spring.

(a) What is the restoring force exerted on the block by the spring?

(b) What is the spring constant?

(c) What force is required to stretch this spring 8.5 cm horizontally?

(d) What will the spring's elongation be when pulled by a force of 77.7 N?

(e) What is the period of this oscillation?

UNIT 2 Newton's Law of Gravitation

Topic in the unit

Topic 3: Newton's Law of Gravitation

Key inquiry question

- Why do planets remain in their orbits while orbiting the sun?
- What are the names of some of the planets?
- How would the speed of satellite be affected when moving in higher orbits?
- How would you relate the orbiting of the planets around the sun to those of the electrons around the nucleus of an atom?

Learning outcomes

Knowledge and understanding

- Understand Newton's law of gravitation, the orbit of planet and satellites.

Skills

- Design investigations on escape velocity, gravitational acceleration.
- Apply Kepler's laws of gravitation, describe and derive mathematical formulae for the motion of planets. Graph variation of gravitational acceleration inside and outside the Earth surface.

Attitude and value

- Appreciate we are living on a moving planet.

TOPIC 3 Newton’s Law of Gravitation

Topic outline

- Introduction
- Newton’s universal law of gravitation
- Kepler’s laws of planetary motion
- Applications of Newton's law of gravitation

Introduction

In unit one, we discussed in details about uniform circular motion. We learnt that an object moving in a circular path, experiences a centripetal force towards the centre of the path. We also, found out that the force is directly proportional to the mass of the object, square of its linear velocity and inversely proportional to radius. We also learnt in Secondary 3 that the force of interaction of two charged bodies separated by a distance r, is given by

$$F = \frac{KQ_1Q_2}{r^2} \quad \text{(Coloumb's law)}$$

In this unit, we will study and investigate forces of interaction of two bodies separated by distance. Then, we will explain what make planets on the solar system not to fall, how scientists lanch satellites in the space and why some bodies e.g stars in the sky appear not moving.

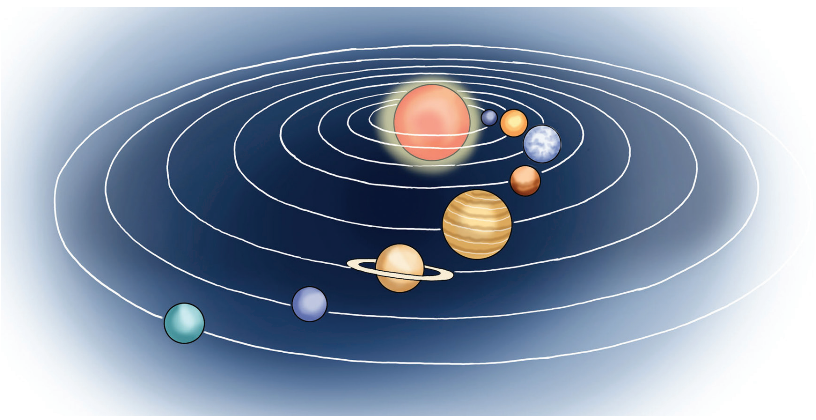


Fig. 3.1: The solar system

3.1 Newton's Universal Law of Gravitation

A story is told that one day Isaac Newton was sitting under an apple tree, and an apple fell on his head. This led him to think hard and conclude that there must be a force of attraction that pulled the apple to the earth. He called this force gravity.

Activity 3.1: **To investigate the Newton's universal law of gravitation**

(Work in pairs)

Materials

A small stone

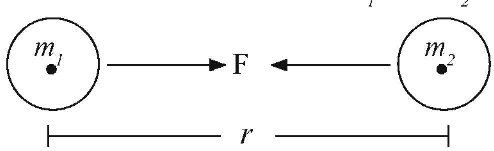
Steps

1. Throw the stone upwards and observe what happens. Expain why the stone falls to the ground.
2. Let the mass of the stone be m, and that of the earth be m_2. Derive the expression for the force that is making the stone to fall to the ground when it is at a height r above the ground.
3. Do a research from reference books on:
   (a) The Newton's universal law of gravitation. What does it state? How is it represented mathematically? Compare this with the equation you derived in step 2.
   (b) How are planets able to orbit one another and around the sun?
4. Make a presentation to the rest of the class.

Newton discovered that, the gravitational force of attraction was not limited to objects falling to the earth but it exists between any two objects in the universe and depends on the mass of the two objects and the separation distance between them. He summarised his observation in a law that is now referred to as Newton's Universal Law of Gravitation.

> The law states that any two bodies in the universe attract each other with a force that is directly proportional to the product of their masses and inversely proportional to the square of the distance between them.

Consider two bodies of masses m_1 and m_2 separated by a distance r as shown in Fig 3.2



(The separation distance r is from the centres of masses of the two objects)

Fig 3.2: Two bodies at a distance

According to Newton's universal law of gravitation, the force (F) of attraction between the two objects is mathematically represented as

$$F \propto \frac{m_1 m_2}{r^2}$$

Hence, $F = \frac{Gm_1m_2}{r^2}$ where G is a constant called the universal gravitational constant.

Note that the constant G is the same everywhere in the universe.

We can obtain the units for G as follows:

$F = \frac{Gm_1m_2}{r^2} \Rightarrow G = \frac{Fr^2}{m_1m_2} \Rightarrow \frac{Nm^2}{kg^2}$. Hence Nm^2/kg^2 are the units

Alternatively, we use m^3s^2/kg

The value of a constant, G is approximately equal to $6.673 \times 10^{-11}\ Nm^2/kg^2$

From the equation, $F = \frac{Gm_1m_2}{r^2}$, we can obtain the other quantities as follow:

Mass of object 1, $m_1 = \frac{Fr^2}{Gm_2}$

Mass of object 2, $m_2 = \frac{Fr^2}{Gm_1}$

This law applies to small objects and planets, and between planets.

Example 3.1

Determine the force of gravitational attraction between a student of mass 60 kg and the earth if the student is standing on the earth surface at a distance of 6.4×10^6 m from the centre of the earth.(mass of the earth = 5.98×10^{24} kg, $G = 6.67 \times 10^{-11}\ Nm^2/kg^2$)

Solution

$m_1 = 60$ kg, $m_2 = 5.98 \times 10^{24}$ kg, $r = 6.4 \times 10^6$ m, $G = 6.67 \times 10^{-11}\ Nm^2/kg^2$

$$F = \frac{Gm_1m_2}{r^2} = \frac{6.67 \times 10^{-11}\ Nm^2kg^{-2} \times (60\ kg) \times (5.98 \times 10^{24}\ kg)}{(6.4 \times 10^6 m)^2}$$

$$= \frac{2393.196 \times 10^{-11} \times 10^{24}}{40.96 \times 10^{12}}\ N$$

$$= 58.4276 \times 10^{(-11+24-12)} N = 584.276\ N$$

Example 3.2

Kampire is 28 kg and is standing 1.2 metres away from Mugisha. What is the mass of Mugisha if a gravitational force of attraction of 3.2×10^{-8} N is acting on each of them? (Assume $G = 6.67 \times 10^{-11}\ Nm^2/kg^2$)

Solution

$m_1 = 28$ kg, $m_2 = ?$, $r = 1.2$ m, $F = 3.2 \times 10^{-8}$N, $G = 6.67 \times 10^{-11}$ Nm^2/kg^2

$$F = \frac{Gm_1m_2}{r^2} \Rightarrow m_2 = \frac{Fr^2}{Gm_1} = \frac{3.2 \times 10^{-8} \times (1.2)^2}{6.67 \times 10^{-11} \times 28} \text{ kg}$$

$$= \frac{4.608 \times 10^{-8}}{186.76 \times 10^{-11}} \text{ kg}$$

$$= 0.02467 \times 10^3 \text{ kg}$$

$$= 24.67 \text{ kg}$$

Example 3.3

What is the separation distance between a stone block of mass 20 kg and another one of mass 35 kg if a gravitational force of attraction of 3.6×10^{-9} N acts between them.

Solution

$m_1 = 20$ kg, $m_2 = 35$ kg, $r = ?$, $F = 3.6 \times 10^{-9}$ N, $G = 6.67 \times 10^{-11}$Nm^2/kg^2

$$F = \frac{Gm_1m_2}{r^2} \Rightarrow r = \sqrt{\frac{Gm_1m_2}{F}} = \sqrt{\frac{6.67 \times 10^{-11} \times 20 \times 35}{3.6 \times 10^{-9}}} \text{ m}$$

$$= \sqrt{\frac{4.669 \times 10^{-8}}{3.6 \times 10^{-9}}} \text{ m}$$

$$= \sqrt{12.96} \text{ m}$$

$$= 3.6 \text{ m}$$

3.1.1 Variation of gravitational field strength with distance

Objects at or near the surface of the earth, experience a force due to gravity acting on them towards the earth. This force acts downward because every particle in the earth is a attracting the object.

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

R – is the radius of the earth,

M_e – Mass of the earth

From the formula

F α mass of the object

The acceleration due to gravity, of a body at an altitude h_o towards the earth surface is given by

$$g = \frac{Gm_e}{R^2} \quad \ldots\ldots(1)$$

When a body is at a point $h_0 + h$ above the earth surface, the acceleration due to gravity g' is

$$g' = \frac{Gm_e}{(R+h)^2} \quad \ldots\ldots\ldots\ldots\ldots(2)$$

When we divide 2 by 1, we get

$$\frac{g'}{g} = \frac{\frac{Gm_e}{(R+h)^2}}{\frac{Gm_e}{R^2}} = \frac{R^2}{(R+h)^2}$$

Simplifying the above

$$g' = g\left(1 - \frac{2h}{R}\right)$$

This means that the value of acceleration due to gravity decreases with increase in height above the surface of the earth.

When a body is at a point h_o-h inside the earth surface, the gravitational force is only due to the inner solid sphere radius (R-h)

$$g'' = \frac{Gm'}{(R-h)^2} \qquad \text{(m – mass of the inner solid sphere of radius (R – h))}$$

dividing g^{11} by g we get

$$\frac{g''}{g} = \frac{R-h}{R}$$

$$g'' = g\left(1 - \frac{d}{R}\right)$$

This means that the value of acceleration due to gravity of decreases with the increase of depth.

The following is a graph of acceleration due to gravity against the distance to the centre of the earth and distance above the earth's surface.

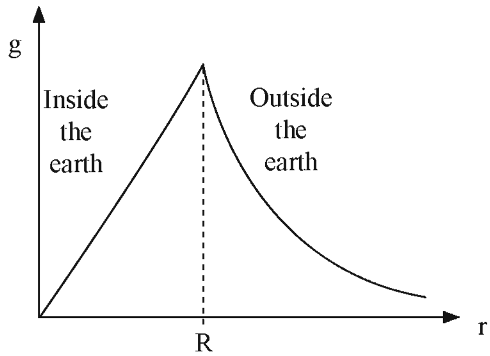


Fig. 3.3: Graph of acceleration due to gravity

Example 3.4

A body of mass m is 500 km above the surface of the earth. If the gravitational field strength on the earth surface is 10 m/s^2, and the radius of the earth is 6.4×10^6m. Determine the acceleration due to gravity at this point.

Solution

Acceleration due to gravity above the earth's surface

$$g^1 = g\left(1 - \frac{2h}{R}\right)$$

$$= 10\left(1 - \frac{2 \times 500000}{6.4 \times 10^6}\right)$$

$$= 8.4375 \text{ m/s}^2$$

Example 3.5

An object is moving around the sun of mass 2.00×10^{30} kg in an orbit. The distance between the sun and the orbit is 1.496×10^{10} m and the G = 6.67×10^{-11} N/m^2. Determine the speed of the object.

Solution

$$V = \sqrt{\frac{Gm_s}{r}} = \sqrt{\frac{6.67 \times 10^{-11} \times 2.0 \text{ x } 10^{30}}{1.496 \times 10^{10}}}$$

$$= 8.9171 \times 10^9 \text{ m/s}$$

Exercise 3.1

In this exercise use: Mass of the earth = 5.98×10^{24} kg, Radius of the earth = 6.4×10^{6} m, Mass of the sun = 1.989×10^{30} kg, Radius of the sun = 6.9858×10^{8} m, Distance from the sun to the earth = 1.496×10^{10} m, Mass of the moon = 7.348×10^{22} kg, Radius of the moon = 1.7374×10^{6} m, $G = 6.67 \times 10^{-11}$ Nm^2/kg^2

1. What is the gravitational force of attraction between the earth and a car of mass 1500 kg resting on the surface of the earth?
2. Determine the earth's force of gravitational attraction on a satellite of mass 500 kg orbiting the earth at a distance 40 000 km above the surface of the earth.
3. If the gravitational force of attraction of the earth on the moon is 2.14×10^{20} N, what is the distance of the moon from the earth?
4. A gravitational force of attraction of 4.4×10^{-10} N exists between a cow of mass 800 kg and a goat when both are 18 m apart. What is the mass of the goat.
5. What is the separation distance between a man of mass 85 kg and a woman of mass 95 kg if the gravitational force of attraction between them is 2.58×10^{-7} N.

3.2 Kepler's laws of planetary motion

Activity 3.2: **To investigate the three Kepler's laws of planetary motion**

Work individually

Materials

- Pencil
- 2 tacks
- Soft board
- String
- Plain paper
- Reference books
- Internet

Steps

1. Fix the plain paper to the soft board using the two tacks. Then, tie the string into a loop and wrap the loop around the two tacks.
2. Take the pencil and pull the string until the pencil and two tacks make a triangle (Fig. 3.4).
3. Then begin to trace out a path with the pencil, keeping the string wrapped tightly around the tacks. The resulting shape will be an ellipse.

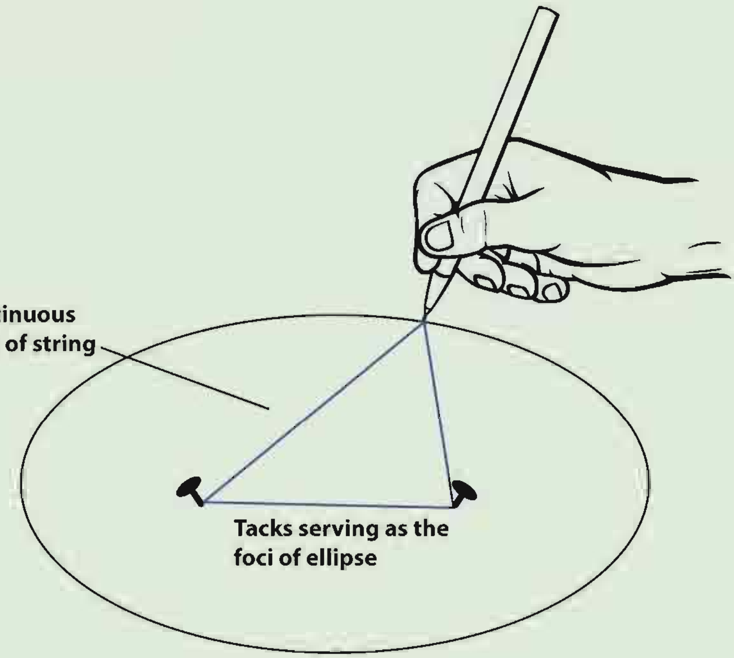


Fig. 3.4: Drawing an ellipse

4. Research from reference books or the Internet the three Kepler's laws of planetary motion. Write them down.
5. The Earth's and Mars periods and distance from the sun are given in Table 3.1.

Table 3.1

Planet	Period T (s)	Average Distance R (m)	T^2/R^3 (s^2/m^3)
Earth	3.156×10^7 s	1.4957×10^{11}	
Mars	5.93×10^7 s	2.278×10^{11}	

Complete the column for T^2/R^3. Compare these values and make a conclusion whether the two planets obey Kepler's third law or not.

6. Present your findings to the rest of the class.

An ellipse is a special curve in which the sum of the two distances from every point on the curve to two other points is a constant. The two other points (represented the two tacks in the ellipse we drew in activity 3.2) are known as the foci of the ellipse (Fig. 3.5).

$a + b = \text{constant}$

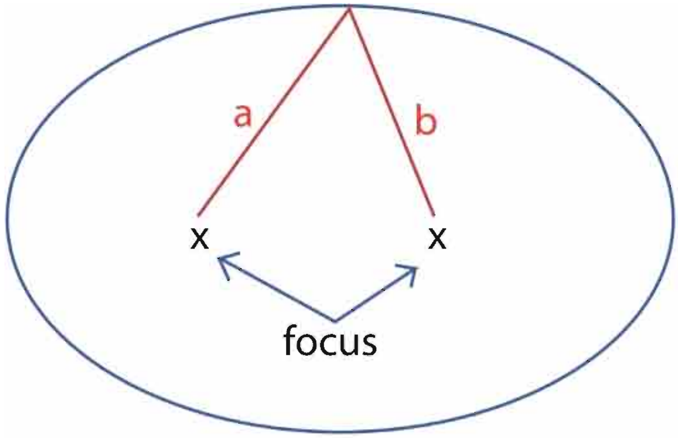


Fig. 3.5

3.2.1 Kepler's 1st law (law of orbit)

Kepler's 1st law states *"all planets move in elliptical path with the sun at one of its focus"*. See Fig. 3.6.

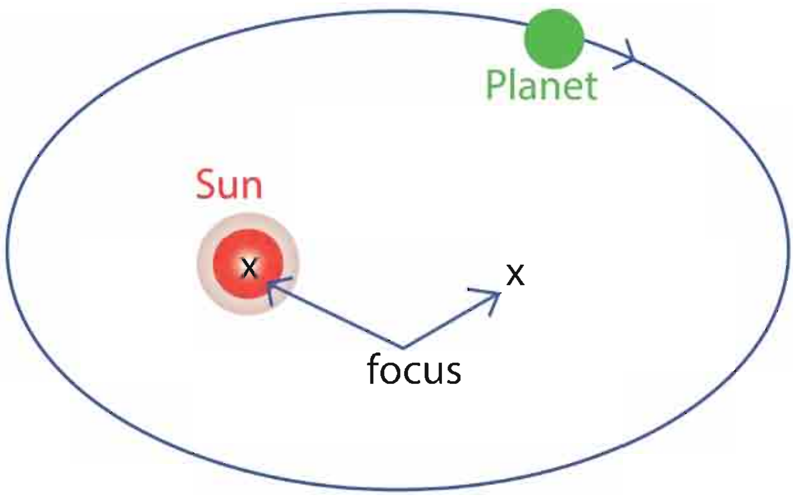


Fig. 3.6

The sun is not at the centre of the ellipse, but is at one focus (generally there is nothing at the other focus of the ellipse). Thus, a planet follows the elliptical path (orbit), meaning that the planet – sun distance is changing as the planet goes around its orbit. The point of nearest approach of the planet to the sun is called perihelion; while that of greatest separation is called aphelion.

3.2.2 Kepler's 2nd law (law of area)

Kepler's 2nd law states that *"the imaginary line joining the centre of the sun to the center of the planet sweeps out equal areas in equal time interval as the planet travels around the ellipse"*. See Fig. 3.7.

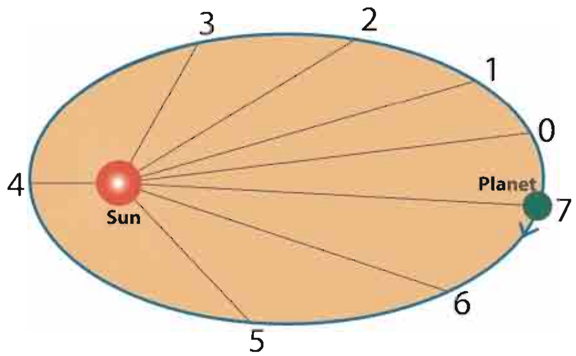


Fig. 3.7

All the sections have same area and are swept out in equal time by the line joining the centres of the planet and sun.

The law means that in any given time interval e.g. 30 days, the line joining the centre of the planet and sun planet sweeps sections of equal area regardless of which 30 day period you consider.

Hence, a planet executes elliptical motion with constantly changing angular speed as it moves about its orbit. The planet moves fastest when it is at *perihelion* and slowest when it is at *aphelion*.

3.3.3 Kepler's 3rd law (law of periods)

Kepler's 3rd law states *"the square of the orbital period of any planet is proportional to the cube of the average distance from the planet sun"*.

$T^2 \propto R^3$ This means $\frac{T^2}{R^3}$ = contant

Thus $\frac{T_1^2}{R_1^3} = \frac{T_2^2}{R_2^3}$

This law implies that the period for a planet to orbit the Sun increases rapidly with the radius of its orbit. As such, Mercury, the innermost planet, takes only 88 days to orbit the Sun but the outermost planet (Pluto) takes 248 years to do the same.

Proof of Kepler's 3rd law

The centripetal force acts on the planet towards the sun as the centre ($F_C = \frac{m_p v^2}{r}$)
This is equal to the gravitational force between the sun and planet.

$$\frac{m_p v^2}{r} = \frac{G m_s m_p}{r^2}$$

m_p – Mass of the planet

m_s – Mass of the sun

$$\Rightarrow v^2 = \frac{G m_s}{r} \quad .... (a)$$

This is the speed of the planet orbiting, the sun

$$v = \sqrt{\frac{G m_s}{r}} \quad .... (i)$$

We learnt in unit 1 that $v = \frac{2\pi r}{T}$ .... (ii)

Equating (i) and (ii)

$$\frac{2\pi r}{T} = \sqrt{\frac{G m_s}{r}}$$

Squaring both sides we get

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

Making T^2 the subject, we get

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

Since $\frac{4\pi^2}{G m_s}$ is constant, then $\frac{T^2}{r^3}$ = constant.

3.3 Applications of Newton's law of gravitation and Kepler's laws

Satellites

Activity 3.3: **Investigating the applications of Newton's law of gravitation**

(Work in groups)

Materials

- Reference books
- Resource person

Steps

1. Discuss the following:
   (a) What makes the planets not to fall off from their orbits?
   (b) How do scientists launch satellites in space?
2. Present the findings to the whole class through your secretary.

A satellite is an artificial object that has been internationally placed in an orbit to move around (orbit) a planet.

There are artificial satellites that are launched into the space and orbits around the sun, earth or other bodies in the space. Figure 3.8 below shows a launched satellite around the earth.

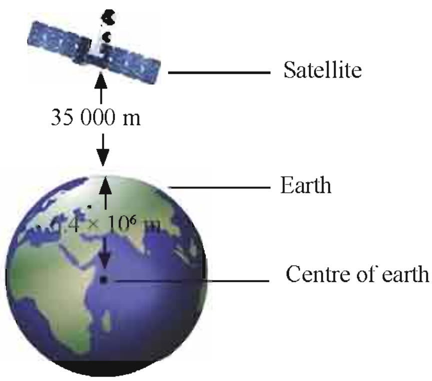


Fig 3.8: A communication satellite

The gravitational force between the earth and satellite is given by

$$F_G = \frac{Gm_1m_2}{r^2}$$

where: m_1 is the mass of planet
m_2 is the mass of the satellite
r – distance of the satellite from the surface of the planet

The satellite has less mass as the planet i.e $m_1 > m_2$.

The centripetal force F_C acts on the satellites towards the planet and is given by

$$F_C = \frac{m_2v^2}{r}$$

where v is the velocity of the satellites

From the proof of Kepler's 3rd law that we learnt in the previous section,

$$T^2 = \frac{4\pi^2 r^3}{Gm_2}$$

Finding square root both sides we get

$$T = 2\pi\sqrt{\frac{r^3}{Gm_2}}$$

where m_2 is the mass of the earth.

r – is the distance the satellite needs to be from the centre of the earth to avoid falling back to the earth.

First astronomical velocity is the velocity which a satellite must move in the orbit to avoid falling back to the earth surface.

Sometimes, a satellite appears stationary (not moving when observed from the earth. This can only happen if the period of the satellite is equal to the earth's period.

At this point the orbit is known as geostationer orbit and has the same altitude as the radius of the earth. Its altitude, r (distance from earth).

$$r = \sqrt[3]{\frac{T^2 Gm_e}{4\pi^2}}$$ where m_e is the mass of the earth.

Geostationary orbit is a circular orbit positioned approximately above earth's equator and have same period and direction as the rotation of the earth.

An object in this orbit appears stationary relative to the rotating earth.

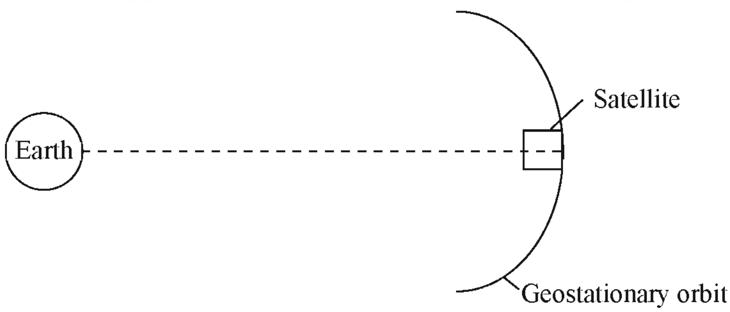


Fig. 3.9

Geostationary orbit is used to launch satellites.

The greater the altitude, the less velocity needed to maintain the satellite in the orbit and vice verses.

At the highest point

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

Therefore, $V = \sqrt{rg}$ (orbital velocity)

Orbital velocity

This is the minimum velocity that is required to maintain a satellite in the orbit.

Orbital velocity depends on the mass of central body and the radius of the orbit.

For an object to leave a planet, it must overcome the pull of gravity by moving at a speed above the orbital velocity. This velocity of an object is called escape velocity.

Escape velocity

It is the velocity of an object for it to just escape from the earth's gravitational pull influence.

Work done on the mass of the object at the earth's surface of mass, m_e and radius R_e is

$$\text{Work done} = \frac{Gm_e m}{R_e}$$

From law of conversation of energy, this is equal to the kineic energy of the object as it escapes the earth's surface.

$$\frac{1}{2} mv^2 = \frac{Gm_e m}{R_e}$$

Escape velocity, $v = \sqrt{\frac{2Gm_e}{R_e}}$, where m_e – mass of the earth

When the mass, m, of the object is on earth's surface, the gravitational force is equal to the weight of the object.

$$mg = \frac{Gm_e m}{r^2}$$

Distance r equals to radius of the earth R_e

$$Gm_e = gR_e^2$$

Substituting in the equation of escape velocity

We get

$$v = \sqrt{2gR_e} \qquad \text{(escape velocity)}$$

This is the minimum velocity required by an object to leave a planet or moon.

For a rocket to leave a planet, it must overcome the pull of gravity by moving at a speed above the escape velocity.

$$V = \sqrt{\frac{2Gm}{R}}$$

r – radius of the place

m – mass of the planet

SI unit is metres per second (m/s)

Example 3.6

A satellite was launched into the orbit in space. If the period of the satellite is 8.64×10^4 s, and the mass of the earth is 5.98×10^{24} kg, determine the distance of the satellite from the ground. $G = 6.67 \times 10^{-11}$ N/m²/Kg²

Solution

$$r = \sqrt[3]{\frac{T^2Gm_e}{4\pi^2}}$$

$$= \sqrt[3]{\frac{(8.64 \times 10^4)^2 \times 6.67 \times 10^{-11} \times 5.98 \times 10^{24}}{4 \times 3.142^2}}$$

$= 4.22504 \times 10^7$ m

distance from the ground $= 4.225 \times 10^7 \text{ m} - 6.4 \times 10^6 \text{ m}$

$= 3.585 \times 10^7$ m

Example 3.7

A rocket has to leave the earth for the moon. Calculate its escape velocity if the radius of the earth is 6.38×10^6 m and mass of earth is 5.98×10^{24} kg

Solution

$$V = \sqrt{\frac{2Gm_e}{R}} = \sqrt{\frac{2 \text{ x } 6.67 \times 10^{-11} \times 5.98 \times 10^{24}}{6.38 \times 10^6}}$$

$= 1.2504 \times 10^8$ m/s

Use of satellites

1. Satellites view a wider area of the earth. This helps in providing information about the earth's clouds, oceans, volcanoes and others. Scientists use the information to predict weather and climate.

2. Satellites are used in communication. Satellites have improved TV signals and mobile phone signals. Signals are sent up to a satellite then sent back down at another place.
3. Satellites are used to observe objects in space.

Exercise 3.2

Use mass of the earth = 5.08×10^{24}kg, Radius of the earth = 6.4×10^{6}m, mass of the sun = 1.989×10^{38}kg, Radius of the sun = 6.9858×10^{8}m, Distance from the sun to the earth = 1.496×10^{10}m, Mass of the moon = 7.348×10^{22}kg, g = 6.6×10^{-11}Nm^2/kg^2.

1. Define the term escape velocity.
2. State Kepler's third law of motion.
3. A body of mass m_1 is 2 500 km into the surface of the earth. If the gravitational filed strength on the earth surface is 9.8m/s^2 and the radius of the earth is 6.4×10^{6} m. Determine the acceleration due gravity at this point.
4. A satellite is a 2.46×10^{10} m from the earth. Determine its orbital speed.
5. Give two uses of satellites in modern world.

Topic summary

- Newton's universal law of gravitation states that any two bodies in the universe attract each other with a force that is directly proportional to the product of their masses and inversely proportional to the square of the distance between them.
- Force of attraction is $F = \frac{Gm_1m_2}{r^2}$
- Kepler's first law states that as the planet moves on ellipses, they are continually accelerating.
- Kepler's second law states that the planet – sun line sweeps out equal to area on equal times.
- Kepler's third law states that the square of the orbital period of a planet is proportional to the cube of the semi-major axis of its orbit.
- Gravitational field of the earth is the region just above the earth surface that experiences gravitational pull towards the centre of earth.
- Satellite is an object that moves around a large object.

Topic Test 3

(Use constants as in exercises in this unit tests.)

1. State Newtons universal law of gravitation.
2. What causes gravitational force between bodies.
3. Explain why sometimes some objects in the sky appear stationary.
4. A communication satellite of mass 300 kg orbits (go round) the earth at a height 35 000 m. Given that mass of earth = 5.97×10^{24} kg, radius of earth = 6.4×10^{6} m and G = 6.67×10^{-11} Nm^2/kg^2, find
   (a) how far the satellite is from the centre of the earth?
   (b) the earth's force of attraction onto the satellite.
5. A satellite is moving around the earth of mass 5.97×10^{24} kg. The distance between the earth and satellite is 30 000 m. determine the speed of the object. (G = 6.67×10^{-11} Nm^2/Kg^2)
6. A satellite was launched into the orbit in space. If the period of the satellite is 9.64×10^{4} s and the mass of the earth is 5.98×10^{24} Kg. find the distance of the satellite from the ground.
7. Derive the escape velocity from the earth.
8. Calculate the orbital energy and orbital speed of a rocket of mass 4×10^{3}Kg and radius 7.6×10^{3} km above the centre of the earth. Assume the orbit is circular (mass of earth 5.98×10^{24}Kg.)

UNIT 3 Wave reflection, refraction, interference and diffraction

Topic in the unit

Topic 4: Wave reflection, refraction, interference and diffraction

Key inquiry question

- Why is it easier to see waves in still water than in running water?
- Why are waves important?
- Why do floating objects on surface of water move up and down as the wave propagate through?

Learning outcomes

Knowledge and understanding

- Use understanding of waves to explain wave interaction, interference and diffraction

Skills

- Design investigations on wave interference, diffraction, and standing waves
- Predict what might happen
- Identify and control variables
- Extract information about wave parameters from graphs

Attitude and value

- Appreciate the importance of waves

TOPIC 4 Wave reflection, refraction, interference and diffraction

Topic outline

- Ripple tank and wavefronts
- Reflection of waves
- Refraction of waves
- Interference of waves
- Stationary waves
- Resonance
- Vibrating air columns

Introduction

In Secondary 2, we learnt about waves, their charactersistics including wave length, frequency, amplitude, and speed. We also classified waves into mechanical and electromagnetic waves. In this topic, we will discuss the following properties of waves: refraction, reflection, superposition, interactions, diffraction and interference properties of waves. We will use an equipment called a ripple tank to study waves in a laboratory.

4.1 The ripple tank, pulses and wave fronts

Activity 4.1: **Investigating the wave fronts in a ripple tank.**

Work as a whole class.

Materials

- The ripple tank.
- Water
- Paper screen

Steps

1. Switch on the motor to start its vibrations.
   Observe the wave patterns on the paper screen.

2. Draw the wave patterns observed in your note book.
3. Repeat the steps 1 to 3 with straight vibrator.
4. Discuss the term wave front based on your observations in this activity.

Fig. 4.1 shows a ripple tank. It consists of a transparent tray containing water, a lamp above the tray and a paper screen below the tank.

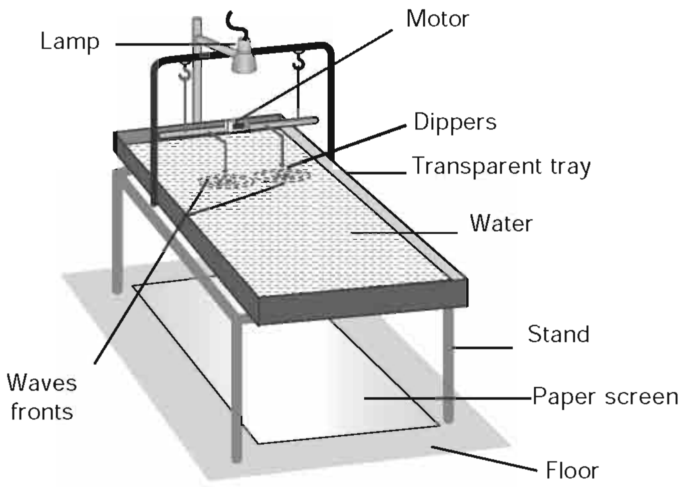


Fig. 4.1: Ripple tank

A pulse of waves (series of short bursts) can be produced by dipping a finger into the water. This produces circular waves which spread out from the position of the finger (Fig. 4.2 (a)). A 30 cm ruler dipped in water and given a quick forward push may produce straight pulses. (Fig. 4.2 (b)).

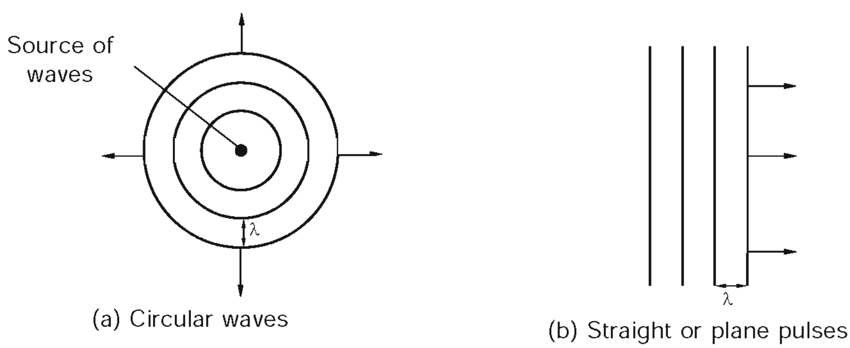


Fig. 4.2: Circular and plane waves

The water waves are also called ripples and are transverse in nature. Continuous ripples may be generated by an electrical motor mounted on the wooden bar on the ripple tank (Fig. 4.1). When the motor is started, the bar is made to vibrate by an eccentric metal disc on the axle of the motor. To generate continuous straight waves, the length of the bar is adjusted so that it just touches the water surface. To generate continuous circular waves, a small ball, called a dipper fitted to the bar is adjusted so that it just touches the water surface.

When the light from the lamp passes through the waves, images of the waves are projected on the paper underneath the tank. A series of alternative bright and dark bands (shadows) are seen on the paper screen.

Wavefronts

A wavefront is an imaginary line which joins a set of particles which are in phase (in step) in a wave motion. Wavefronts can be seen on the white paper underneath the ripple tank. The formation of circular wavefronts and plane wavefronts are shown in Fig. 4.3 (a) and (b).

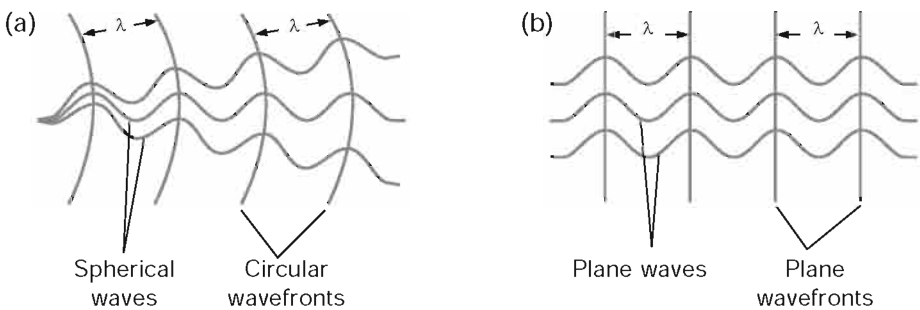


Fig. 4.3: (a) Circular and (b) Plane wavefronts

A ray

A ray is a line drawn perpendicular to the wavefront showing the direction of travel of the wave energy. (Fig. 4.4 (a) and (b)).

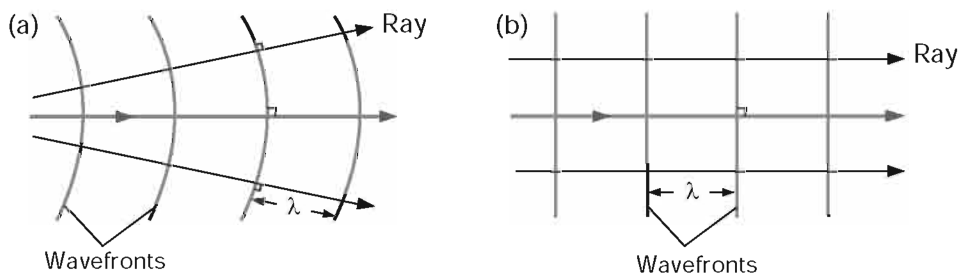


Fig. 4.4: Ray

4.2 Reflection of waves

Activity 4.2: **Reflection of waves on a straight barrier**

Work in groups.

In this activity, you will design and conduct an investigation of water waves in a ripple tank.

Instructions

1. Design and carry out a simple investigation on how water waves are reflected in a ripple tank.
2. From your investigation:
   (a) Draw the diagram of reflection of water waves.
   (b) Explain the relationship between the angle of incidence and angle of reflection of the waves.

At any surface, waves are reflected at an angle equal to the angle of incidence. Thus, the angle of reflection (r) is always equal to the angle of incidence (i).

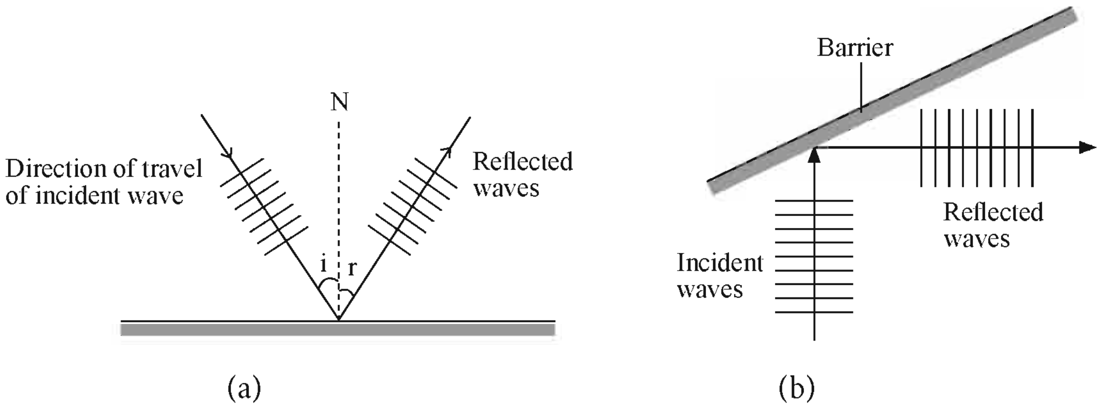


Fig. 4.5 (a) and (b): Reflection of wave

Activity 4.3: **Reflection of waves on curved barriers**

Work in groups.

Materials

- Ripple tank
- Curved metal
- Water

Steps

1. Place a curved barrier in the ripple tank with the concave surface facing the water tank.
2. Send ripples across the tank and look carefully at the reflected waves. What do you observe? Sketch the incident and reflected waves. Explain their shape.
3. Repeat the activity with the convex surface of barriers facing the water. What do you observe? Sketch the incident and reflected waves. Explain their shape.

Figure 4.6 (a) and (b) shows the reflection of waves on concave and convex barriers respectively.

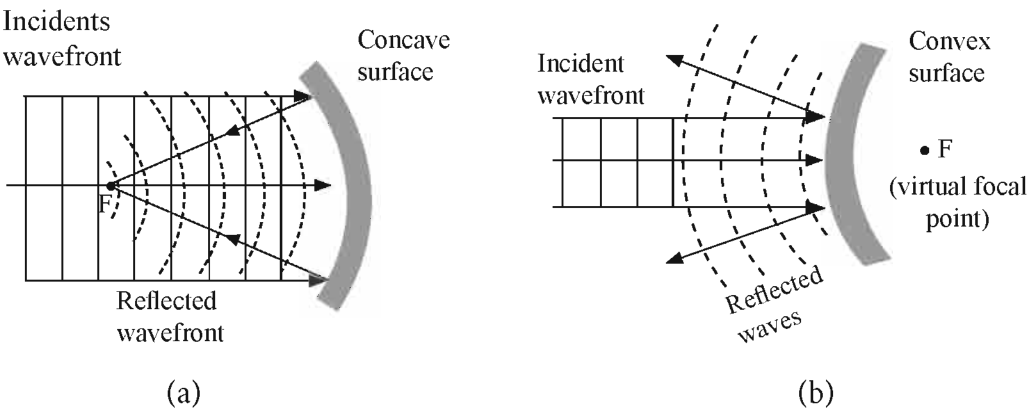


Fig. 4.6: Reflection of waves on concave and convex barriers

When the incident wavefront strikes the concave barrier, it is reflected in a way that it changes direction and heads towards a point (the principal focus of the barrier). It is as though all the energy being carried by the waves converge at a single point. The point is known as the focal point. (See Fig. 4.6(a)).

When the incident wavefront reach a convex barrier, it is reflected in a way that it change direction and move as though it has been generated from a point in the convex barrier (the focal point of the convex barrier). It is as though all the energy being carried by the waves diverges from the focal point. (See Fig 4.6(b)).

Reflection is the bouncing off of a wave when it strikes an obstacle. When reflection occurs, only the direction of the wave changes. Activities 4.3 and 4.4 will help us understand how waves are reflected

Applications of reflection of waves

- Reflection of waves such as sound wave is applied in measuring distance.
- Reflection of sound wave is applied in navigation, communication and detection objects on the floor of the sea.
- Reflection of light wave is applied in the design of mirrors used in periscopes.

- Bats judge the distance away from an object by emitting ultrasound and interpreting the time taken for the wave reflected by (echo) the object to return.
- Ultrasonic waves are used to determine the depth of shoals of fish or the seabed.
- Ultrasonic echoes are used to determine the shape and size of an object that is not visible such as sunken ship or a baby in the womb.
- Reflection of light is applied in the working of fibre optics, by CD players in reading CDs and helps animals to see objects.
- Radio waves are reflected off the ionosphere to reach the recipient on the ground. Television, mobile phones and radio use this reflection to transfer information.

4.3 Refraction of waves

Activity 4.4: **To observe refraction of waves-change in speed**

Work in groups.

Materials

Ripple tank, thin glass sheet, water

Steps

1. Place a thick sheet of glass in the ripple tank and adjust the depth so that the water is very shallow over the glass sheet.
2. Send waves across the tank and study the waves as they travel through the shallow water. Write down your observation. Sketch the incident and refracted waves. Explain the change in the separation distance of the wavefronts.
3. What happens to:

   (a) The speed of the waves as they move into the shallow water.

   (b) The wavelength of the wave when they move into the shallow water.

Activity 4.5: **To observe refraction of waves - change in direction**

Work as whole class.

Materials

- Ripple tank
- Thin glass sheet
- Water
- Curved thin glass

Steps

1. Now place the thin glass sheet at an angle and repeat Activity 4.4. Sketch the incident and refracted waves.

   What happens to the direction of the wave as they slow down in the shallow water?
2. Replace the thin glass sheet with curved thin glass. Sketch the incident and refracted waves.

In Activity 4.4 and 4.5, when the glass plate was in the ripple tank, it created a shallow end on the tank (Fig. 4.7).

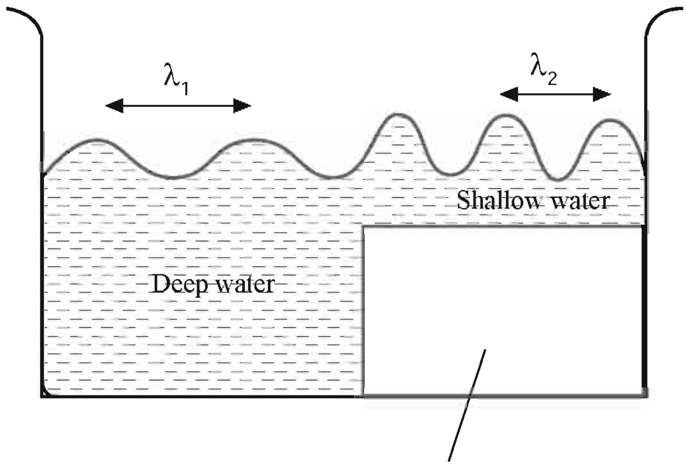


Fig. 4.7: Refraction of water waves

As the waves moved from the deep to shallow water the speed and wavelength of the wave decreases causing the direction of the wave to change. When waves change their speed and direction like this, we say they have been refracted.

Refraction is the bending or change in direction of waves as they pass from one medium to another.

Note

The frequency of the waves is same in both the shallow end and the deep ends. Thus, the decrease in the speed of the wave is as a result of the decrease in wavelength (λ) of the wave must change.

$$\underset{\text{decrease}}{v} = f\underset{\text{decrease}}{\lambda}$$

The behaviour of water waves during the refraction is similar to that of light. The refracted light wavefronts are refracted towards the normal line. The direction of travel is bent towards the normal in the shallow region. The figures 4.8 (b) and (c) shows refraction of water waves at plane and curved boundaries.

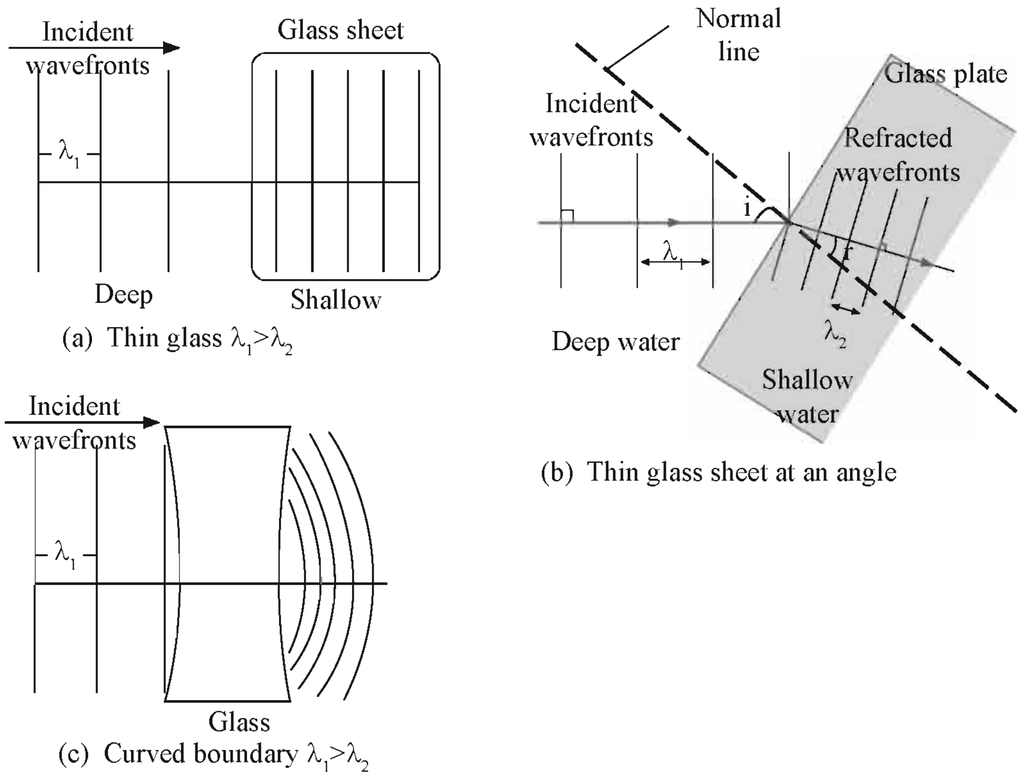


Fig. 4.8: Refraction of water waves

Applications of refraction of waves

1. Refraction is used in medicine to determine refractive error in eye.
2. Refraction is used in optical instruments such as microscopes, lenses, camera, the eye and telescopes which focus and spread light.
3. Refraction is used in the dispersion of light waves by glass triangular prism.

4.4 Diffraction of waves

Activity 4.6: To observe diffraction of waves through a wide gap

Work as whole class.

Materials

- Ripple tank
- 2 metal barriers
- Water
- 1 cm barrier

Steps

1. Dip the 2 metal barriers in the ripple tank and arrange them to leave a gap between them.
2. Use a ripple tank to send straight waves across water to a wide gap between two barriers.
3. Look at the wave after they have passed through the gap. Sketch the incident waves and after they emerge from the gap. Explain the change in their shape?

The wave spread out and change in shape slightly after passing through the gap (Fig. 4.9).

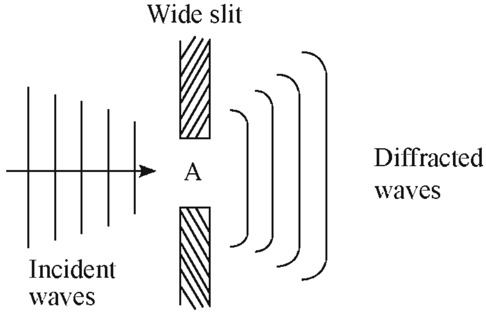


Fig. 4.9 : Diffraction of waves through a wide slit

Activity 4.7: To observe diffraction of waves through a narrow gap

Work in groups or a whole class.

Materials

Ripple tank, metal barriers, water.

Steps

1. Repeat activity 4.6 but with a very small gap between the metal barriers.
2. Look at the wave after they have passed through the gap. Sketch the incident waves and after they emerge from the gap. Explain the change in their shape.

The waves spread out and change in shape completely after passing through the narrow slit (Figure 4.10).

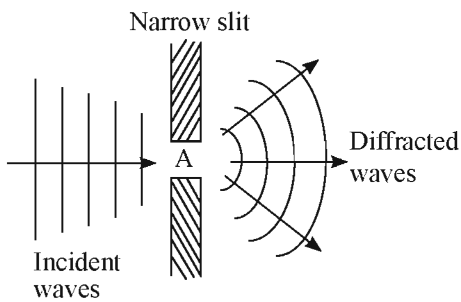


Fig. 4.10: Diffraction of waves through a narrow slit

Similarly, waves spread out at the edge of an obstacle (Figure 4.11)

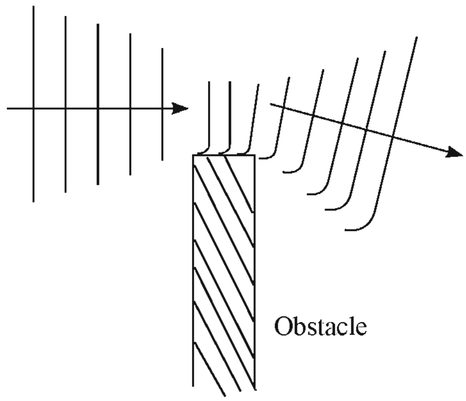


Fig. 4.11: Bending of wave around an obstacle

Waves have the ability to travel around obstacles and through openings. If a barrier is placed in the path of water waves, the water wave are seen to pass around the barriers into the region behind it. The water behind the barrier is subsequently disturbed.

Diffraction *of waves is the spreading of waves as they pass through an opening or around a barrier in their path.*

The extent of diffraction also referred to as the *sharpness of the bending* increases with increase in wavelength and decreases with decreasing wavelength. If the wavelength is smaller than the opening (slit), no noticeable diffraction occurs.

This is clearly observed when water flowing down a stream meets a rock, it goes round the rock thus bending.

The diffraction of sound waves around corners of walls and buildings enable us to hear other people who are speaking from adjacent rooms or calling us from behind a building.

Note: *Diffraction of light waves* only occur when the light waves encounter obstacles with extremely small wavelength such as particles suspended in the atmosphere.

Applications of diffraction of waves

- It is applied in the study of the the structure of a crystal.
- Diffraction is applied in the determination of the coefficient of thermal expansivity, sizes of crystal and thicknesses of thin films.
- It is used to determine phases and types of particles present in a specimen where the spacing of atom is between 4 nm and 3 nm.

Diffraction grating

When parallel rays of a monochromatic light of wavelength, λ incidence on double slit with distance of separation, *d* and grating has N lines metre, grating spacing is given by

$$d = \frac{\lambda}{N}$$

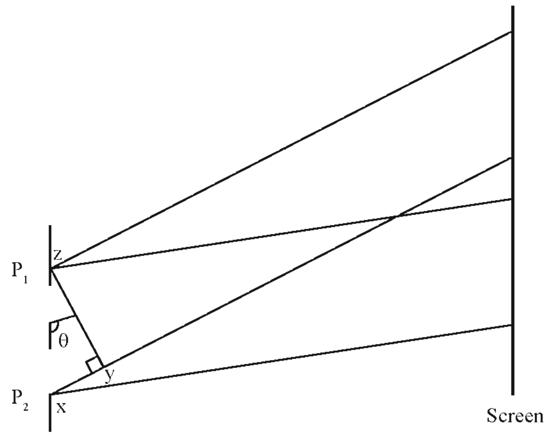


Fig. 4.12

Constructive interference, occurs only when wave from A is in phase with waves from B. The path difference is a whole number.

$XY = \lambda n$ where $n = 0, 1, 2, 3 \ldots$

So, $XY = d \sin \theta$

Where θ is angle of diffraction.

Therefore the equation relating wavelength, distance of separation and angle of diffraction is given by

$$d \sin \theta = n\lambda$$

where $n = 0, 1, 2, 3, \ldots$ n order

Example 4.1

A diffraction grating is of width 6 cm and produces a deviation of 20 in the second order with light of wavelength 580 nm. Calculate the slit spacing.

Solution

$$d = \frac{n\lambda}{\sin \theta} = \frac{2 \times 580 \times 10^{-9}}{\sin 20}$$

$$= 3.4 \times 10^{-6} \text{ m}$$

4.5 Interference of waves

Activity 4.8: **Interference of waves**

Work in groups or as whole class.

Materials

- Ripple tank
- 2 marbles
- Water

Steps

1. Drop two marbles at the same time but at distance between them in a ripple tank to make two circular waves that spread out and overlap.
2. Keenly observe the waves as they overlap.
   (a) What happens when the crest of one wave overlaps with the crest of another wave?
   (b) What happens when the crest of one wave overlaps the trough of another wave?

When two crest overlap they give a rise to a bigger crest. When a crest and a trough overlap, they give rise to a crest or trough with a smaller amplitude.

The overlapping or combination of two or more waves resulting in the formation of one wave wave is called interference of waves.

Interference is the phenomenon that occurs when two waves meet while travelling along the same medium.

There are two types of interference: constructive interference and destructive interference.

Constructive interference

Consider two transverse waves, each amplitude 0.5 m are travelling in opposite directions in the same medium (Figure 4.13).

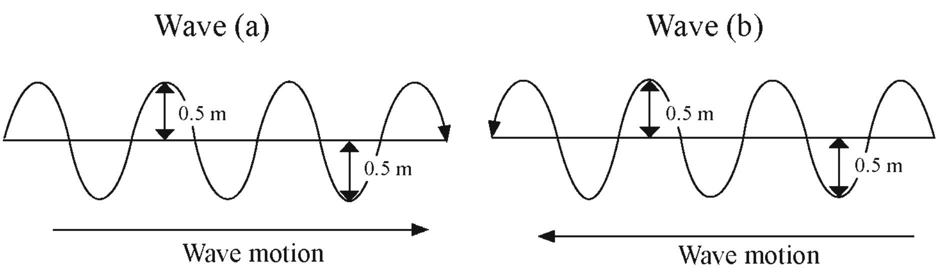


Fig. 4.13: Wavefronts in-phase moving in opposite direction

As the waves move towards each other, they eventually overlap completely. If a trough of wave (a) coincides with a trough of wave (b), the amplitude of the resulting trough is the sum of the amplitudes of the two troughs (Figure 4.14 (a)). If their crests meet, the resulting crest is the sum of the amplitudes of the two crests (Figure 4.14(b)). This is known as constructive interference.

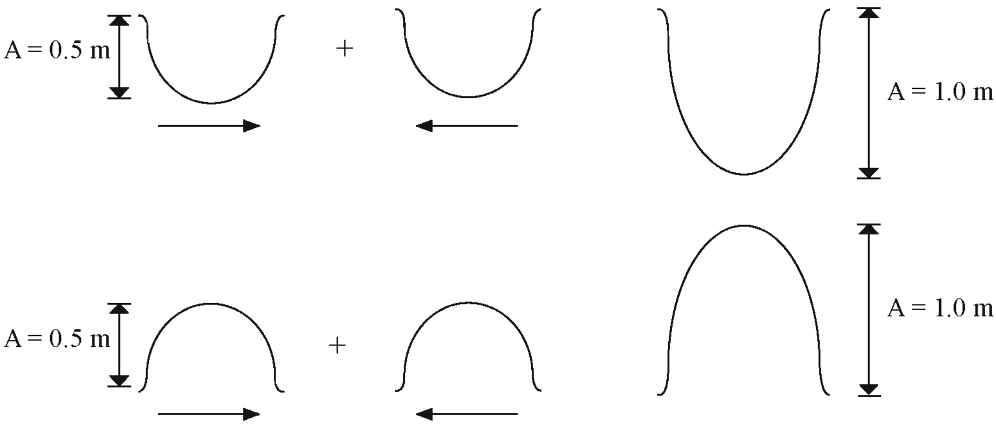


Fig. 4.14: Constructive interference

When two crest or troughs of two waves coincide, the waves are said to be *in-phase.*

Destructive interference

Consider two waves that are moving in opposite directions such that the crest of one wave coincides with the trough of the other.

Such waves are said to be *out of phase (antiphase).* The result is that the two pulses cancel each other. This is known as destructive interference (Figure 4.15).

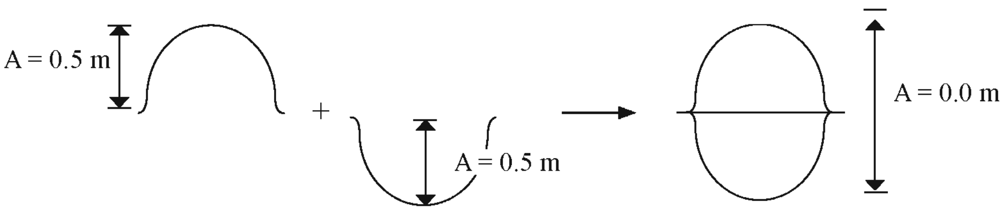


Fig. 4.15: Destructive interference

After destructive interference there is no net displacement of the particles of the medium.

This destruction is not a permanent condition. Once the coinciding pulses pass through each other the waves continue with the upward and downwards motion just us they were before the interference.

The two interfering waves do not have to have equal amplitude in opposite directions for destructive interference to occur.

Principle of superposition

The principle of superposition is applied to determine the shape of the resultant wave during interference. It states that; "*When two waves interfere, the resulting displacement of the medium at any location is the algebraic sum of the displacement of the individual waves at the same location*."

Applications of interference of waves

- Destructive interference is used to reduce the noise level of machinery.
- Destructive interference is applied in the construction of sound proof halls.
- Interference is applied in making holograms - photographs of an interference pattern which can produce a three-dimensional image when illuminated.
- Interference is applied in the making of an automobile muffler that produces a sound out of phase with that of the exhaust system hence cancels the noise by destructive interference.

4.6 The dual nature of light

The dual nature of light refers to the fact that light can act as both a wave and a particle. Over time, various scientists have tried to proof these two natures of light.

Light as a wave

In 1678, Christian Huygens came up with a theory that every point on a wave-front may be considered a source of secondary spherical wavelets which spread out in the forward direction at the speed of light. The new wave-front is the tangential surface to all of these secondary wavelets. According to his theory, light from a source is propagated in form of longitudinal waves in uniform velocity in homogenous medium. However it was later proofed that light is a transverse wave. Though his theory could explain the phenomena of reflection, refraction, polarisation and total internal reflection of light, it could not explain rectilinear propagation, and photoelectric effect.

In 1801, Thomas Young's proofed that light is a wave by performing the double slit. He shone light between two parallel slits; the light waves interfered with each other and formed a patter of dark and light bands through constructive and destructive interference (see the previous sections in this topic). He concluded that if light was primarily a particle, interference would not have occurred but rather, the stream of particles would have emerged as parallel lines after passing through the slits.

Light as a particle

Newton's corpuscular theory: Newton proposed that light was composed tiny perfectly elastic particles of negligible mass called corpuscles that travel in straight lines. As such his theory supported explain rectilinear propagation of light. His theory also supported reflection of light in that the bouncing of either particles or waves off a planar surface follows the same laws of reflection. The main draw back of his theory was the fact to explain refraction of light; he had to presume that the particles travelled faster in a more optically dense material than in a lighter one. This was disapproved by But Foucault's (1850) experiment showed that light travelled more slowly in a denser media

Albert Einstein's proved that light could behave as a particle by showing that a beam of light could eject electrons from metal. This suggested that light consisted of photons that could eject electrons of similar frequency. Einstein's discovery altered the prevalent theory at the time, which held that light was only a wave.

Quantum mechanics explains the *duality of light* by describing it as a wave-packet. A wave-packet refers to waves that may interact either as spatially localized, acting as particle, or interacting like waves. This means light photons can either act as a particle or wave, depending on the circumstances.

Exercise 4.1

1. Define:
   (a) Interference of a wave.
   (b) Diffraction of a wave.
2. Differentiate between the following properties of waves:
   (a) Refraction and reflection.
   (b) Destruction interference and constructive interference.
3. State one effect that would be observed when water waves pass from deep to shallow water.
4. State one condition not involving a phase difference for interference pattern to be observed.
5. The sketch graph in Figure 4.16 shows the results of an experiment to study diffraction pattern using double silt.

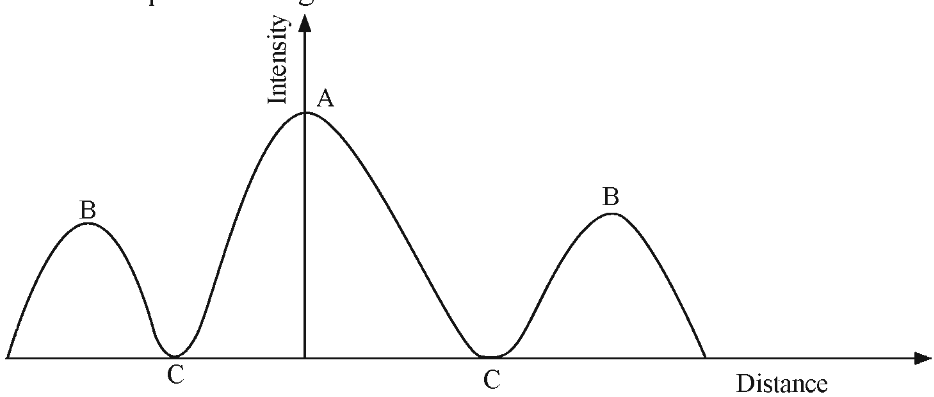


Fig. 4.16: A graph from an experiment to study diffraction

   (a) Sketch an experimental set up that may be used to obtain such a pattern.

(b) Name an instrument for measuring intensity of waves.

(c) Explain how the peaks labelled A and B and troughs labeled C are formed.

(d) State the condition necessary for noticeable diffraction to occur.

(e) Explain why we can hear the sound of a person speaking inside a room through an open door though we cannot see him as the walls block the straight line of sight linking the person and us.

6. Fig. 4.17 shows two similar loudspeakers connected to a common signal generator and vibrating in phase. The loudspeakers are 0.50 m apart and emit a note of frequency 1 500 Hz. An observer walks along a line 3.0 m from the speakers, as shown in the figure. He hears a loud sound at A, which decreases to a minimum at B, and then increases in intensity as he walks towards C.

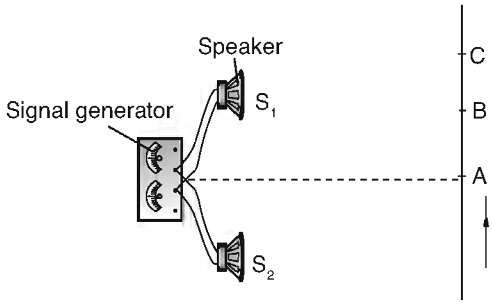


Fig. 4.17: Two loud speakers vibrating in phase.

(a) Explain why the observer detects a loud sound at A.

(b) Explain why the loudness of the sound detected decreases as the observer walks from A to B and is minimum at B.

(c) Calculate the wavelength of the sound emitted by the loudspeaker. The speed of sound in air is 340 ms^{-1}.

(d) The connections to the terminals of one of the loudspeakers are reversed. What difference does the observer notice while walking from A to C? Explain why these differences occur

4.7 Stationary waves on a vibrating string

4.7.1 To investigate the waves produced by a vibrating string

Activity 4.9: **Investigating the stationary waves on a vibrating string**

Work in pairs.

Materials

- Rubber band
- Two pegs

Steps

1. Insert the rubber band into your thumb and first finger and stretch it. (Fig. 4.18).

Fig. 4.18

2. Pluck the rubber band at the centre and observe the wave produced.

   Identify the regions of highest amplitude and zero amplitude in the wave and explain how they arise. What names are they given?

When a string instrument such as a guitar or violin is played, a transverse wave travels along the vibrating string. At the end of the string, the wave is reflected back. This results to two waves with the same frequency, amplitude, wavelength and speed travelling in opposite directions along the string and so they interfere (superpose) to form a stationary wave also known as a standing wave (Figure 4.19).

A stationary wave can also be produced by attaching one end of a thread to the vibrator (clapper) (P) and the other end of a thread is passed over a pulley to a mass hanger(scale pan). When weights are placed on the scale pan and adjusted the thread can be seen vibrating with stationary loops along its length (Figure 4.19). The successive wave positions are shown by a, b, c, d and e..

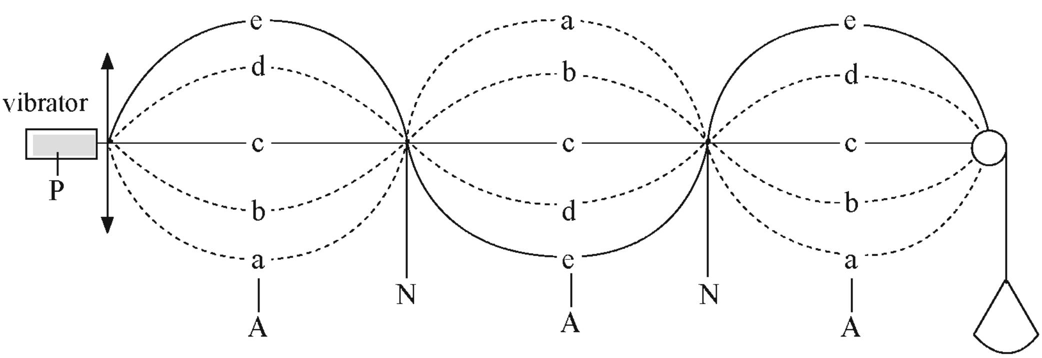


Fig. 4.19: Stationary Waves

In a stationary wave, some points denoted by N are always at rest, no displacement. These points are known as nodes. Some other points denoted by A have maximum amplitude (maximum displacement) and are known as antinodes.

We can therefore summarise the characteristics of stationary wave as follows:

A stationary wave: A transverse or longitudinal in which the waveprofile does not move but remains stationary.

Nodes: Points on a stationary wave with zero amplitude (zero displacement).

Antinodes: Points on a stationary wave with maximum amplitude (maximum displacement).

4.7.2 Factors affecting the frequency of the waves produced by a vibrating string

The frequency of a musical note can be changed by changing some factors. Experiments show that, the frequency of a musical note is affected by the following four factors; length, tension, mass and thickness of a string. These factors can be investigated in the laboratory by using an instrument called a Sonometer.

(a) Variation of frequency with the length of string

Activity 4.10: **To investigate the relationship between frequency and length of a vibrating wire**

Work in groups.

Materials

- Set of tuning forks
- slotted weights
- sonometer
- steel wire paper rider.

Steps

1. Set up the Sonometer as shown in the Figure 4.20.

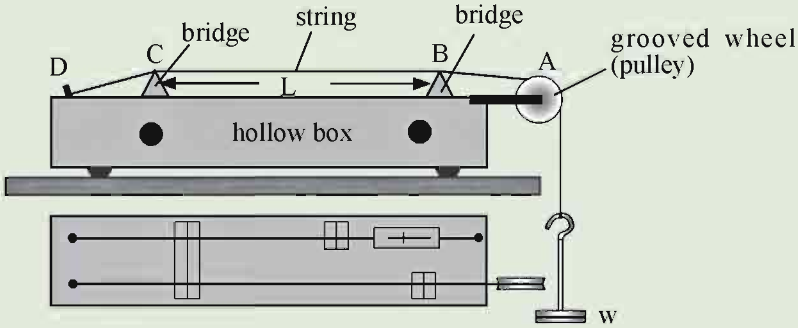


Fig. 4.20: Sonometer

2. Select a tuning fork with lowest frequency and set it into vibration. Pluck the wire at the same time. If the two sounds are not in unison, add or reduce weight until they are in unison.
3. Record the frequency 'f' of the tuning fork as the frequency of the sonometer and the length between the bridges L.
4. Sound another tuning fork of different frequency and adjust the length between the bridges until the sounds produced match. How is the pitch of the sound affected by a decrease in the length of the string?
5. Repeat the procedure for the remaining tuning forks, record your results in a table.

Frequency of sonometer, f (Hz)				
Length of the wire, L (cm)				
$\frac{1}{L}$ (cm^{-1})				

Table. 4.3: Table of Frequency of sonometer against length of wire

6. Plot a graph of f against $\frac{1}{L}$.
7. From your graph, how does the frequency of vibration vary with the length of the string.

A Sonometer is an instrument used to study the variation of the frequency of a stationary wave with length, tension, mass and thickness of a stretched wire in a string instrument. It consists of a thin wire attached to one end of a hollow sounding box and the other end of the wire is passed over a grooved wheel and the wire is kept taut by a heavy weight. The factors that affect the frequency of a musical note are discussed below in detail follows:
A graph of f against $\frac{1}{L}$ is a straight line passing through the origin as shown in Figure 4.21.

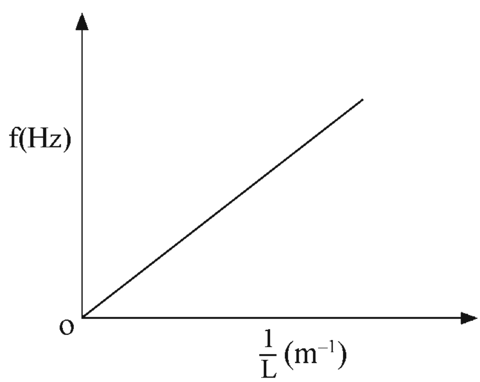


Fig. 4.21: Graph of f versus $\frac{1}{L}$

From the graph, it shows that $f \propto \frac{1}{L}$

From the experiments conducted at a constant tension, increase in the Length of the string lowers the frequency of the tone produced. This means that, frequency is inversely proportional to the length of the string i.e.

$$f = \text{constant} \times \frac{1}{L} \Rightarrow fL = \text{constant}$$

Example 4.2

Under constant tension the note produced by a plucked string is 300 Hz when the length of the string is 0.9 m.

(a) At what length is the frequency 200 Hz?

(b) What frequency is produced at a length of 0.3 m.

Data:

$f_1 = 300$ Hz; $L_1 = 0.9$ m.

Solution

(a) To find L_2 When $f_2 = 200$ Hz.

Since $f \propto \frac{1}{L}$

$$f_2L_2 = f_1L_1$$

$$200\text{ Hz} \times L_2 = 300\text{ Hz} \times 0.9\text{ m.}$$

$$L_2 = \frac{300\text{ Hz} \times 0.9\text{ m}}{200\text{ Hz}}$$

$$= 1.5 \times 0.9\text{ m}$$

$$= 1.35\text{ m}$$

The length will be 1.35 m

(b) To find f_2 when $L_2 = 0.3$ m

$$f_2L_2 = f_1L_1$$

$$f_2 \times 0.3\text{ m} = 300\text{ Hz} \times 0.9\text{ m}$$

$$f_2 = \frac{300\text{ Hz} \times 0.9\text{ m}}{0.3\text{ m}}$$

$$= 300\text{ Hz} \times 3$$

$$= 900\text{ Hz}$$

The frequency will be 900 Hz

(b) Variation of frequency with tension

Activity 4.11: **To investigate the relationship between frequency and tension in a vibrating wire**

Work in groups.

Materials

- Set of tuning forks
- slotted weights
- sonometer
- steel wire paper rider.

Steps

1. Tune both the fork and the string of the sonometer simultaneously and adjust weight until the sounds produced are in unison. Record the frequency '*f* and corresponding

weights (W) for a constant length. How is the pitch of the sound affected by an increase in the weight suspended?

2. Repeat this procedure for several values of *f* and W.
3. Record your results and then plot a graph of *f* against $\sqrt{W}$.
4. Based on the graph you have obtained, how does the frequency of vibration vary with the tension in the string.

The graph is a straight line passing through origin as shown in Figure 4.22.

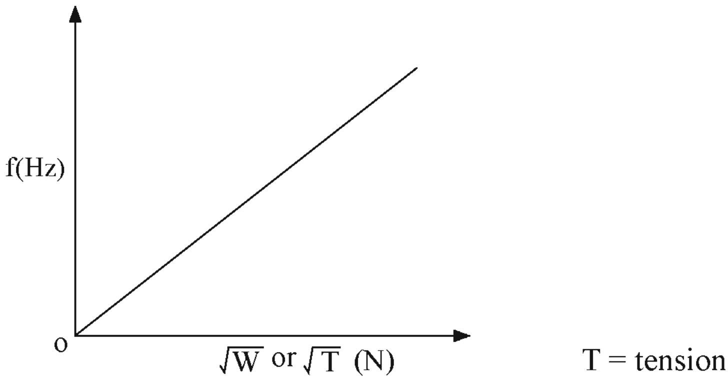


Fig. 4.22: Graph of f versus $\sqrt{W}$ or $\sqrt{T}$

From the graph above, it means that $f \propto \sqrt{W}$ or $f \propto \sqrt{T}$.

Keeping the length of wire (string) between the bridges of sonometer constant, the tension T, in the wire can be changed by altering the weight (w). The frequency of the note obtained by plucking the wire changes with tension. This experiment show that frequencies (f) is directly proportional to square root of tension ($\sqrt{T}$) i.e.

$$f \propto \sqrt{T} = f = \text{constant} \times \sqrt{T} \Rightarrow \frac{f}{\sqrt{T}} = \text{constant}$$

Example 4.3

The frequency obtained from a string is 800 Hz when the tension is 4 N. Calculate:

(a) The frequency when the tension is increased to 16 N.

(b) The tension needed to produce a note of frequency 1200 Hz

Data

$F_1 = 800$ Hz; $T_1 = 4$ N

Solution:

(a) To find f_2 when $T_2 = 16$ N

Since $f \alpha \sqrt{T}$.

Implying; $\frac{f_1}{f_2} = \sqrt{\frac{T_1}{T_2}}$

$\frac{800 \text{ Hz}}{f_2} = \sqrt{\frac{4N}{16N}}$

$\frac{800 \text{ Hz}}{f_2} = \sqrt{\frac{4\cancel{N}}{16\cancel{N}}}$

$\frac{800 \text{ Hz}}{f_2} = \frac{2}{4} = \frac{1}{2}$

$f_2 = 2 \times 800 \text{ Hz} = 1600 \text{ Hz}$

The frequency will be 1600 Hz

(b) To find T_2 when $f_2 = 1200$ Hz

$\sqrt{\frac{T_1}{T_2}} = \frac{f_1}{f_2}$

$\sqrt{\frac{T_2}{4N}} = \frac{1200 \cancel{\text{Hz}}}{800 \cancel{\text{Hz}}} = \frac{3}{2}$

$\frac{T_2}{4 \text{ N}} = \frac{9}{4}$

$T_2 = 4 \text{ N} \times \frac{9}{4} = 9 \text{ N}$

The tension needed = 9 N

(c) Variation of frequency with mass (m)

At a constant tension and length, experiments show that the frequency, 'f' of a vibrating string is inversely proportional to the square root of mass of the string ($\sqrt{m}$), i.e

$$f \alpha \frac{1}{\sqrt{m}} \Rightarrow f = \text{constant} \times \frac{f}{\sqrt{m}} = f \times \sqrt{m} = \text{constant}$$

(d) Variation of frequency with thickness of the wire (string)

Activity 4.12: **To investigate the relationship between frequency and thickness (diameter)**

Materials

- Strings of different diameters (thicknesses)
- sonometer
- steel wire
- paper rider
- set of tuning forks.

Steps

1. Select a tuning fork of known frequency, identify a string that produces a sound that is in unison with the one produced by the tuning fork. Record the thickness (diameter) of the string.

2. Repeat procedure (1) above using strings of different thickness and identifying their corresponding frequencies using tuning forks. Record the thickness of the strings and their corresponding frequencies.
3. Plot a graph of f against $\frac{1}{d}$.
4. From the graph, describe how the frequency of the vibrating string varies with the thickness of the string.

The graph is a straight line as shown in Figure 4.23.

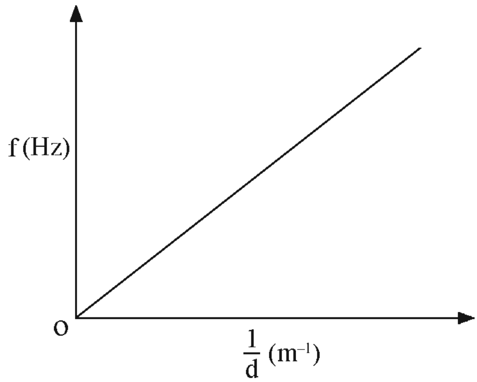


Fig. 4.23: Graph of f versus $\frac{1}{d}$

The frequency*(f)*, varies inversely to diameter of string.

At a constant tension and length, experiments shows that, a thinner wire produces a note of higher frequency while a thicker wire produces a note of lower frequency. This shows that frequency *(f)* is inversely proportional to the diameter of the wire, d, i.e

$$f \propto \frac{1}{d}; \text{ Where } d = \text{diameter}$$

$$\therefore f = \text{constant} \times \frac{1}{d} \Rightarrow fd = \text{constant}$$

Violins have four strings of different densities, so the mass per metre is different for each. This helps the violinist to obtain a wide range of frequencies from the strings.

In general, the frequency, 'f' of a plucked string depends on the length of string, tension on the string and mass of the string as shown by the equations below:

(a) $f \propto \frac{1}{L}$ (at constant tension and thickness of string)

(b) $f \propto \sqrt{T}$ (at constant length and thickness of string)

(c) $f \propto \frac{1}{\sqrt{m}}$ (at constant tension and length)

By combining the three relationships:

$$f \alpha \frac{1}{L} \times \sqrt{T} \times \frac{1}{\sqrt{m}}$$

$$f \alpha \frac{1}{L}\sqrt{\frac{T}{M}}$$

$$f = \frac{1}{2L}\sqrt{\frac{T}{m}}$$

Where $\frac{1}{2}$ is a constant obtained from experiments.

4.7.3 Fundamental frequency formula for a vibrating string

The same combined relationship can be obtained by considering the stationary wave set up along a string. The *lowest possible note* or *fundamental frequency* is obtained by plucking the string gently at the middle which sets up a simple stationary wave as shown in Figure 4.24.

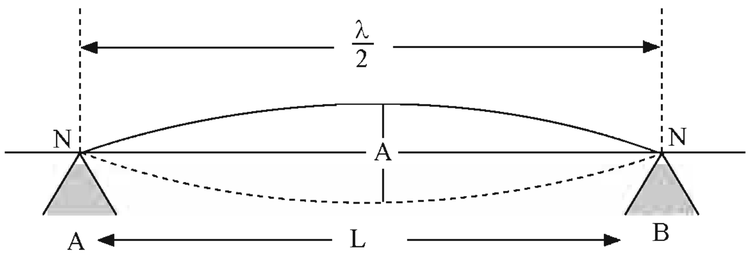


Fig. 4.24: Simple stationary wave from a bowed string

From Figure 4.24

Distance NN = $\frac{\lambda}{2}$ where λ is the wavelength produced.

Thus: $L = \frac{\lambda}{2}$ implying; $\lambda = 2L$

But $f_o = \frac{v}{\lambda}$ and $\lambda = 2L$, where f_o is fundamental frequency.

$$\therefore f_o = \frac{v}{2L}$$

The square of the velocity (v^2) of the wave along the string depends on its mass per unit length, M and its tension, T.

Thus;

$$v^2 = \frac{T}{m} \Rightarrow v = \sqrt{\frac{T}{m}}$$

From $f_o = \frac{v}{2L} \Rightarrow f = \frac{1}{2L}\sqrt{\frac{T}{m}}$

Example 4.4

The tension in a sonometer string of length 0.3 m is 0.5 N. Find the frequency of the string if its mass per unit length is 0.01 kg/m.

Given:

L = 0.3 m; T = 0.5 N (0.5 kgm/s^2); M = 0.01kg/m; f = ?

Solution

$$f = \frac{1}{2L}\sqrt{\frac{T}{M}} = \frac{1}{2 \times 0.3\ m} \times \sqrt{\frac{0.5\ N}{0.01\ kg/m}}$$

$$= \frac{1}{0.6\ m} \times \sqrt{\frac{0.5\ \cancel{kg}\ m/s^2}{0.01\ \cancel{kg}/m}}$$

$$= \frac{1}{0.6\ m} \times \sqrt{50\ m^2/s^2}$$

$$= \frac{1}{0.6\ \cancel{m}} \times 7.07\ \cancel{m}/s$$

$$= 11.8\ Hz.$$

The frequency of the string is 11.8 Hz.

Determining the frequencies of fundamental note and overtones for vibrating strings

Earlier in this unit, we learnt that:

- The lowest note obtained from a bowed string is called its fundamental note. This is obtained when the vibrating string is at its lowest frequency called fundamental frequency (first harmonic).
- Overtones are tones obtained by frequencies higher than fundamental frequency. Usually overtones are tones which are multiple of fundamental tones. Thus, an overtone is a higher frequency of a note.

  Higher frequencies than the fundamental frequency can be obtained from a bowed string as shown in Figure 4.25, They are also called harmonics.

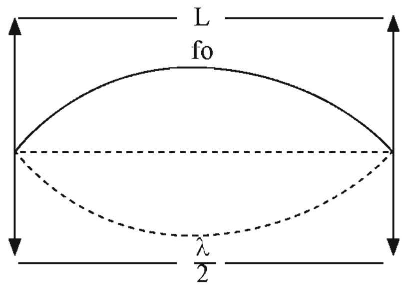


Fig. 4.25: Fundamental frequency

(a) 1st harmonic (fundamental frequency f_o).

$$L = \frac{\lambda}{2}$$

$$\lambda = 2L$$

But from $v = f\lambda$, $f = \frac{v}{\lambda}$

If, $f = \frac{v}{\lambda}$ and $\lambda = 2L$

Then, $f = \frac{v}{2L}$. But $f = f_o$

Therefore, $f_o = \frac{v}{2L}$ which is fundamental frequency formula.

Higher harmonic occur when there are additional nodes in second harmonic.

(b) 2nd harmonic or 1st overtone (f_1)

The 2nd harmonic occurs when the frequency of the string is twice the fundamental frequency. (Figure 4.26)

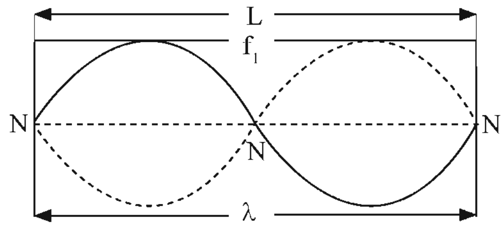


Fig. 4.26: Second harmonic (1st overtone)

From above $L = \lambda$

But $v = f\lambda$ implying; $f = \frac{v}{\lambda}$

But $\lambda = L$. And $f = f_1$

$$f_1 = \frac{v}{L}$$

From $f_0 = \frac{v}{2L}$ implying; $\frac{v}{L} = 2f_0$

$\therefore f_1 = 2f_0$, which is the 2nd harmonic (1st overtone).

(c) 3rd Harmonic or 2nd overtone (f_2)

The 3rd harmonic occurs when the frequency of the vbrating string is thrice the fundamental frequency.

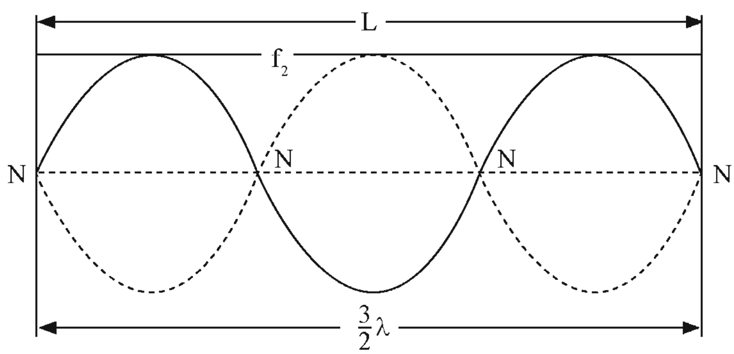


Fig. 4.27: Third harmonic (2nd overtone)

From above: $L = \frac{3}{2}\lambda$, implying; $\lambda = \frac{2L}{3}$

But $v = f\lambda$

$f = \frac{v}{\lambda}$ but $f = f_2$ and $\lambda = \frac{2}{3}L$

$$f_2 = v \div \frac{2L}{3} = \frac{3v}{2L}$$

$$f_2 = \frac{3v}{2L}$$

From $f_0 = \frac{v}{2L}$; But $\frac{v}{L} = 2f_0$

$$f_2 = \frac{3}{\not{2}} \times \not{2}\, f_0$$

$\therefore$ $f_2 = 3f_0$, which is the 3rd harmonic (2nd overtone).

Generally, the frequency of nth harmonic is given by;

$f_{(n-1)} = nf_0$, where: f_0 = fundamental frequency or first harmonic.

For example, to get the 4th harmonic

4th harmonic (3rd overtone)

n = 4. Substituting n = 4 in $f_{(n-1)} = nf_0$, we obtain;

$f_3 = 4f_0$, which is the 4th harmonic (3rd overtone).

Example 4.5

A rope of length 50 cm and a mass of 100 g per unit length is set into vibration. If the tension is 10 N, find the frequencies of:

(a) 1st harmonic.

(b) 3rd harmonic (show your working).

Data

L = 50 cm = 0.5 m; M = 100 g/m = 0.1 kg/m; T = 10 N

Solution

(a) To find 1st harmonic = fundamental frequency f_0

$$f_0 = \frac{1}{2L}\sqrt{\frac{T}{M}} = \frac{1}{2 \times 0.5\text{ m}} \times \sqrt{\frac{10\text{ N}}{0.1\text{ kg/m}}}$$

$$= \frac{1}{1\text{ m}} \times \sqrt{\frac{10\text{ kg m/s}^2}{0.1\text{ kg/m}}}$$

$$= \frac{1}{1\ m} \times \sqrt{100\ m^2/s^2}$$

$$= \frac{1}{1\ \cancel{m}} \times \overset{10}{\cancel{40}}\ \cancel{m}/s$$

$$= 10/s = 10\ Hz$$

∴ The frequency of 1st harmonic = 10 Hz

(b) To find 3rd harmonic, $f_o = 10$ Hz, n = 3

$$f_{n-1} = nf_o$$

$$f_{3-1} = 3f_o = 3 \times 10\ Hz$$

$$f_2 = 30\ Hz$$

The frequency of 3rd harmonic = 30 Hz

4.7.4 Resonance

The pendulum is a simple mechanical system which can be set into vibration. If the bob is pushed gently and then left, it vibrates with a natural frequency which depends on the length of the pendulum.

All types of vibrating system have their own natural frequencies of vibration. Figure 4.28 shows four pendulums P, Q ,R and S of different lengths each carrying a mass of about 200 g as a bob. The pendulums are hanging on a horizontal string. Another pendulum A, with a heavier bob such as 2 kg, is also suspended from the string.

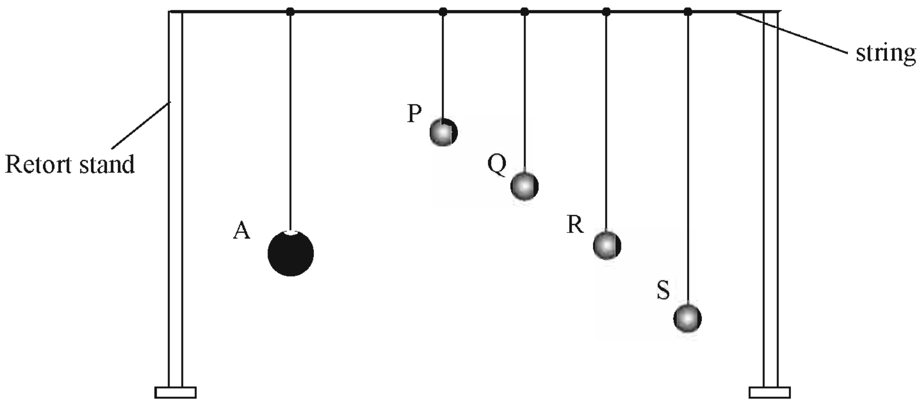


Fig. 4.28: Resonance of pendulums

Pendulum A has the same length as the pendulum R. When A is set to oscillate on its own in a short time pendulums P, Q and S begin oscillating with small swings, pendulum R oscillating with a large swing than P, Q and S. Since all the pendulums are attached to the horizontal string, they have been forced to vibrate. After sometimes, pendulum R vibrates with the same frequency as pendulum A. We say that R has been set into a resonant vibration by A or that resonance has occurred.

Pendulum R has the same length as A, so it has the same natural frequency as A. Therefore a mechanical system can be set into a large amplitude of vibration or resonance by a vibrating force which has the same frequency as its own natural frequency .

Resonance is a phenomenon which occurs whenever a particular body or system is set into an oscillation at its own natural frequency as a result of impulses received from some other system or body which is vibrating with the same frequency.

Illustrating resonance using a swing

A swing with someone sitting on it has its own frequency. If you are asked to push the swing to make it go higher (at maximum amplitude) you will obviously push it each time it comes near you. The frequency of your push will be the same as the natural frequency of the swing. Then the swing vibrates with a large amplitude. This is an example of resonance. We say the swing is resonating. If you push at a different frequency, it will not swing as high (and might hurt your hands).

Therefore resonance occurs when;

The applied frequency of the push = the natural frequency of the object.

Under these conditions, it is possible for a very large amplitude of vibration to be set up.

Effects of resonance

- Cases have been known in the past where suspension bridges has been damaged by resonant vibrations caused by marching military columns. If they match in steps over the bridge, they can make the bridge vibrate so much at its natural frequency that it may break. Nowadays, in order to guard against accidents soldiers are always given the order to break step when crossing a bridge.
- If a singer sings near a wine glass with a frequency equal to the glass's natural frequency, it may resonate so strongly and break.
- When steel bodies were first introduced for motorcars, it was noticed that a drumming sound was made when the engines spedup to certain frequencies. This was caused by resonance between the body panel and the engine vibration. It was soon discovered that it could be prevented by coating the inside of the panel with a layer of plastic material. This reduced the period of vibration of the panel.
- A radio receiver is tuned to broadcasting station when an electrical oscillating circuit inside the receiver is set into resonance by the incoming radiowaves.

We shall now discuss the production of resonance between a tuning fork and a column of air in a closed and open pipes (or tubes).

Exercise 4.2

1. Define the terms:

   (a) Pitch (b) Loudness

   (c) Tone (d) Harmonics

2. Differentiate between:
   (a) Music and noise
   (b) Fundamental frequency and overtone
   (c) Stationary wave and progressice wave
   (d) Node and antinode
3. State the properties of musical notes.
4. Explain how the following factors affect the frequency of a musical note.
   (a) Length
   (b) Tension
   (c) Mass
   (d) Thickness
5. A string produced a frequency of 750 Hz at a tension of 12 N, Calculate:
   (a) The tension that would produce a frequency of 2450 Hz.
   (b) The frequency when the tension is 74 N.
6. A string of length 1.4 m has a frequency of 430 Hz. Determine the:
   (a) Length that would produce a frequency of 1800 Hz.
   (b) Frequency that will be produced by a string of length 0.75 m.
7. A string in a sonometer has a length of 0.76 m and experience a tension of 23.4 N. Find the frequency of the string if it has a mass of 0.04 kg per unit length.
8. A string of length 240 cm has a mass of 56 g per unit length, The string experiences a tension of 25.86 N. Determine the frequency of:
   (a) 1^{st} harmonic
   (b) 4^{th} harmonic
9. State the ways by which the pitch of a stringed musical instrument can be adjusted.

4.8 Vibrating air columns

(a) Vibrating air columns in closed pipes

Activity 4.13: **To investigate longitudinal stationary waves in vibrating air column**

Materials

- Turning fork
- Two tubes
- Clamp and boss
- Water
- One open glass tube
- One glass tube closed at one end

Steps

1. Set up the arrangement of two tubes as shown in Fig. 4.29. The inner tube can be moved up and down and clamped in any position, with the lower end always beneath the water level in the wider tube.

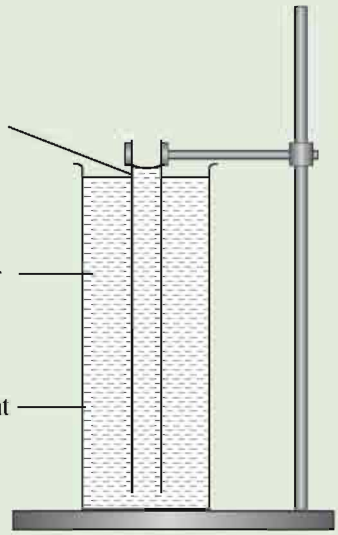


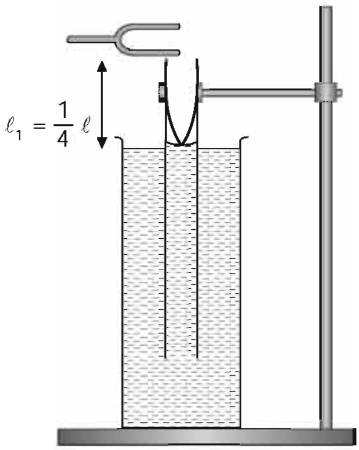
Fig. 4.29: Arrangement to produce longitudinal stationary wave

2. Adjust the inner glass tube so that its open end is just above the water level.
3. Hold a vibrating tuning fork as shown in the Fig. 4.30 (a) and gradually raise the inner tube, till a loud sound is heard. Measure the length of the air column l_1.

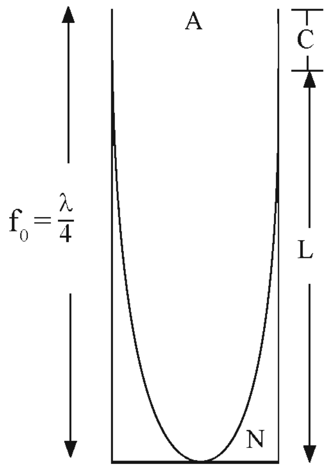
   Why is the loud sound produced when the fork is at a specific distance above the pipe? Describe this distance in terms of the wavefronts of the wave produced. Sketch the incident and refracted waves.

   The frequency of the air molecules is equal to the frequency of the tuning fork and a stationary wave is formed with the shortest length of air column. The air molecules vibrate at the same frequency of tuning fork and produce the loud sound due to resonance.
4. Raise the inner tube gradually further up until another loud sound is heard. Measure the length l_2 of the air column. Express this length in terms of the wavelength of the wave. Sketch the incident and reflacted wave.
5. From lengths l_1 and l_2, determine the wavelength of the wave produced by the turning fork.

The sound waves produced in a pipe are longitudinal standing waves. The lowest note (harmonic) is produced by a wave with a node (N) at the closed end and an antinode at the open end. Figure 4.30(b).



(a)



(b) With end correction

Fig. 4.30: 1st harmonic

Note that the node and antinode are separate by a distance equal to $\frac{1}{4}$ of a wavelength. The frequency produced by the pipe in Figure 4.30 is the fundamental frequency (f_o). If L is the length of the tube, then the waves length λ is equal to L + C.

$$\text{Thus, } \frac{\lambda}{4} = L + C$$

$$\lambda = 4(L + C).$$

Where C is called the end correction i.e; the small distance outside the tube where the antinode forms.

From $v = f\lambda$

$$f = \frac{v}{\lambda}\text{: But } \lambda = 4(L + C)$$

$$f = \frac{v}{4(L + C)}$$

If, $f = f_o$ (fundamental frequency 1st harmonic)

$$f_o = \frac{v}{4(L + C)} \quad \text{(with end correction)}$$

When the frequency of the fork is increased gradually wavelength reduces the first (2nd harmonic (1st overtone) is obtained when the 2nd antinode is at the open end of the tube (Figure 4.31(b)).

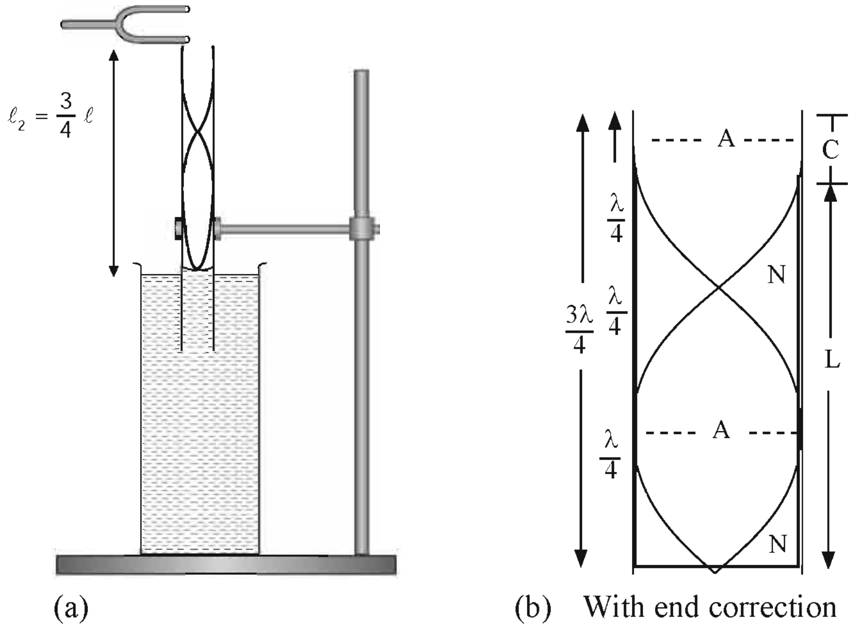


Fig. 4.31: 2nd harmonic

Thus, $\frac{4\lambda}{3} = L + C$. (With end correction)

$$\lambda = \frac{4}{3}(L + C)$$

But $f = \frac{v}{\lambda}$ and $f = f_1$

$$f_1 = \frac{v}{\frac{4}{3}(L + C)}$$

$$f_1 = \frac{3v}{4(L + C)}$$

but $\frac{v}{4(L + C)} = f_0$

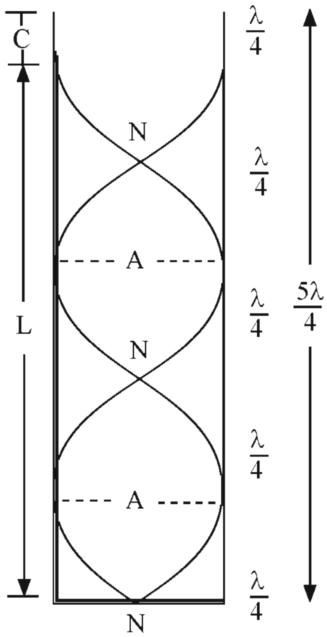
$\therefore f_1 = 3f_0$, for second harmonic or first overtone.

We can see that $\ell_2 - \ell_1 = \frac{3\lambda}{4} + c - (\frac{\lambda}{4} + c) = \frac{\lambda}{2}$ (approximately).

Hence wavelength, $\lambda = 2(\ell_2 - \ell_1)$. The speed of wave in air $v = f\lambda$ where f is the frequency of the air molecules which is equal to the frequency of the tuning fork.

For 3rd harmonic or 2nd overtone

On further increasing the frequency of the fork, the third harmonic is obtained when the 3rd antinode is at the open end (Figure 4.32).



From the Figure 4.32;

$$\frac{5\lambda}{4} = L + C.$$

$$\lambda = \frac{4}{5}(L + C)$$

But $f = \frac{v}{\lambda}$ and $f = f_2$

$$f_2 = \frac{v}{\frac{4}{5}(L + C)}$$

$$f_2 = \frac{5v}{4(L + C)} \quad \text{but} \quad \frac{v}{4(L + C)} = f_0$$

$f_2 = 5f_0$ for 2nd overtone or 3rd harmonic

Fig. 4.32: 3rd harmonic or 2nd overtone

Note: For a closed pipe the harmonic occur when the frequencies are odd number multiples of the fundamental frequency.

Example 4.6

A pipe closed at one end has a length of 8 cm and end correction of 2 cm. If the velocity of sound in the air inside the pipe is 340 m/s, calculate:

(a) Fundamental frequency

(b) Frequency of the first overtone.

Solution

Length of pipe L = 8 cm (0.08 m); End correction length, C = 2 cm (0.02 m)

velocity of sound in air v = 340 m/s.

(a) Fundamental frequency for closed pipe $(f_0) = \frac{v}{4(L + C)}$.

$$= \frac{340 \text{ m/s}}{4(0.08 \text{ m} + 0.02 \text{ m})}$$

$$f_0 = \frac{340 \text{ m/s}}{4 \times 0.1 \text{ m}} = 850 \text{ Hz}$$

(b) Frequency of the first overtone = (f_1).

$$f_1 = 3f_0.$$

$$= 3 \times 850 \text{ Hz}$$

$$= 2\,550 \text{ Hz}$$

(b) Vibrating air columns in open pipes

An open pipe is a pipe which is open at both ends. The waves produced by vibrating air in such pipes have antinodes (A) at both ends and nodes within the pipe.

1st harmonic or fundamental (one note)

The first harmonic occurs when the length L of the pipe is equal to half the wavelength (Figure 4.33).

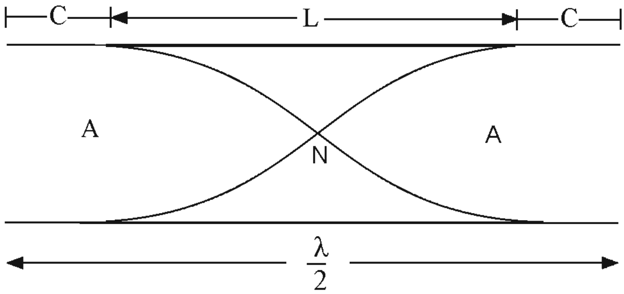


Fig. 4.33: 1st harmonic or fundamental (one note)

That is $L = \frac{\lambda}{2}$

$\lambda = 2L$ with no end correction

But $\frac{\lambda}{2} = L + 2C$

$\lambda = 2(L + 2C)$ with end correction

$\lambda = 2L$ with no end correction

The fundamental frequency f_0 can be derived as follows:

$v = f\lambda$

$f_0 = \frac{v}{\lambda}$ but $\lambda = 2(L + 2C)$

$f_0 = \frac{v}{2(L + 2C)}$ with end correction

$f_0 = \frac{v}{2L}$ with no end correction

Second harmonic or 1st overtone

The second harmonic or first overtone can be obtained by increasing the length but the wavelength (λ) remains constant. This occur when the length of the pipe $L = \frac{3}{4}\lambda$ (Figure 4.34).

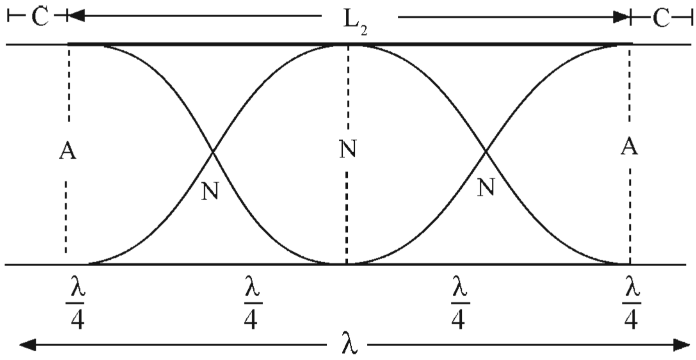


Fig. 4.34: Second harmonic in an open pipe (2 nodes)

$\lambda = L_2 + 2C$ with end connection

But $f = \frac{v}{\lambda}$ and $f = f_1$

$$f_1 = \frac{v}{L_2 + 2C} \text{ but } \frac{v}{L + 2C} = 2f_0$$

$$f_1 = 2f_0$$

3rd harmonic or 2nd overtone

The 3rd harmonic occurs when the length of the pipe $L = \frac{3}{2}\lambda$ (Figure 4.35) .

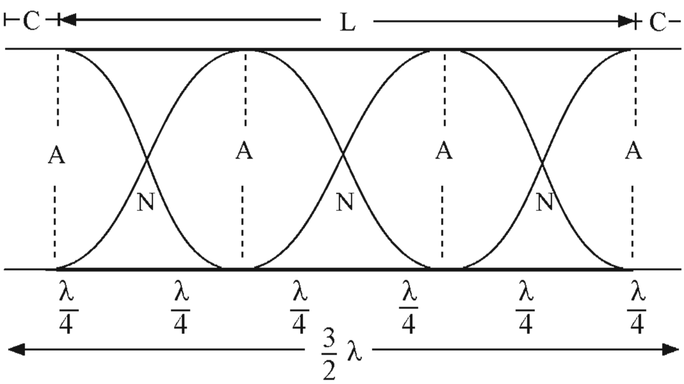


Fig. 4.35: Third harmonic/2nd overtone in an open pipe, 3 nodes.

$$\frac{3}{2}\lambda = L + 2C$$

$$\lambda = \frac{2}{3}(L + 2C)$$

But $f = \frac{v}{\lambda}$ and $f = f_2$

$$f_2 = \frac{v}{\frac{2}{3}(L + 2C)}$$

$$f_2 = \frac{3v}{2(L + 2C)} = \text{but } \frac{v}{2(L + 2C)} = f_0$$

$f_2 = 3f_0$. For 3rd hormonic it is 3 times f_0.

In general, the harmonics in open pipes have frequencies with natural multiples of the fundamental frequencies i.e $f_0 = 1f_0$, $f_1 = 2f_0$, $f_2 = 3f_0$ and so on.

Example 4.7

A tuning fork of frequency 250 Hz is used to produce resonance in an open pipe. Given that the velocity of sound in air is 350 m/s and the end-correction is 2 cm. Find the length of the tube which gives;

(a) The first resonance (first harmonic)

(b) Third resonance (3rd harmonic or 2nd overtone)

Data

$f_o = 250$ Hz; $v = 350$ m/s; $C = 2$ cm $= 0.02$ m

Solution

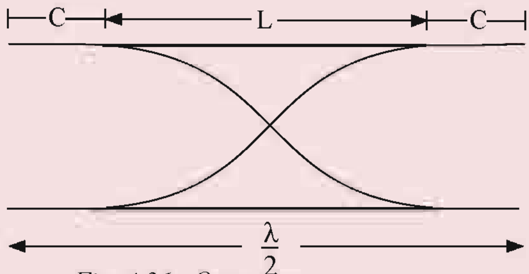


Fig. 4.36: Open pipe

(a) To find the length L

The first resonance or f_0

From $v = f_0\lambda$ and $\lambda = 2(L + 2C)$

$$f_0 = \frac{v}{2(L + 2C)}$$

$$250 \text{ Hz} = \frac{350 \text{ m/s}}{2(L + 2(0.02 \text{ m})}$$

$$250 \text{ Hz} = \frac{350 \text{ m/s}}{2(L + 0.04 \text{ m})}$$

$$2(L + 0.04 \text{ m}) \times 250/\text{s} = 350 \text{ m/s}$$

$$L + 0.04 \text{ m} = \frac{350 \text{ m/s}}{500/\text{s}}$$

$$L + 0.04 \text{ m} = 0.7 \text{ m}$$

$$L = 0.7 \text{ m} - 0.04 \text{ m}$$

$$L = 0.66 \text{ m}$$

The length of the tube = 0.66 m.

(b) To calculate L for 3rd harmonic (2nd overtone)

$$f_2 = 3f_0 = 3 \times 250 \text{ Hz}$$

$$= 750 \text{ Hz} = 750/\text{s}$$

$$\text{But } f_2 = \frac{3v}{2(L + 2C)}$$

$$750 \text{ Hz} = \frac{3 \times 350 \text{ m/s}}{2(L + 2(0.02 \text{ m})}$$

$$2(L + 2(0.02\ m) \times 750\ Hz = 3 \times 350\ m/s$$

$$2(L + 0.04\ m) \times 750\ Hz = 1050\ m/s$$

$$L + 0.04\ m = \frac{1050\ m/s}{1500/s}$$

$$L = 0.70\ m - 0.04\ m$$

$$= 0.66\ m$$

The length of the tube = 0.66 m.

Alternatively

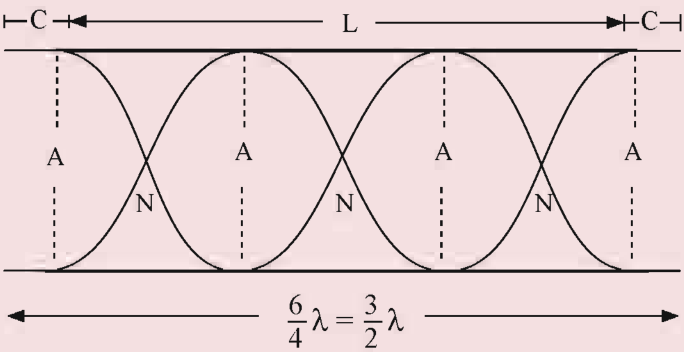


Fig. 4.37: 3rd harmonic

$$L + 2C = \frac{3}{2}\lambda$$

But frequency of 3rd harmonic is f_2

$$f_2 = 3f_0 = 3 \times 250\ Hz$$

$$= 750\ Hz = 750/s$$

$$\text{and } \lambda = \frac{v}{f_2} = \frac{350\ m/s}{750/s} = 0.47\ m$$

$$\therefore\ L + 2C = \frac{3}{2}\lambda$$

$$L + 2(0.02\ m) = \frac{3}{2} \times 0.47\ m$$

$$L = 0.7\ m - 0.04\ m = 0.66\ m$$

The length of the tube = 0.66 m.

4.9 Beats

Activity 4.14: **Investigating beats**

Work in groups.

Materials

- Two turning forks
- Plasticine
- Closed pipe

Steps

1. Fix some plasticine on the forks of one turning fork.
2. Set the two turning forks into vibration together and bring them both at the mouth of a closed pipe.
3. Listen to the resultants sound produced. Explain with the help of a diagram the regular rise and fall in the loudness of the sound produced.

Two tuning forks of equal frequency may be used to produce beats. The frequency of one of them is reduced slightly by weighting its prongs with a tiny piece of wax or plasticine. Suppose fork P of frequency 256 Hz is sounded together with fork Q whose frequency is reduced to 252 Hz by loading its prongs with tiny wax, the frequency of the beat produced by P and Q is equal to the difference in their frequencies is 4 Hz. i.e. f_b = 256 Hz – 252 Hz = 4 Hz.

A beat is a regular rise and fall in the loudness of a tone when two notes of nearly equal pitch (frequency) are sounded together.

Figure 4.38 shows the resultant waveform when two nearly equal waves combine to produce beats. The variation in the amplitude of the resultant wave indicates clearly how beats occur.

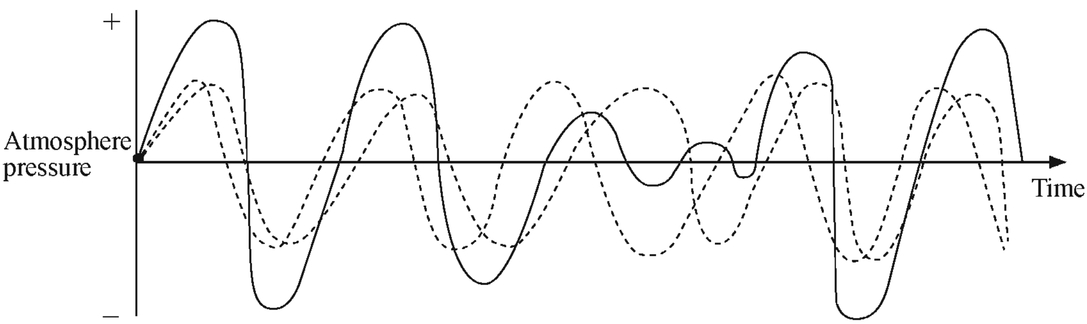


Fig. 4.38: Beat waveform from two notes of frequencies 5 and 6 Hz.

The beat frequency or the number of beat *f* is given as the difference between the two frequencies of sound.

Thus, Beat frequency = High frequency – Low frequency

$$f_b = f_h - f_L$$

Example 4.8

A 256 Hz tuning forks produces sound at the same time with a 252 Hz fork. What is the beat frequency?

Data

High frequency = 256 Hz; Low frequency = 252 Hz; Beat frequency, f = ?

Solution

$f = f_h - f_L$

$= 256\text{ Hz} - 252\text{ Hz} = 4\text{ Hz}$

Therefore; beat frequency is 4 Hz

Example 4.9

The beat frequency of two notes of nearly equal frequency is 6 Hz. If one is loaded with wax, the beat frequency becomes 4 Hz. What is the frequency of the other note if the frequency of the loaded fork is 250 Hz.

Data

Beat frequency before loading f_o = 6 Hz.

Beat frequency after loading f_a = 4 Hz.

Frequency of loaded fork f_L = 250 Hz.

Frequency of other note, f_1 = ?

Frequency of lower note before loaded, f_2 = ?

Solution

Before loaded

$f_1 - f_2 = f_0$

$f_1 - f_2 = 6\text{ Hz}$ ....(1)

After loading

$f_2 > f_L$

$f_2 - f_L = f_a$

$f_2 - 250\text{ Hz} = 4\text{ Hz}$

$f_2 = 4\text{ Hz} + 250\text{ Hz}$

$f_2 = 254\text{ Hz}$

Frequency of other note, f_1

$f_1 - f_2 = f_0$

$f_1 - 254\text{ Hz} = 6\text{ Hz}$

$f_1 = 6\text{ Hz} + 254\text{ Hz}$

$f_1 = 260\text{ Hz.}$

The frequency of the other note is 260 Hz.

4.10 Wave polarisation

This is a process in which waves of light are restricted to certain direction of vibration in terms of electric fields.

Rays of light show different properties of different direction in state in which all the vibrations take place in one direction.

For example transverse waves, vibrations are confined to one plane.

In circular polarisation, the electric vector rotates about the direction of propagation as the wave passes.

Light is polarised by reflection or passing it through filters such as certain crystals, that transmit vibration in one plane but not in the other.

Exercise 4.3

1. State the condition for resonance.
2. A 120 m long pipe has an end correction of 15 cm, if the velocity of sound in air is 340 m/s determine the:
   (a) Fundamental frequency
   (b) 1^{st} overtone
3. A tuning fork of frequency 330 Hz is used to produce resonance in an open tube. Given that the velocity of sound in air is 330 m/s and the end correction is 5 cm. Determine the length of the tube which causes:
   (a) The first resonance
   (b) The third resonance
4. A 220 m long pipe has an end correction of 2 cm, if the velocity of sound in air is 330 m/s. Determine the:
   (a) Fundamental frequency
   (b) 2^{nd} overtone

Topic Summary

- A ripple tank is an apparatus used to demonstrate the various properties of waves like reflection, refraction, diffraction and interference.
- A wavefront is an imaginary line which joins a set of particles which are in phase in a wave motion.
- A ray denotes the direction of travel of the wave energy and is perpendicular to the wavefront.
- If the continuous waves are frozen using a stroboscope, the waves appear to be at rest or stationary.
- Water waves and sound waves like light waves obey the laws of reflection of light.
- Diffraction means the spreading of waves at the edges and corners of obstructions.
- Coherent sources are those which emit waves in phase and of the same frequency.
- When two waves meet in phase, they interfere constructively. When they meet out of phase, they interfere destructively.
- Sound waves, water waves and light waves undergo interference.
- A stationary wave is one where there is no energy propagation, unlike a progressive wave where energy is continuously transferred from particle to particle.
- Nodes are position of no (zero) displacement and antinodes are positions of maximum displacement. The wavelength of a stationary wave is the distance between two alternate nodes or antinodes.
- Resonance is a phenomenon when one system in the vibrating state induces vibrations to another system by which both vibrate with the same natural frequency.
- A beat is regular fall and rise in the loudness of a tone when two notes of nearly equal frequency are sounded together.

Topic Test 4

1. State three applications for refraction of waves.
2. Explain the concept of diffraction of waves?
3. Describe situations where interference of waves is applied.
4. State the principle of superposition.
5. State the condition for a minimum amplitude to occur in an interference pattern.

6. Describe how the double slit diffraction experiment may be made in a laboratory.
7. What condition is necessary for a wave incident on a slit to be diffracted?
8. Explain how you would make a diffraction grating on a piece of glass slide.
9. What happens to the wavelength of the water wave when it moves from the deep part to the shallow part of a ripple tank?
10. A string of length 2.4 m has a frequency of 330 Hz. Determine the:
    (a) Length that would produce a frequency of 760 Hz.
    (d) Frequency that will be produced by a string of length 2.75 m.
11. A string in a sonometer has a length of 1.54 m and experience a tension of 4.54 N. Find the frequency of the string if it has a mass of 0.24 kg per unit length.
12. A string of length 95 cm has a mass of 156 g per unit length. The string experience a tension of 52.0 N. Determine the frequency of:
    (a) 1^{st} harmonic
    (b) 3^{rd} harmonic
13. Mention the ways by which the pitch of a stringed musical instrument can be adjusted.
14. State the condition of resonance.
15. A tuning fork of frequency 430 Hz is used to produce resonance in an open tube. Given that the velocity of sound in air 330 m/s and the end correction is 2 cm. Determine the length of the tube which causes:
    (a) First resonance
    (b) Third resonance
16. Describe an experience to show that speed of a wave depends on the medium in which it travels.
17. Demonstrate that waves carries energy.
18. What happens to the wavelength of a water wave when it moves from the deep part to the shallow part of a ripple tank?

UNIT 4 Electric Fields and Capacitance

Topic in the unit

Topic 5: Electric Fields and Capacitance

Key inquiry question

- How do we relate electric force to electric potential?
- How can we experience the presence of electric field?
- Why is it advisable not to touch a person who is hit by thunder lightning?

Learning outcomes

Knowledge and understanding

- Understand electric fields, capacitance, magnetic fields and electromagnetic induction

Skills

- Design investigations on electric field to electric potential, electric field, flux density and capacitance.
- Draw electric field lines between two like and unlike charges
- Carry out investigations to demonstrate and practice the connections of capacitors in series and in parallel
- Interpret results in terms of Coulomb's law

Attitude and value

- Appreciate the importance of electric fields

TOPIC 5

Electric Fields and Capacitance

Topic outline

- Introduction
- Electric field
- Electric field patterns
- Electric field strength
- Electric potential
- Charge distribution on conductor
- Capacitors
- Capacitance
- Application of electrodes

Introduction

Newton proposed that a gravitational field exists around the earth attracting all the bodies towards its centre. The gravitational field is the region or space where a mass experiences a force towards the earth's centre. Michael Faraday on the other hand, suggested the idea of an electric field around a charged body. An American scientist Benjamin Franklin, after his risky experiments with kites during thunderstorm weather, proposed that lightning is a large electric spark discharge which occurs between two charged clouds or between a charged cloud and the earth. He also proposed that a vertical insulated iron rod must be charged when a thunderstorm cloud passes over it. His ideas were used to develop lightning arrestors to protect tall buildings from the devastating effect of lightning. A Dutch physicist Pieter Van Musschenbroek in 1746 gave the basic idea of capacitors where charge can be stored.

In this chapter, we shall study some of the details of the electric field, field pattern, and charge distribution on conductors.

5.1 Electric field

We are familiar with the observation that a charged body attracts small pieces of paper, dust, hair etc. The basic law of electrostatics states that like charges repel and unlike charges attract. So a charged body can affect other nearby objects without touching them. This *action at a distance* can be explained by what is called the *electric field* of a charged body.

Activity 5.1: **To demonstrate the electric fields produced by charged bodies**

Work as a whole class.

Materials: glass dish, castor oil, electrodes connecting wires

Steps

1. Assemble a pair of straight metal wires, called the *electrodes*, in a shallow glass dish so that their ends are just covered by a layer of an insulating liquid like castor oil or carbon tetrachloride (Fig. 5.1).

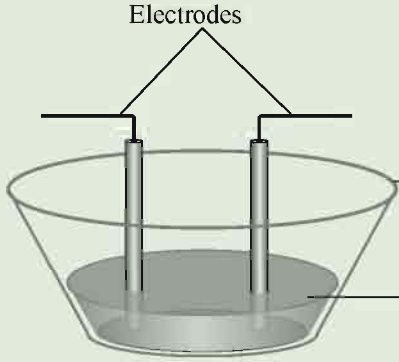
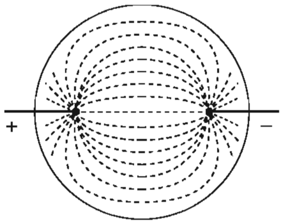


Fig. 5.1: Arrangement to study the electric field

2. Apply a very high potential difference, from a suitable power supply, to the two electrodes so that they have opposite charges.
3. Then sprinkle grass seeds or semolina powder on the surface of the liquid.
4. Observe what happens to the grass seeds or powder and draw the resulting pattern. Explain the distribution of the grass seeds in the pattern.
5. Repeat the activity with different charges of electrodes and observe the pattern formed.
6. Draw the various patterns and alignments of the seeds. Explain why the seeds are distributed as they are in each pattern.

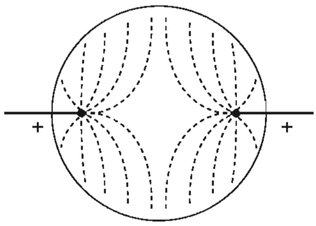
In Activity 5.1, the seeds acquire induced opposite charges at their ends and align themselves in a particular pattern (Fig. 5.2 (a)). This pattern depends upon the charge of the electrodes.

(a)



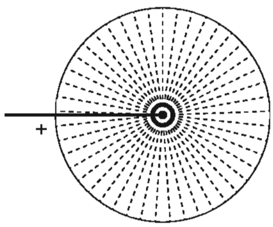
Two straight wires dipped into the liquid and connected to the opposite polarities of a high voltage power supply (Fig. 5.2 (a)).

(b)



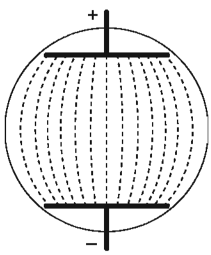
Two straight wires dipped into the liquid, both connected to the same positive potential terminals (Fig. 5.2 (b)).

(c)



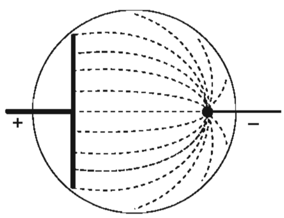
A straight vertical wire dipped into the liquid having a high positive charge (Fig. 5.2 (c)).

(d)



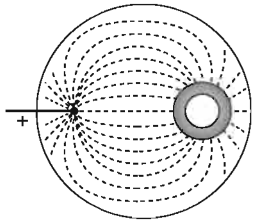
Two parallel metal plates dipped into the liquid and connected to the opposite polarities of high voltage power supply (Fig.5.2(d)).

(e)



A straight horizontal metal wire electrode and a point electrode dipped into the liquid and connected to opposite polarities of high voltage power supply (Fig. 5.2(e)).

Fig. 5.2: Electric fields due to different shapes of electrodes

(f) 

A straight vertical wire electrode and an uncharged metal ring in the liquid. The wire electrode is connected to the positive polarity of high voltage power supply (Fig. 5.2(f)).

Fig. 5.2: Electric fields due to different shapes of electrodes

The above alignments of seeds depict the electric field produced in different arrangements.

An electric field may be described as the region or space surrounding a charge. In this region another charged body may move away from or towards the charged body producing the electric field. In Fig. 5.3, P is a positively charged body and N is a negatively charged body producing an electric field. If another light charged body T is introduced in this field, the body T may experience a force away from P or towards N.

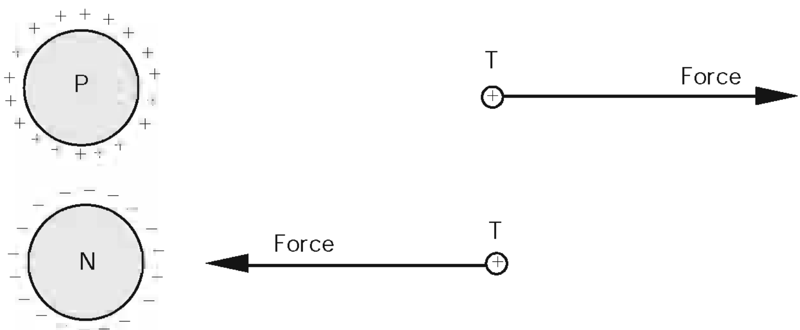


Fig. 5.3: Force between charges in an electric field

If a body is positively charged and has a charge of 1 coulomb it is called a *test charge* or *a unit positive charge*. A unit positive charge experiences a force in the electric field.

An electric field is defined as *the region where a charged body experiences a force*.

The direction of an electric field at a particular point is the direction in which a positive point charge would move when placed at that point. Therefore in the electric field lines, the arrow points away from a positive charge and into a negative charge.

5.2 Electric field patterns

Activity 5.2: **To draw electric field patterns**

(Work in groups)

1. With the help of a research from reference sources, draw electric field patterns of:
   (i) A point positive charge and point negative charge.

(ii) Two positive point charges.
(iii) Two negative point charges.
(iv) A positive point charge and a negative charged plate.

2. Explain the distribution and direction of the electric field lines in each case.

The electric field pattern around a charged body depends on whether the body is completely isolated or is in the presence of other bodies. The following are some examples of electric field patterns for isolated and non-isolated bodies.

1. Fig. 5.4 shows an isolated positive point charge. The field lines are radially outwards from the positive charge.

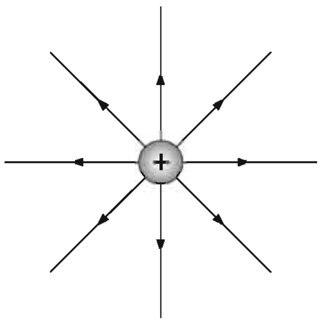


Fig. 5.4

2. Fig. 5.5 shows an isolated negative point charge. The field lines are radially inwards towards the negative charge.

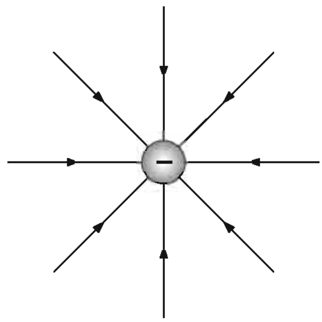


Fig. 5.5

3. Fig. 5.6 shows two equal positive point charges. The field lines start radially outwards from each charge. The resultant field is due to the electric field produced by each charge.

A point N lies midway between the two charges, on the line joining them. Here the resultant force acting on the unit positive charge is zero and is called a *neutral point. A neutral point in an electric field is one where the resultant force acting on the unit positive charge is zero* (Fig. 5.6). Force due to A = force due to B.

i.e. $F_A = F_B$

No field lines exist at the neutral point.

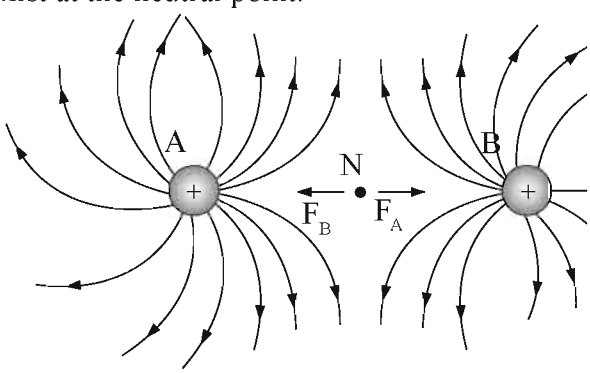


Fig. 5.6: Two equal positive point charges

4. Fig. 5.7 shows two equal unlike point charges. The field lines start from the positive charge and end on the negative charge. In this case there is no neutral points as a unit positive charge placed at any point experiences a force.

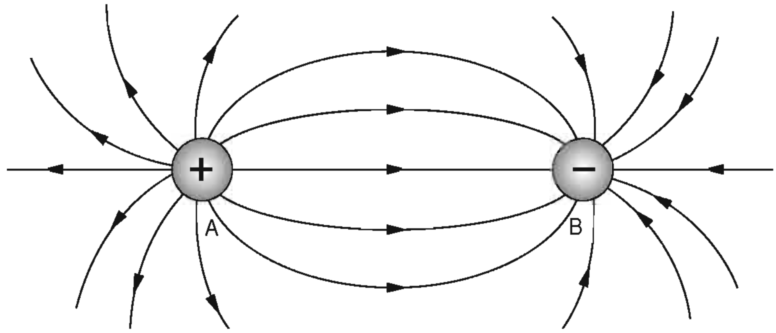


Fig. 5.7: Two equal unlike point charges

5. Fig. 5.8 shows a positive point charge and a straight metal plate having a negative charge.

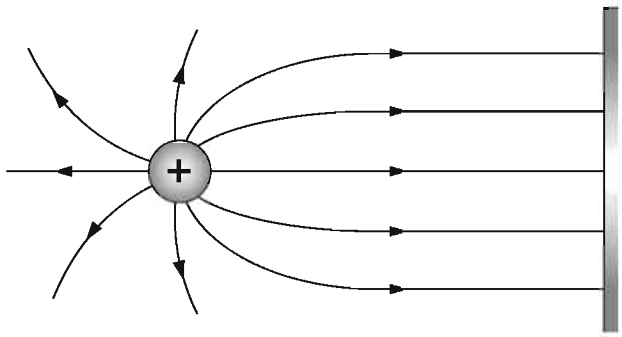


Fig. 5.8: A positive point charge and a negative metal plate

6. Fig. 5.9 shows a positive point charge and an uncharged ring placed in the electric field. The metal ring placed near the positive charge gets charged by electrostatic induction. The field lines are as shown in Fig. 5.13. The field lines do not pass through the conductor. The conducting ring acts as an electric shield for the space enclosed by the ring.

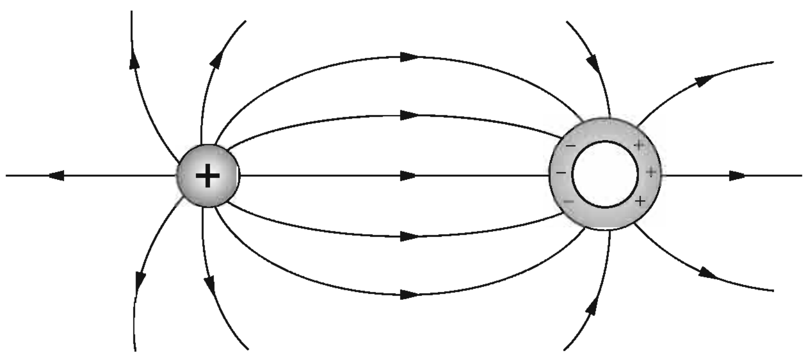


Fig. 5.9: A positive point charge and uncharged ring

7. Fig. 5.10 shows two parallel metal plates having opposite charges and placed close together. In this case the field lines are parallel except at the edges, unlike in cases 1 to 7. If the field lines are parallel, the *electric field is uniform*.

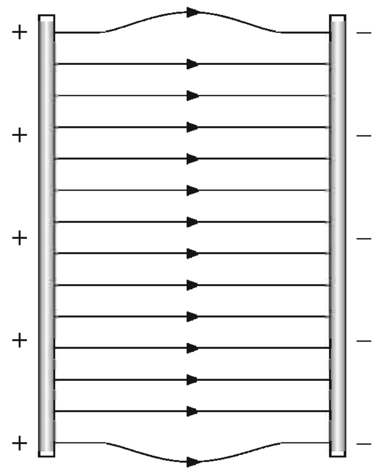


Fig. 5.10: Two parallel metal plates having opposite charges

5.3 Electric field strength

Activity 5.3: **To define electric field strength**

(Work in groups)

Materials: Reference books

Step

1. With the help of a research from reference sources define electric field strength and derive its formula.
2. State its SI units.
3. Describe how electric field strength varies with the strength of the charge and distance from the charge.
4. Derive an expression for electric field strength.

Electric strength is defined as the force per unit charge acting at a point in the field. It is electric field strength is a quantitative expression of the intensity of an electric field at a particular location. So an equation for it is:

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

Where: E is the electric field strength

F is the force acting in newtons

q is the charge in coulombs

The standard unit of measuring electric field strength is the volt per meter (V/m) NC^{-1}. A field strength of 1 V/m represents a potential difference of one volt between points separated by one meter.

5.3.1 Uniform Fields

There is one special example you also need to know:

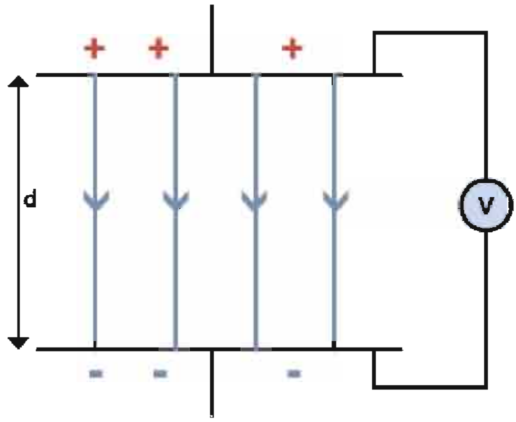


Fig 5.11

This is a uniform field. The field strength at any point in this field is:

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

Where:

V – the potential difference between the plates

d – the distance separating the plates.

Field strength is a vector quantity- it has direction as well as magnitude.

This is important to remember because in electric fields you can have field strengths acting in different directions due to different signs of charge.

5.3.2 Radial Fields

A particularly useful equation to find field strength around a point charge is:

$$E = \frac{Q}{4\pi\varepsilon_o r^2}$$

where:

Q – the charge causing the field

r – the separation between the charge and the point you are considering

ε_o – permittivity of free space = $8.854^2 \times 10^{-12} m^{-3} kg^{-1} s^4 A^2$

or $8.854^2 \times 10^{-12}$ Farads per metre (Fm^{-1})

This shows that:

1. $E \propto Q$ - the bigger the charge, the stronger field.
2. $E \propto \frac{1}{r^2}$ - another inverse square relationship. The further you are from the charge, the weaker the field strength.
3. The constant of proportionality is $\frac{1}{4\pi\varepsilon}$. Its value varies depending on what material / medium the field is in. An electric field in water has different properties to a field in a vacuum, for example. So for each medium, you need a value of ε, the permittivity. The permittivity of a vacuum is abbreviated as ε_0, which is almost the same as permittivity for air.

Example 5.1

What's the field strength at a point 2 cm from a charge of 2×10^{-6} C in air?

($\varepsilon_0 = 8.8542 \times 10^{-12}\ \text{Fm}^{-1}$)

Solution

$$E = \frac{Q}{4\pi\varepsilon_0 r^2} = \frac{2 \times 10^{-6}}{4 \times 3.14 \times 8.8542 \times 10^{-12} \times (2 \times 10^{-2})^2} = 4.496 \times 10^7\ \text{NC}^{-1}$$

5.4 Electric potential

Activity 5.4: **To define electric potential and state its SI units**

(Work individually)

1. Research from the books the definition of electric potential.
2. State and explain the quantities affect the magnitude of electric field potential. Use this to derive its formula and state its SI units.

From activity 5.4 you must have found that an electric potential (also called the electric field potential or the electrostatic potential) is the amount of energy that a unitary point electric charge would have if located at any point in space, and is equal to the work done by an electric field in carrying a unit of positive charge from infinity to that point.

Electric potential is a scalar quantity denoted by V, equal to the electric potential energy of any charged particle at any location (measured in joules) divided by the charge of that particle (measured in coulombs). By dividing out the charge on the particle a remainder is obtained that is a property of the electric field itself.

Force and potential energy are directly related. A net force acting on any object will cause it to accelerate. As an object moves in the direction in which the force accelerates it, its potential energy decreases: the gravitational potential energy of a cannon ball at the top of a hill is greater than at the base of the hill. As it rolls downhill its potential energy decreases, being translated to motion, inertial (kinetic) energy.

Electric field potential (V) is defined as the work done in moving a unit charge through a distance (d) in an electric field.

Electric field potential, $V = \dfrac{\text{Work done}}{\text{Charge (Q)}} = \dfrac{\text{Force (F)} \times \text{Distance (d)}}{\text{Charge (Q)}}$

Example 5.2

A p.d of 12V was used to move 200 C from a positive plate to a negative plate. Determine the work done to move the charges.

Solution

Work done = Potential difference × charge

= 12 × 200

= 2 400 J

Example 5.3

A 6 500 J electrical energy was needed to move charges across a parallel plate conneced to 240 V source. Determine the number of charges moved.

Solution

$$\text{Charge} = \frac{\text{Work done}}{\text{Potential difference}} = \frac{6\,500}{240} = 27.1 \text{ C}$$

5.5 Charge distribution on conductors

We will use an apparatus called proof plane to investigate distribution of charge on conductors.

A *proof plane* can be used to sample the charge in various places of a conductor. It consists of a small metal disc with an insulating handle (Fig. 5.12).

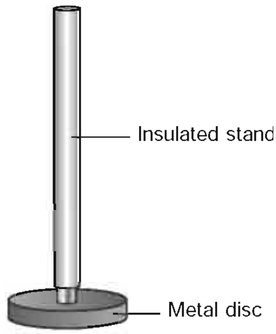


Fig. 5.12: A proof plane

The disc is charged by touching a charged conductor. If the cap of an uncharged electroscope is touched with the proof plane, there is a divergence in the leaves of the electroscope. If the proof plane is removed, the divergence remains the same.

5.5.1 Charge distribution in a charged hollow conductor

Activity 5.5: **To demonstrate that charges reside only on the outside of a conductor**

(Work in groups)

Materials

- A hollow metal sphere
- Insulated stand
- Proof plane

Steps

1. Take a hollow metal sphere with a hole in it and charge it positively by electrostatic induction.
2. Touch the inside of the sphere with a proof plane (Fig. 5.13) and then place the plane on the cap of an uncharged electroscope.

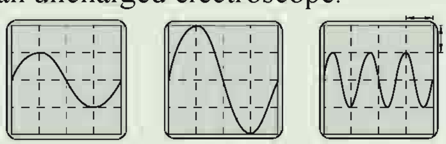


Fig. 5.13: To test the charge on a conductor

3. Observe what happens to the leaf of the electroscope.

4. Repeat the activity by touching the outside of the sphere with a proof plane.
5. What happens to the leaf of the electroscope in each case? Explain the observation.

From Activity 5.5, it is seen that there is a divergence on the leaf of the electroscope only when the proof plane is placed on the outside of the charged sphere. This shows that the charges reside only on the outside of a conductor and there are no charges on the inside.

5.5.2 Distribution of charges on a spherical conductor

Activity 5.6: To show charge distribution on a spherical conductor

(Work in groups)

Materials: Metal sphere on an insulated stand, proof plane, uncharged gold leaf electroscope

Steps

1. Charge a metal sphere when mounted on an insulated stand.
2. Place a proof plane on its surface at a particular place (Fig. 5.14 (a)). What do you notice?
3. Test the charge carried by the proof plane by touching the cap of uncharged electroscope.
4. Repeat the exercise by placing the proof plane at different places on the surface of the conductor. Describe the distribution of charge on the surface of the sphere.

In activity above, the metal disc of the proof acquires the same charge present at the metal sphere. When it is removed, it takes some charge with it to the gold leaf electroscope. The divergence in the leaf of the electroscope is the same for all the positions. This shows that the charge on the surface of the spherical conductor is the same everywhere. Thus charge distributes itself uniformly over the surface of a spherical surface.

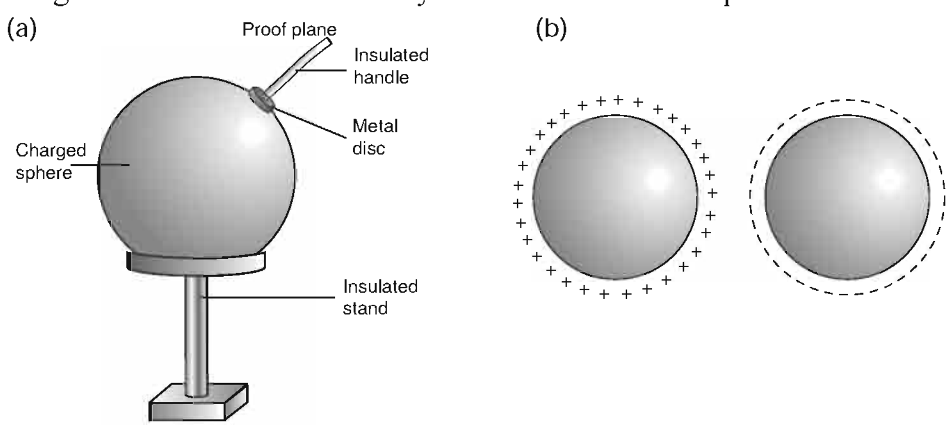


Fig. 5.14: Charge distribution on a spherical conductor

5.5.3 Distribution of charges on a pear shaped conductor

Acticity 5.7: **To show charge distribution on a pear shaped conductor.**

(Work in groups)

Instructions

1. Having done Activity 5.6, design and carry out an investigation to establish how charge is distributed on a conductor with a sharp pointed end.
2. Write down your procedure.
3. Carry out the investigation and write down your observations.
4. Use your investigation to describe how charge is distributed over such conductors and one application of such distribution.
5. Define the following terms as used to describe charges. Derive their mathematical expressions and SI units.
   (a) Surface charge density.
   (b) Electric flux.
   (c) Electric flux density.
6. Make a presentation to the rest of the class.

The result shows that the divergence of the leaf is almost uniform over the curved surface whereas the divergence is bigger at the pointed edge. This shows that the charges are almost equally distributed near the curved spherical side, but are crowded near the pointed end (Fig. 5.15).

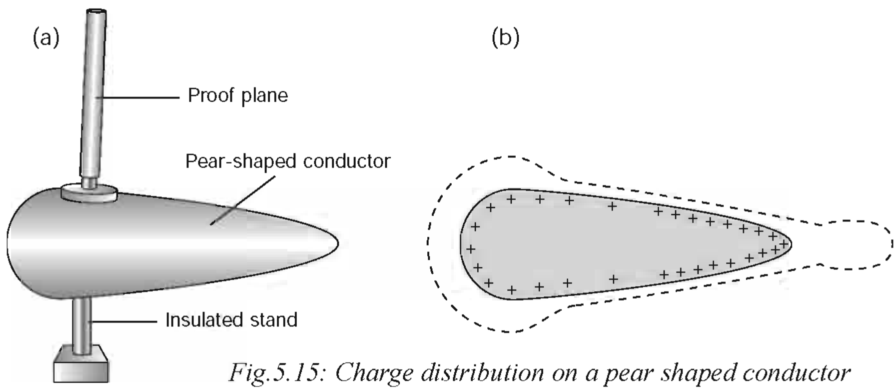


Fig.5.15: Charge distribution on a pear shaped conductor

Surface charge density

Just like the density of matter which is the mass per unit volume, we can define surface charge density as the quantity of charge per unit area of a conductor's surface.

$$\text{Charge density} = \frac{\text{charge}}{\text{area}}$$

SI unit of charge density is coulomb per squares metre (C/m^2)

The charge density for a charged conductor is greater at the sharp points on the object. A flat surface has a low charge density compared to a pointed edge. The charge density is highest at the edges and lowest on flat surfaces as shown in Fig. 5.15 and 5.16, represented by dotted lines.

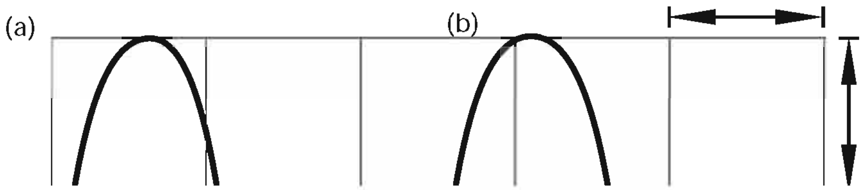


Fig. 5.16: Charge distribution in (a) a rectangular and (b) a cylindrical conductor

Electric flux (Φ_E)

This is the measure of flow of electric fields through a given area.

Electric flux is proportional to number of electric field lines passing a normally perpendicular surface.

$\Phi_E \alpha E$

Electric flux density

This is the amount of electric flux, passing through a given area.

Gauss law states that:

Electric flux through any closed surface is equal to the net charge enclosed inside the surface divided by permittivity in vacuum.

$$\Phi = \frac{\text{Total charge enclosed}}{\text{Permittivity in vacuum}}$$

$$= \frac{q}{\varepsilon_0}$$

ε_0 is the permittivity in vacuum

Consider a stationary point charge q, with an electric field around it of radius r.

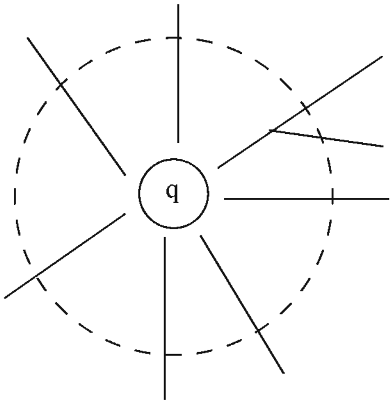


Fig. 5.17: Point charge

The region around the point charge forms a spherical (gauss) surface. From coulomb's law, the electric field around a stationary charge is given by

$$E = \frac{q}{4\pi\, \varepsilon_0 r^2}$$

That electric flux Φ_E is given by

$$\Phi_e = \int \bar{E}.d\vec{A}$$

Over a very small area

From Coulomb's law, $E = \frac{q}{4\pi\, \varepsilon_0 r^2}$

$$\Phi_e = \int \Phi \frac{q}{4\pi\, \varepsilon_0 r^2} .\, d\bar{A}$$

$$= \frac{q}{4\pi\, q_0 r^2} \int d\bar{A}$$

$$= \frac{qA}{4\pi r^2 \varepsilon_0}$$

But the surface area of a sphere is given by $4\pi r^2$. Substituting in the equation, we get

$$\Phi_e = \frac{q\, 4\pi r^2}{4\pi r^2 \varepsilon_0}$$

$$\Phi = \frac{q}{\varepsilon_0} \qquad \text{(Gauss' law)}$$

where Φ is electric flux

ε_0 is permittivity in vacuum

q is the charge

The above equation is the Gauss' law of the electrostatics when a charge is at rest.

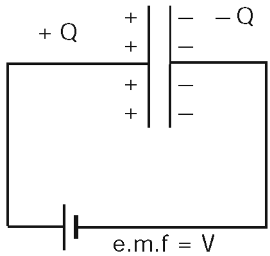


Fig. 5.19: A capacitor stores charge

If the battery is disconnected, the charge remains stored on the plates. The capacitor is now said to be charged. When the capacitor is charged, one of the plates gain electrons while the other loses electrons.

5.6.2 Capacitance

When a capacitor is charged, there is a potential difference, V, between the plates due to the presence of opposite charge on the plates. When connected in the circuit, charge and potential difference across the plates vary as shown in Fig. 5.20. What is the relationship between the charge Q stored and the potential difference V between the plates of the capacitor? It has been found from experiments that the charge Q on each plate is directly proportional to the potential difference V (Fig. 5.20).

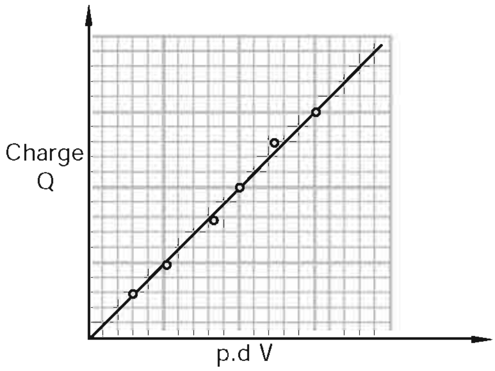


Fig. 5.20: A graph of charge against potential difference

The gradient of the line $\frac{Q}{V}$ is a constant.

From the graph it is clear that

Charge α potential difference

$$Q \propto V$$

$$\therefore \quad Q = CV$$

where C is a constant called the capacitance of a capacitor.

$$\text{Capacitance} = \frac{\text{charge}}{\text{potential difference}}$$

The *capacitance C* of a capacitor is defined as *the ratio of the charge stored on the plates to the potential difference between the plates.*

SI unit of capacitance

The unit of capacitance is *farad* (F). One farad is the capacitance when charge on either plate is 1 coulomb and the potential difference between the plates is 1 volt.

1 farad = 1 coulomb per volt

1 farad is the capacitance of an extremely large capacitor. In practical circuits, the capacitors used have much lower value. In a radio receiver capacitors of capacitance in the order of 10^{-6} F (microfarads μF) are used. The common type of capacitors have sizes of several microfarads (10^{-6} F). Other sizes include millifarads (mF) i.e 10^{-3} F ; nanofarads (nF) i.e 10^{-9} F; picofarads (pF) i.e 10^{-12} F.

Example 5.4

Calculate the charge stored in a capacitor of 100 mF capacitance when connected to a 2 V d.c supply.

Solution

$C = 100 \text{ mF} = 100 \times 10^{-6} \text{ F}$

$V = 2 \text{ V}$

charge $Q = VC = 2 \times 100 \times 10^{-6} = 2 \times 10^{-4}$ coulomb

$= 0.2 \times 10^{-3}$ C

∴ Charge stored is 0.2 mC

From the graph in figure 7.25, the area under the graph is equal to energy stored by a capacitor.

Area under the graph $= \frac{1}{2}QV$

Therefore the total energy stored by a capacitor is given by

Energy (E) stored in the capacitor $= \frac{1}{2}QV$ …… (i)

But $Q = CV$, substituting in (i) we get

$E = \frac{1}{2}CV^2$ …… (ii)

Also making V the subject in $Q = CV$, we get $V = Q/C$. Putting V in equation 1, we get

$E = \frac{1}{2}\frac{Q^2}{C}$ …… (iii)

Example 5.5

A 2μF capacitor was charged fully using 240 V source. Determine energy stored in the capacitor.

Solution

$$E = \frac{1}{2}CV^2$$

$$= \frac{1}{2} \times 2 \times 10^{-6} \times 240^2$$

$$= 0.0576 \text{ J}$$

Example 5.6

A 5 μF capacitor is fully charged when 200 C charges is stored from a source. Determine the total energy stored.

Solution

$$E = \frac{Q^2}{2C} = \frac{1}{2} \times \frac{200^2}{5 \times 10^{-6}} = 4 \times 10^9 \text{ J}$$

5.7 Charging and discharging a capacitor

5.7.1 Charging

Activity 5.9: Charging a capacitor through a fixed resistor

(Work in groups)

Materials

- A uncharged capacitor
- Two voltmeter
- A milliammeter
- Fixed resistor
- Connecting wires
- Source of current

Steps

1. Connect the circuit as shown in Fig. 5.21.

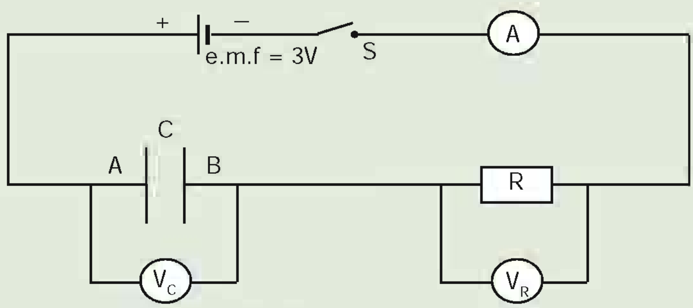


Fig. 5.21: Charging of a capacitor

2. Note the voltmeter reading V_C as soon as the switch is closed and continue to record this voltmeter reading at regular intervals of time. Record your result in a table (Table 5.1).

Table 5.1

Time(*s*)	0	30	60	90	120						
$V_C(V)$											

3. Plot a graph of V_C (Volts) against time (seconds)
4. From the graph describe the flow of charge with time into the capacitor during the charging process.

Since charge Q on each plate is directly proportional to the p.d. V_C, then the charge Q on the plates increases with increase in V_C (Fig. 5.22(b)). The charge Q on the plates of the capacitor increases with time. This is the *charging process*. A graph of current and potential difference between the plates is as shown in Fig. 5.22 (c) and (d).

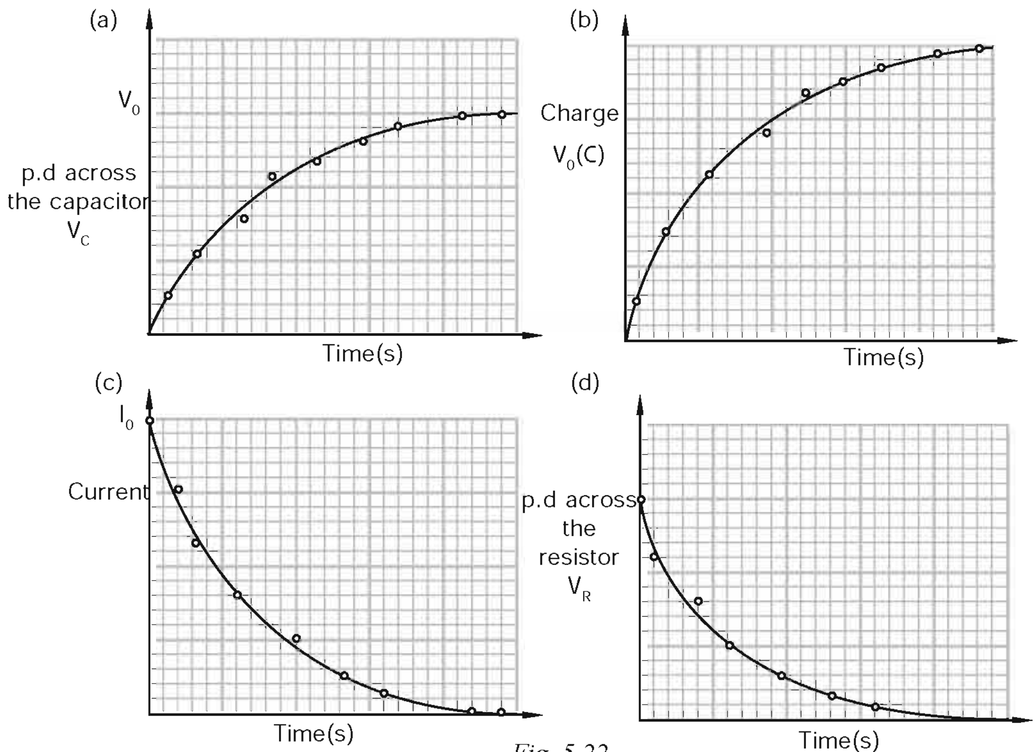


Fig. 5.22

At time $t = 0$, the potential difference, V_C across the capacitor is zero, showing that the charge Q on either plate is zero. Initially the current in the circuit is high while the potential difference between the plates is zero since there is no charge on the plates.

As time progresses the plates become more and more charged making potential difference across the capacitor to increase. The potential difference on the plates opposes the flow of electric current hence current in the circuit decreases with time until it is equal to zero when the capacitor is fully charged. When the potential difference across the capacitor V_C is at maximum possible, the capacitor is said to be *fully charged*. The charge on the capacitor in Fig. 5.21 is given by; $Q = V_0C$. V_0 is the potential difference across the capacitor plates, and is approximately equal to the electromotive force of the battery.

In Fig. 5.22, graph (a) shows how the potential difference V_C across the capacitor increases exponentially with time. Graph (b) is similar to graph (a). Since charge $Q = CV_C$, then Q increases in a similar way to the potential difference V_C across the capacitor. Charge builds up to a final value $Q = V_0C$. The curve is called a *build-up exponential*. Graph (c) shows how the charging current decreases with time. The current decreases exponentially with time. The graph is called an *exponential decay curve*. In graph (d), the potential difference V_R across R also decreases exponentially at the same rate as the current.

5.7.2 Discharging of a capacitor

Activity 5.10: **To discharge a charged capacitor through a fixed resistor.**

(Work in groups)

Materials

- A charged capacitor
- Two switches
- A cell
- Connecting wires
- A resistor

Steps

1. Connect the circuit as shown in Fig. 5.23 keeping switch S_2 open and switch S_1 closed. The capacitor gets charged almost immediately.

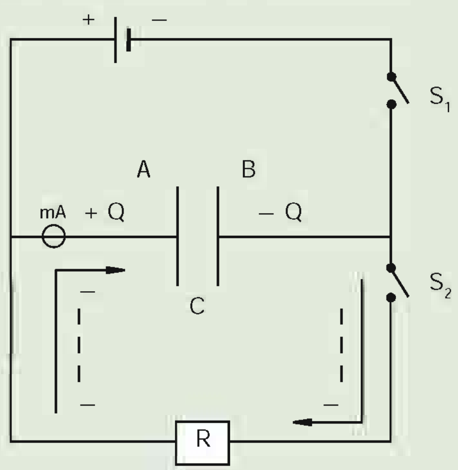


Fig. 5.23: Discharging of a capacitor

2. When the micro-ammeter reading decreases to zero, open switch S_1 and carefully without touching the terminals of the capacitor close switch S_2 and simultaneously start a stop watch.
3. Note the ammeter reading at regular intervals of time and record your result in a table (Table 5.2).

Table 5.2

Time(s)	0	30	60	90	120	150	180	240	300		
I/(mA)											

4. Plot a graph of current *I* against time *t* (Fig. 5.24).
5. From the graph describe the flow of charge out of the capacitor during the discharging process.

A graph of current against time for a capacitor during discharging is as shown in figure 5.24.

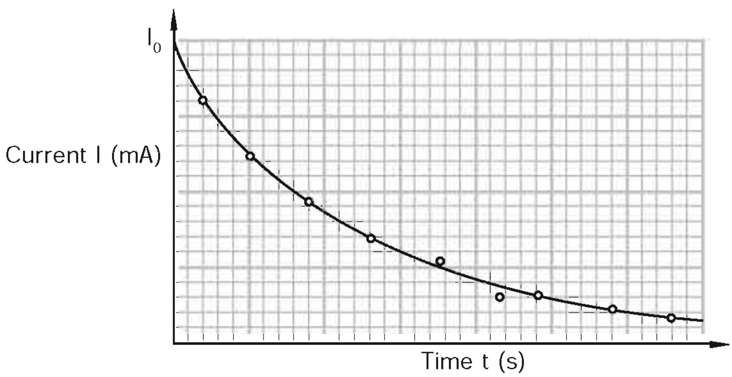


Fig. 5.24: Graph of current against time

Electrons flow from plate B to plate A. At the start, the rate of discharge is high as the electrons flow off the plates at a high rate i.e. I_0 is maximum. As time progresses, the potential difference across the plates decreases and the rate of discharge also decreases.

So the discharge current I_0 is initially high, as read from microammeter. The current becomes less and less as the capacitor discharges. It takes a long time for the current to become zero. The time for the capacitor to discharge fully depends on the size of the capacitor and the resistance in the circuit. The higher the values the more is the time for discharge.

The discharge of the capacitor lowers both the potential difference and the charge across its plates as shown in Fig. 5.25(a) and (b).

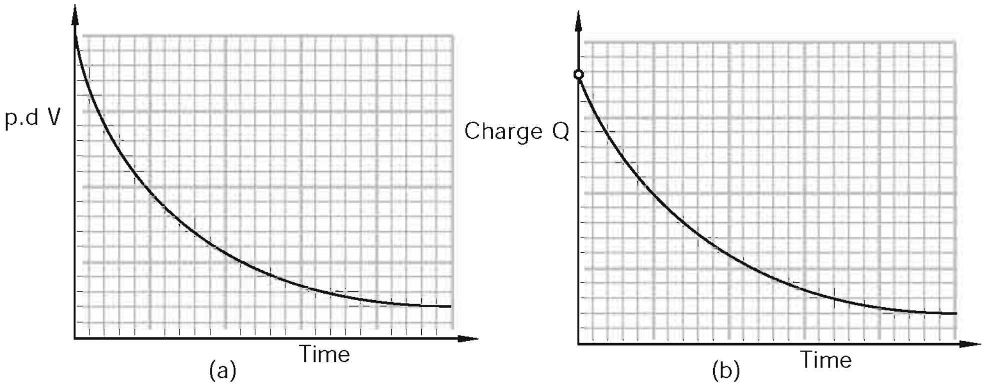


Fig. 5.25: Graphs of potential difference, V, and charge, Q, with time

5.8 Factors that determine the capacitance of a parallel plate capacitor

Activity 5.11: **To investigate factors that determine capacitance of a parallel plate capacitor**

Work individually.

Materials

- Reference books
- Internet

Steps

1. Identify three factors that determine capacitance of a parallel plate capacitors.
2. Explain how each of the factors you identified in step 1 affects the capacitance of the capacitor..
3. Present your research findings to the class.

It has been established that the capacitance of the capacitor depends on the:

- Distance between the plates,
- Area of overlap of the plates
- The nature of the material between the plates called the dielectric medium.

1. Distance between the plates

Experiments have shown that when the distance between the plates is decreased, the potential difference between the plates decreases and hence capacitance increases.

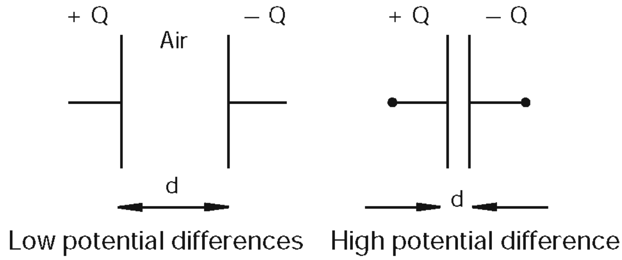


Fig. 5.26: Potential difference between plate of a capacitor

Hence capacitance is inversely proportional to the distance between the plates i.e.

$$Capacitance \ \alpha \ \frac{1}{\text{distance between the plates, d,}} \quad or\ C\ \alpha\ \frac{1}{d}$$

2. Area of overlap of the plates

An increase in the effective area or the area of overlap of the plates increases the capacitance due to increased surface for holding charges (Fig. 5.27).

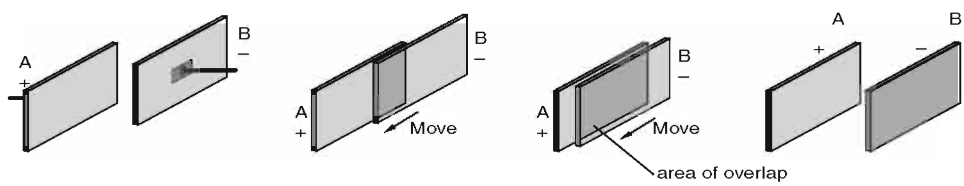


Fig. 5.27

Capacitance, C_1 is therefore proportional to the area of overlap i.e
$C\ \alpha\ A$

3. Nature of the medium between the plates, called the dielectric

An insulating medium like mica, paraffin wax, ebonite, polythene or polystyrene sheet, waxed paper, glass can be introduced in the space between the plates of an air capacitor, covering the entire area between the plates. This material is called a *dielectric material.*

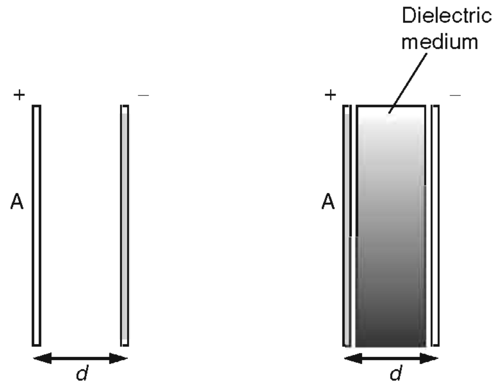


Fig. 5.28: Capacitance depends upon the dielectric

Introduction of a dielectric material decreases the potential difference, *V*, between the plates and hence the capacitance of the capacitor increases. The ratio of the capacitance with a dielectric material to the capacitance without a dielectic material is called the *dielectric constant* of the material.

We can conclude that:

Since $C \propto \frac{1}{d}$, $C \propto A$ and C increases when a dielectric material is placed between the plates then,

$C = \varepsilon_0 \times \frac{A}{d}$, where ε_0 is the permittivity of the dielectric material used.

and is called

A – area of overlap of plates and d is distance of separation.

Example 5.7

The plate separation for a capacitor is 1×10^{-3} m, determine the area of the plates if the capacitance is 1F. $\varepsilon_0 = 8.85 \times 10^{-12}$

Solution

$$C = \frac{\varepsilon_0 A}{d}$$

$$1 = \frac{8.85 \times 10^{-12} \times A}{1 \times 10^{-3}}$$

$A = 1.1299 \times 10^{8}\ cm^2$

Example 5.8

Calculate the voltage of a battery connected to a parallel plate capacitor with a plate area of 3 cm^2 and a plate separation of 2 mm if the charge a stored on the plate is 5 pc (1pC = 1×10^{-12} C.

Solution

$$A = \frac{3}{10\ 000} = 3 \times 10^{-4}\ m^2$$

$$C = \frac{\varepsilon_0 A}{d} = \frac{8.85 \times 10^{-12} \times 3 \times 10^{4}}{2 \times 10^{-3}} = 1.3275 \times 10^{-4}\ F$$

$$C = \frac{Q}{V}$$

$$V = \frac{Q}{C} = \frac{5 \times 1 \times 10^{-12}\ C}{1.327 \times 10^{-4}\ F} = 3.7665 \times 10^{-8}\ V$$

5.9 Types of capacitors

Activity 5.12: **Investigating different types of capacitors**

(Work in groups)

Materials

- Internet
- Reference books
- Variable capacity
- Electrolytic capacitor

Steps

1. Use reference books to find the different categories of capacitors that are in common use.
2. Discuss how each category works.

Capacitors come in a variety of forms and sizes. But basically they are all forms of parallel plate capacitors.

(a) Variable capacitor

A variable capacitor is one in which the area of overlap of the plate can be adjusted and the dielectric between the metal plates is usually air as shown in Fig. 5.29.

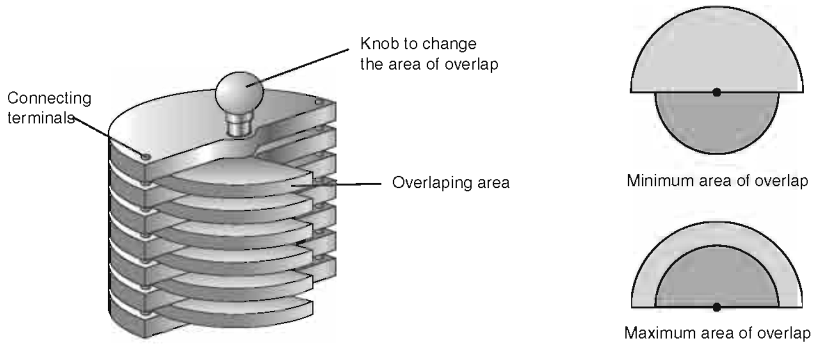


Fig. 5.29: Variable capacitor

Variable capacitor is useful in radio 'tuning circuits' where radio stations of different frequencies can be selected by changing the value of the capacitance of the variable capacitor. The symbol for a variable capacitor: 

(b) Electrolytic capacitor

The electrolytic capacitor is a special type of capacitor where one plate is always connected to the positive terminal of the battery and the other plate to the negative terminal (Fig. 5.30).

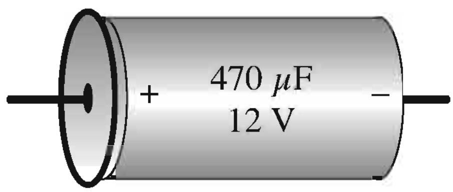


Fig. 5.30: Electrolytic capacitor

If the polarities are interchanged the dielectric layer may be damaged. These capacitors have large capacitance and are useful in power supply circuits e.g. as *power packs* in the laboratories, time-delay electronic circuits, to control a lamp in a photographic dark room or head light of a car. The symbol for this capacitor is: 

(c) Metal foil plastic capacitor

A metal foil capacitor has plastic as its dielectric. It has a small volume compared to others (Fig. 5.31). These capacitors are available in a variety of shapes and sizes.

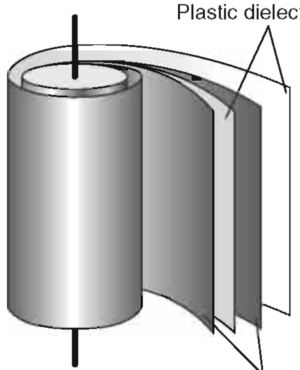


Fig. 5.31: Metal foil plastic capacitor.

Car mechanics use the term 'condenser' instead of a capacitor as the original name given was a condenser. Capacitors of large capacitance are used in the ignition system of car engines and buses. Photographic camera flash-units use capacitors which can get charged and discharged very quickly. Without capacitors electric and electronic circuits would be quite limited in application. A capacitor is a boost to the modern scientific technology.

5.10 Combination of capacitors

Activity 5.13: **Investigating capacitance of combined resistors**

(Work in groups)

Materials

- One, 10 μF capacitors
- One, 100 μF capacitor
- One, 1000 μF resistors
- Switch
- Connecting wires
- Dry cells

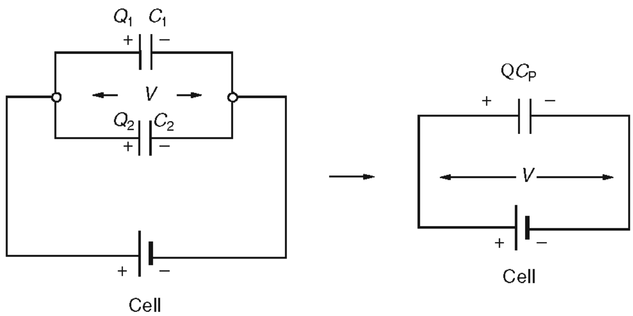
Steps

1. Given that Q = CV, derive an expression for the effective capacitance for three capacitors in C_1, C_2 and C_3 arranged in (a) series (b) parallel
2. Use all the above materials to set up a circuit with a total effective capacitance of
   (a) 110 μF (b) 9.01 μF (c) 99.1 μF

In electrical and electronic circuits capacitors are connected together in parallel or in series in order to achieve the required effective capacitance. The *effective capacitance* or the equivalent capacitance of any combination is the capacitance of a single capacitor which if substituted for the combination, acquires the same charge for the same potential difference applied.

(a) Capacitors in parallel

Fig. 5.32 (a) shows two capacitors of capacitance c_1 and c_2 connected in parallel across a cell and Fig.5.32 (b) shows the effective capacitance of the two capacitors (C_p).



(a) (b)

Fig. 5.32: Capacitors in parallel

In this connection, the potential difference, V, across the plates of each capacitor is the same.

The total charge Q of the effective capacitor, C_p, should be equal to the sum of the charge Q_1 and Q_2

$$Q = Q_1 + Q_2, \text{ where charge } Q = CV$$

$$\text{hence} \quad C_pV = C_1V + C_2V$$

$$VC_p = V(C_1 + C_2)$$

$$\therefore \quad C_p = C_1 + C_2$$

The effective capacitance C_p has increased and it is the sum of the individual capacitance.

This combination is used for obtaining a capacitor of a large capacitance from a few given capacitors of small capacitance. i.e.

$C_P = C_1 + C_2 + C_3 + \ldots\ldots + C_n$

where n = 1, 2, …… n

(b) Capacitors in series

Fig. 5.33 (a) shows two capacitors of capacitances c_1 and c_2 connected in series with a cell and Fig. 5.33 (b) shows the effective capacitance (C_s) of the two capacitors.

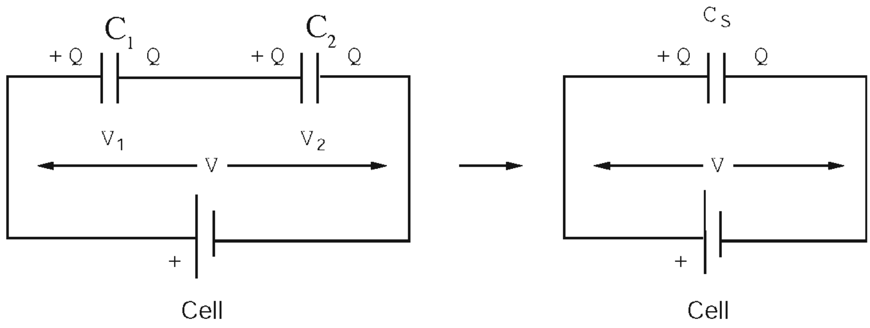


Fig. 5.33: Capacitors in series

In this connection, the charge Q on each plate of the capacitor is the same, but the total potential difference, V, is split as V_1 and V_2 across each capacitor.

$$V = V_1 + V_2 \quad \text{but charge } Q = VC \qquad \therefore \; V = \frac{Q}{C}$$

Hence $\dfrac{Q}{C_S} = \dfrac{Q}{C_1} + \dfrac{Q}{C_2}$

$$\frac{Q}{C_S} = Q\left(\frac{1}{C_1} + \frac{1}{C_2}\right)$$

$$\therefore \quad \frac{1}{C_S} = \frac{1}{C_1} + \frac{1}{C_2}$$

The effective capacitance C_S has decreased and is always less than the least value of capacitance. It is worthwhile to note that the combination of capacitors is the opposite of combination of resistors discussed in lower classes.

This combination is used when it is desired to divide a high voltage between several capacitors when none of them can individually be able to hold this high voltage.

Example 5.9

Two capacitors of capacitance 2 mF and 4 mF are connected in (a) parallel (b) series. Calculate the effective capacitance in each combination.

Solution

(a) In parallel $\quad C_p = C_1 + C_2 = 2 + 4 = 6$ mF

(b) In series $\dfrac{1}{C_S} = \dfrac{1}{C_1} + \dfrac{1}{C_2} = \dfrac{1}{2} + \dfrac{1}{4} = \dfrac{2+1}{4} = \dfrac{3}{4}$

$\therefore \quad C_s = \dfrac{4}{3} = 1.33$ mF.

Example 5.10

A 3 μF capacitor is placed in parallel with a 6 μF capacitor and the combination is joined to a 12 V battery (Fig. 5.34). Calculate (a) the effective capacitance and (b) the charge on each capacitor.

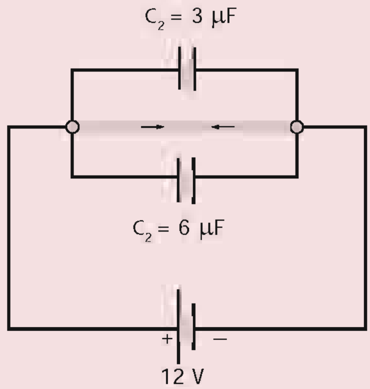


Fig. 5.34

Solution

(a) Effective capacitance in parallel $C_p = C_1 + C_2$

$= 3 + 6 = 9$ μF.

(b) In parallel combination, the potential difference V across each capacitor is the same i.e. 12 V

Hence charge Q_1 on capacitor C_1 = $Q_1 = VC_1$

$= 12 \times 3 = 36$ μC

charge Q_2 on capacitor C_2 = $Q_2 = VC_2$

$= 12 \times 6 = 72$ μC.

Example 5.11

Three capacitors are connected as shown in Fig. 5.35 with a battery of a e.m.f of 6 V and zero internal resistance. Calculate

(a) the effective capacitance of the capacitors

(b) the potential difference across each capacitor the charge stored in each capacitor.

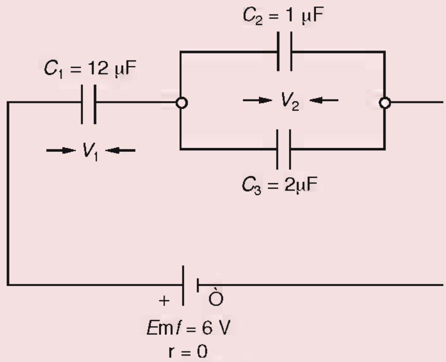


Fig. 5.35

Solution

(a) The capacitors C_2 and C_3 are connected in parallel

$\therefore\ C_p = C_2 + C_3 = 1 + 2 = 3\ \mu F$

This combination of effective capacitance 3 μF and C_1 are connected in series.

$$\therefore\ \frac{1}{C_s} = \frac{1}{C_1} + \frac{1}{C_p} = \frac{1}{12} + \frac{1}{3} = \frac{1+4}{12} = \frac{5}{12}$$

$$C_s = \frac{12}{5} = 2.4\ \mu F$$

$\therefore$ The effective capacitance = 2.4 μF

(b) As C_1 (12 μF) and C_p (3 μF) are in series, the total e.m.f of 6 V is split as V_1 and V_2 in the inverse ratio of the capacitance (12 : 3 = 4 : 1)

$$V_1 = \frac{6}{5} \times 1 = 1.2\ V; \quad V_2 = \frac{6}{5} \times 4 = 4.8\ V$$

Also capacitors C_2 and C_3 are in parallel and hence potential difference across each capacitor is the same i.e. 4.8 V.

(c) Charge Q_1 on capacitor C_1 $= V_1C_1$
$= 1.2 \times 12$
$= 14.4\ \mu C$

Charge Q_2 on capacitor C_2 $= V_2C_2$
$= 4.8 \times 1$
$= 4.8\ \mu C$

Charge Q_3 on capacitor C_3 $= V_2C_2$

$= 4.8 \times 2$

$= 9.6$ mC

(Note that the total charge $Q_2 + Q_3 = 4.8 + 9.6$

$= 14.4$ mC which is the same as Q_1)

Example 5.12

You have been provided with three identical capacitors each of capacitance 6 μF. How would you combine them to get an effective capacitance of (a) 2 μF (b) 18 μF (c) 9 μF (d) 4 μF. Draw the combination of the capacitors and show the effective capacitance in each case.

Solution

See Fig. 5.36

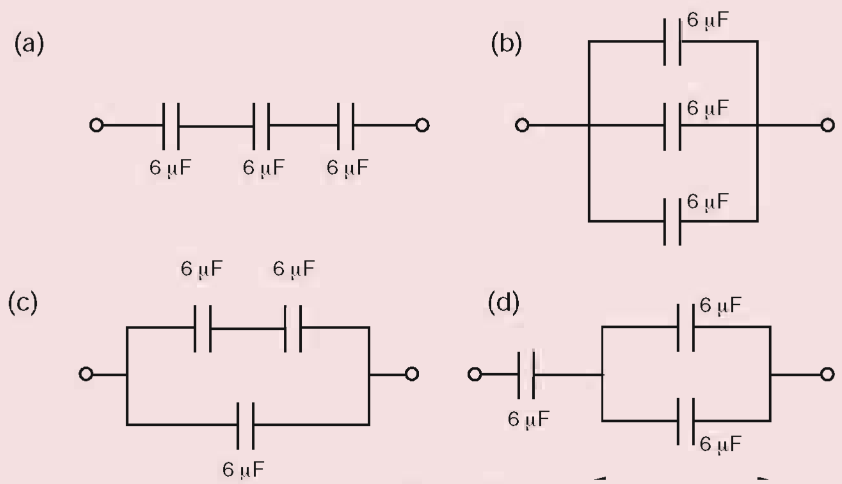


Fig. 5.36

All the three capacitors in parallel will give the largest capacitance which is 18 μF and all the three in series will give the least capacitance which is 2 μF. So the other two effective capacitance may be obtained by mixed grouping, 2 in series and 1 in parallel or 2 in parallel and 1 in series.

(a) In series $\frac{1}{C_S} = \frac{1}{6} + \frac{1}{6} + \frac{1}{6} = \frac{3}{6} = \frac{1}{2}$

$\therefore\ C_S = 2$ μF

(b) In parallel $C_p = 6 + 6 + 6 = 18$ μF

(c) 6 μF, 6 μF in series $\frac{1}{C_S} = \frac{1}{6} + \frac{1}{6} = \frac{2}{6}$

$C_S = 3$ μF.

C_S in parallel with 6 μF

$C_p = 3 + 6 = 9$ μF

(d) In parallel 6 + 6 = 12 μF

In series $\frac{1}{C_S} = \frac{1}{6} + \frac{1}{12} = \frac{2+1}{12} = \frac{3}{12} = \frac{1}{4}$

$\therefore C_S = 4$ μF

Hence maximum capacitance is obtained when capacitors are arranged in parallel while minimum is obtained when capacitors are arranged in series.

Exercise 5.1

1. What is a capacitor?
2. In terms of electron flow, explain how a capacitor stores charges.
3. Define the term capacitance of a capacitor and state its SI unit.
4. When a capacitor is connected to a battery of e.m.f 12 V, the charge stored on each plate is 0.06 mC. Calculate the capacitance of the capacitor in μF.
5. Explain the charging process of a capacitor through a fixed resistor. Sketch a graph to show how the p.d across the plates of the capacitor varies with time.
6. Explain the discharging process of a capacitor through a fixed resistor. Sketch a graph to show how the charge on the plates of the capacitor decreases with time.
7. (a) State the factors which affect the capacitance of a parallel plate capacitor.
   (b) Explain how the factors affect the capacitance of the capacitor.
8. Define the term effective capacitance, when several capacitors are connected in a circuit.
9. Two capacitors of capacitance 10 μF and 15 μF are connected in (a) series (b) parallel. Calculate the effective capacitance in each case.
10. In the circuit shown in Fig. 5.37, calculate (a) the effective capacitance of the capacitors (b) the charge on each capacitor and (c) the potential difference across each capacitor.

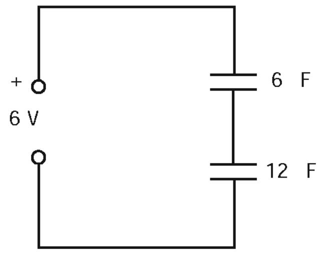


Fig.5.37

11. In each of the following circuits (Fig. 5.38), calculate (a) the effective capacitance of the capacitors and (b) the charge on the capacitor C_1.

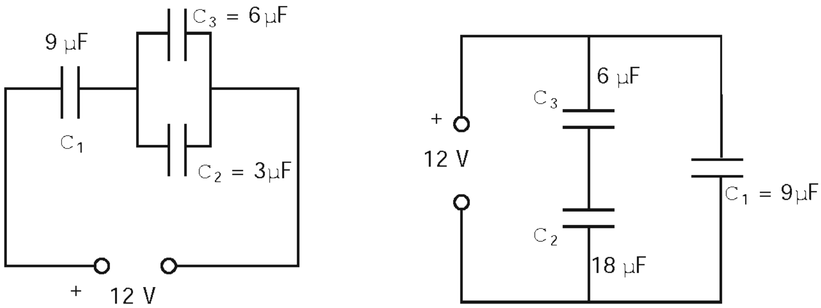


Fig. 5.38

5.11 Discharging action at points

Activity 5.14: **To demonstrate discharge action at points**

(Work in pairs or in groups)

Materials:

Needle, or optical pin, leaf electroscope

Steps

1. Charge the electroscope positively by induction.
2. Place a needle or optical pin on the cap (disc) of a leaf electroscope.
3. Observe what happens to the leaf of the electroscope. Explain this observation.

In step 2 of the activity the leaf quickly falls, i.e. divergence decreases rapidly. *A charged point allows leakage of charge to the surrounding quickly leading to discharge.*

When a body which has sharp points and edges is charged heavily, the net charge per unit area about the sharp points is much greater than the flatter parts of the body. The charge is very dense and crowded over the sharp points. The effect of this is to '*ionise*' the surrounding air, i.e. to remove electrons from some of the air molecules. The released electrons are free to move about and usually get attached to other neutral atoms of air which thus become negatively charged. The result is that both positive and negative ions are produced.

The positive ions are repelled by the pointed edge of the needle and the negative ions are attracted. These negative ions neutralise the charge on the needle and the electroscope's leaf quickly falls.

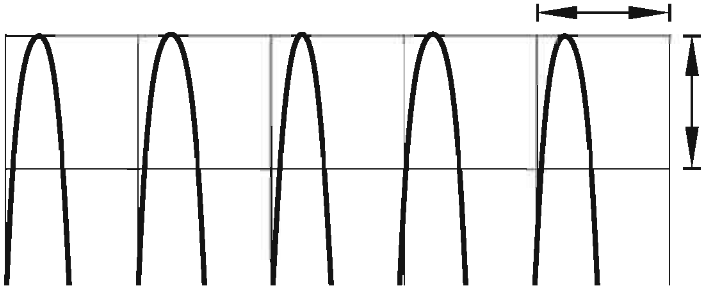


Fig. 5.39: Discharge action of a pointed edge

If the point is negatively charged, the positive ions are attracted towards the point and the negative ions are repelled away from it. We can say that the negative ions are 'sprayed' by the pointed edge (Fig. 5.40 (a)). If the point is positively charged, the positive ions are 'sprayed' by the pointed edge. (Fig. 5.40 (b)). In either case, a sort of an '*electric wind*' blows from the charged point.

The action of the point is to drive away ions with similar charge and to attract opposite charge. This means that the point and the body attached to it become discharged by the action of the point.

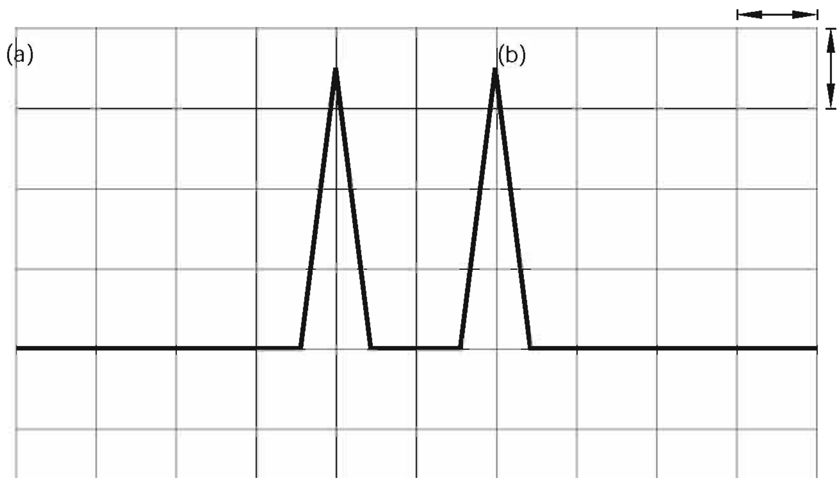


Fig. 5.40: Action of points

The action of the point is to drive away ions with similar charge and to attract opposite charge. This means that the point and the body attached to it become discharged by the action of the point.

5.12 Applications of electrostatics

Acitivity 5.15: **To investigate the application of electrostatics**

(Work individually)

Materials:

Reference sources

Steps

1. Do a research about the application of the concept of electrostatics in the working of the following devices: printer, lightning arrestor, van de graaf generator, paint sprayer, defibrillator
2. Describe other applications of electrostatics in daily life apart from those listed above.
3. Make a presentation of your findings to the test of the class.

Static electricity has many practical uses. Photocopiers and laser printers, xerography and the painting of automobiles, defibrillators, lightning rods, electrostatic dust precipitators and paint sprayers are all practical applications of static electricity. Scientific devices based on the principles of electrostatics include electrostatic generators, the field-ion microscope, and ion-drive rocket engines.

(a) Defibrillators

A defibrillator is a machine that can be used by paramedics to restart your heart if it stops or to stabilise an irregular heartbeat. They work by discharging electric charge.

Two paddles with insulated handles are charged from a high voltage supply. They are put in good electrical contact with the patient's chest. It is important that only the patient gets a shock:

- This is why the paddles have insulating handles
- The operator and any one nearby stand clear.

The defibrillator passes charge through the patient to make the heart contract.

(b) Paint spraying

Car manufacturers can save money by using charged paint spray guns. They work because like charges repel and unlike charges attract.

Electrostatics can be useful for spraying liquids. For example:

- Spraying paint
- Spraying crops with pesticides and herbicides.

The spray gun is given a charge. This means that the droplets of paint also become charged:

- They gain the same charge, so they repel each other and produce a fine spray.

The car body part is given an opposite charge to the spray gun and paint droplets. This means:

- The paint droplets are attracted to the body part, producing an even coat with little waste, even in awkward 'shadow' surfaces that the operator cannot see.

You need to be able to explain paint spraying in terms of gaining and losing electrons. For example:

1. The paint gun loses electrons so that it becomes positively charged
2. The paint droplets lose electrons and so also become positively charged
3. The object to be painted gains electrons and so becomes negatively charged
4. The positively charged paint droplets repel each other and are attracted to the negatively charged surface.

Health matters

Pesticides and herbicides are poisonous chemicals. Wear protective clothing while spraying them

(c) Xerography (electrophotography)

Xerography, also known as electrophotography, is a printing and photocopying technique that works on the basis of electrostatic charges. The xerography process is the dominant method of reproducing images and printing computer data and is used in photocopiers, lasers and fax machines. The term xerography derives from the Greek words xeros, meaning dry and graphos, meaning writing.

Xerography was invented in the late 1930s by an American patent lawyer named Chester Carlson. At first, engineers considered the idea useless and several years passed before the potential of the invention was appreciated by industry. During those years, IBM, Kodak, General Electric and RCA were among the companies that turned Carlson away. The Battelle Memorial Institute, a nonprofit organization, invested in Carlson's research and eventually signed a licensing agreement with a company called Haloid. Battelle and Haloid collaborated in research and demonstrated the technique in 1948. Haloid subsequently became Xerox.

The one feature of this process that makes it unique is the use of a photoconductive material to form an image. (A photoconductor is a material that is a poor electrical conductor in the dark but that becomes a good electrical conductor when exposed to light.)

(d) Photocopy machine

A photocopier uses electrostatic charge to produce a copy. The original (the page you want copied) is placed onto a sheet of glass. An image of this page is projected onto a positively charged drum.

The drum has a coating that conducts electricity when light falls on it. The parts of the drum which are lit by the projected image lose their electrostatic charge when they start to conduct.

A black powder (called toner) is negatively charged.The toner is attracted to the positively charged parts of the drum.The drum rotates and rolls against a piece of copier paper. The toner is transferred from the drum to the paper making a black and white image of the original.

Finally, the paper is heated which makes the toner stick to it. This is called "fixing" the image. When you use a photocopier you can feel that the copier paper is still warm.

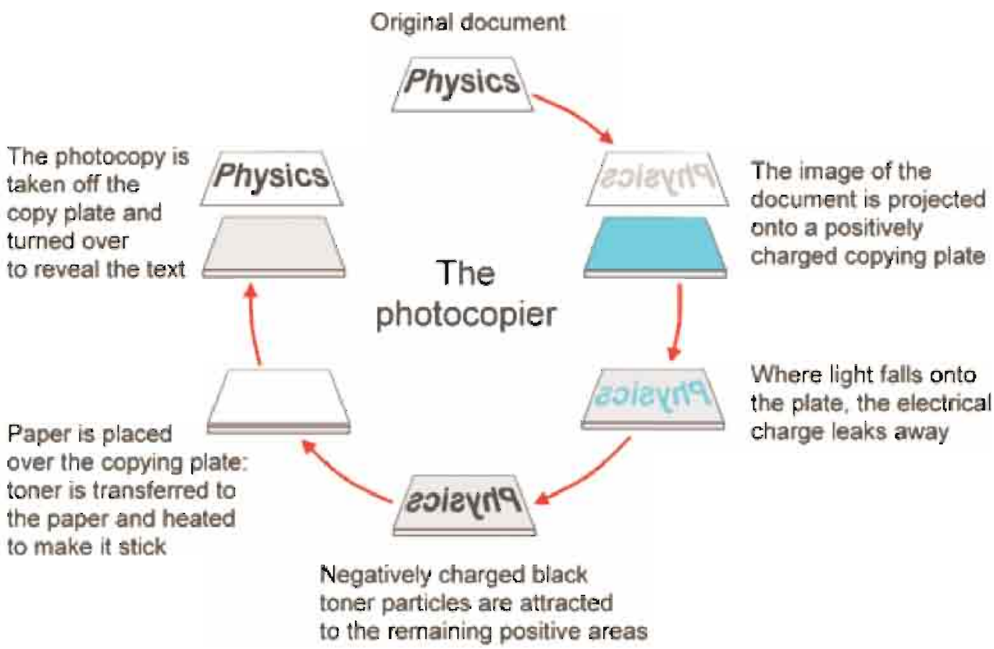


Fig. 5.41: Diagram showing how photocopier works

The diagram shows how a photocopier works. A laser printer works in a similar way.

(e) Electrostatic Precipitator

Tiny particles of soot, ash, and dust are major components of the airborne emissions from fossil fuel-burning power plants and from many industrial processing plants. Electrostatic precipitators can remove nearly all of these particles from the emissions.

The flue gas containing the particles is passed between the series of positively charged metal plates and negatively charged wires. The strong electric field around the wires creates negative ions in the particles. The negatively charged particles are attracted by positively charged plates and collect on them. Periodically, the plates are shaken so that the collected soot, ash, and dust slide down into a collection hopper. One important application of electrical discharge in gases is the electrostatic precipitator. This device removes particulate matter from combustion gases, thereby reducing air pollution. Precipitators are especially useful in coal-burning power plants and in industrial operations that generate large quantities of smoke. Current systems are able to eliminate more than 99% of the ash from smoke.

Figure 5.42 a shows a **schematic diagram of an electrostatic precipitator**.

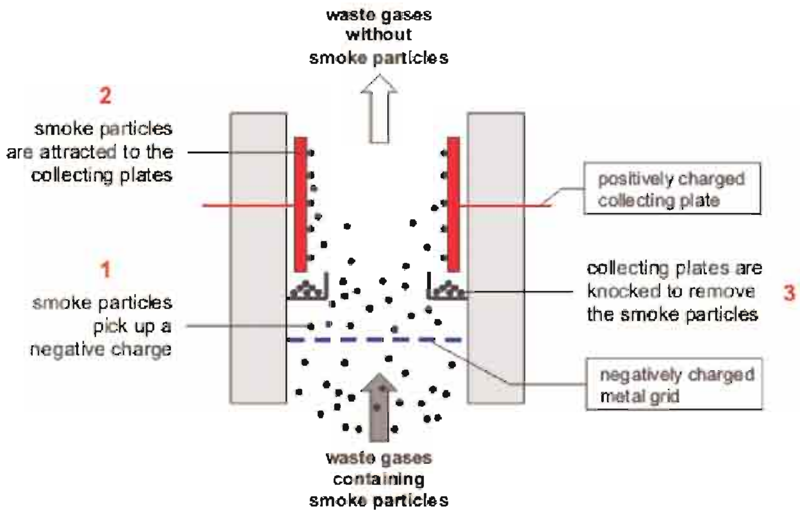


Fig. 5.42: Electric precipitator

A high potential difference (typically 40 to 100 kV) is maintained between a wire running down the center of a duct and the walls of the duct, which are grounded. The wire is maintained at a negative electric potential with respect to the walls, so the electric field is directed toward the wire. The values of the field near the wire become high enough to cause a corona discharge around the wire; the discharge ionizes some air molecules to form positive ions, electrons, and such negative ions as O_2^-. The air to be cleaned enters the duct and moves near the wire. As the electrons and negative ions created by the discharge are accelerated toward the outer wall by the electric field, the dirt particles in the air become charged by collisions and ion capture. Because most of the charged dirt particles are negative, they too are drawn to the duct walls by the electric field. When the duct is periodically shaken, the particles break loose and are collected at the bottom.

Fig 5.43 (a) Schematic diagram of an electrostatic precipitation.

(a) (b) (c)

Fig. 5.43: Schematic drawing an electrostatic precipitation.

The high negative electric potential maintained on the central coiled wire creates an electrical discharge in the vicinity of the wire. Compare the air pollution when the electrostatic is (b) operating and (c) turned off.

In addition to reducing the level of particulate matter in the atmosphere (compare Figs. 5.43 (b) and (c), the electrostatic precipitator recovers valuable materials in the form of metal oxide.

(f) Lightning arrestor

Activity 5.16: **To investigate how a lighting arrestor works.**

(Work in groups)

Steps

1. Discuss the cause(s) of lightning.
2. Discuss how the lightning conductor (arrestor) works.
3. Why is it not advisable to take shelter under a tree during raining?

The discharge action of points is utilised in an important device called *lightning arrestor or conductor* used to prevent tall buildings and towers against the destructive effect of lightning.

A lightning conductor is a thick metal rod. One end is attached to a metal plate and buried deep in the ground. The other end, which is pointed, sticks up above the building. The conductor provides a path for electrons to flow easily through it (Fig. 5.44).

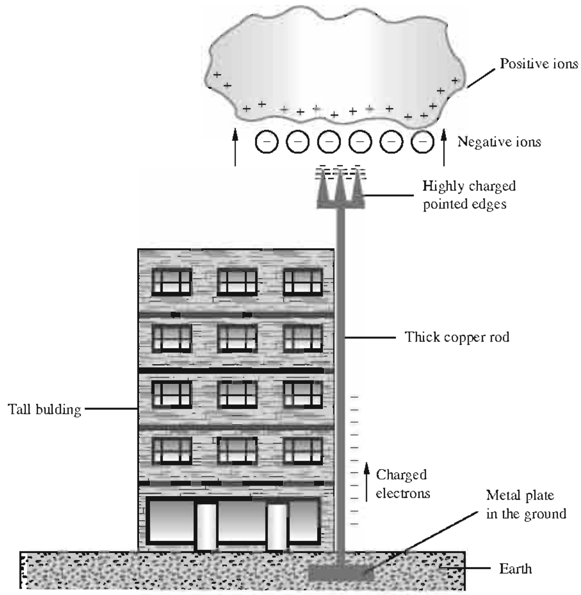


Fig. 5.44: Lightning arrestor

If a positively charged cloud is above the building, a negative charge will be induced on the pointed edges of the lightning conductor. Electrons concentrate on these points and by the discharge action of the pointed edges, *negative ions are sprayed into the air* and are attracted by the positive charges on the cloud. Thus the charge on the base of the cloud is reduced. This prevents a large build-up of charges which otherwise would result in discharges to the earth in the form of lightning. If the neutralising effect is insufficient and even if the lightning strikes, the huge electrical charge is conducted through the metal rod, to the earth. Thus the building is saved from any damage. In the absence of a lightning arrestor, lightning would strike the highest point of a building and a large current would pass to the earth through the building. The heat generated by the passage of this large current can set fire to the building.

Exercise 5.2

1. Define the following terms: electrical field, electric field strength, electric line of force, neutral point.
2. Is electric field strength a scalar or a vector quantity? Explain your answer.
3. Draw field lines for the arrangement of charges given in Fig. 5.45. Indicate with a letter N the position of the neutral point in Fig. 5.45 (a) and (b).

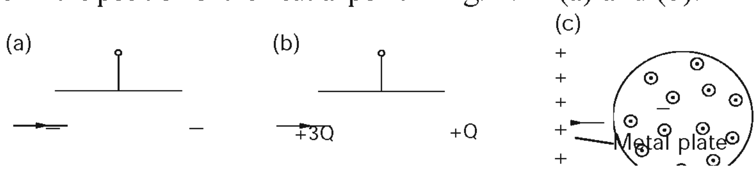


Fig. 5.45

4. What do you understand by the term 'surface charge density'? Explain how charges are distributed in (a) a spherical conductor and (b) a pear shaped conductor.
5. Explain how a negatively charged pointed edge gets discharged by itself.
6. Describe the construction of a lightning arrestor and explain how it helps to neutralise the positive charges on a cloud during thunderstorm.

Topic summary

- An electric field is the region where a charged body experiences an electrostatic force.
- The direction of electric field is the direction in which a unit positive test charge would move when placed at that point.
- An electric line of force is the path along which a unit positive charge would tend to move in the electric field.
- A neutral point in an electric field is one where the resultant force acting on the unit positive charge is zero.
- The electric field is uniform if the field lines are parallel.
- Electric lines of force start from the positive charge and end on the negative charge.
- Electric lines of force do not cross each other.
- A proof plane is a device which can be used to sample the charge in various parts of a conductor.
- Electric charges reside only on the outside of a conductor.
- In a spherical conductor charge is distributed uniformly over the surface.
- Charges are concentrated near the pointed edge of a pear shaped conductor.
- Accumulation of charges at a pointed edge ionise the surrounding air.
- Ionisation means to remove or add an electron from an atom or to an atom.
- Action of pointed edges are utilised in the construction of lightning arrestors used to protect tall buildings from being struck by lightning.
- The following factors affect the capacitance of a parallel plate capacitor.

  (a) distance (d) between the plates

  (b) area of overlap (A) of the plates.

  (c) dielectric medium between the plates.
- Experiments show that

  Capacitance $C \propto \frac{1}{d}$, $C \propto A$ and $C \propto \in_0$
- Capacitors are available in a variety of shapes and sizes according to the application.

Capacitors are used in radio, television, computer, amplifier, power supply units, car engine ignition system, photographic camera flash-units etc.

- Capacitors may be combined in a number of ways to acquire the desired effective capacitance.
- A parallel combination of capacitors gives a large capacitance.

$$C_p = C_1 + C_2 + \ldots\ldots$$

- A series combination of capacitors decreases the effective capacitance C_s, which is always less than the least value of capacitor in the arrangement.

$$\frac{1}{C_S} = \frac{1}{C_1} + \frac{1}{C_1} + \ldots$$

Topic Test 5

1. The electric field pattern shown in Fig. 5.46 is for two points charges.

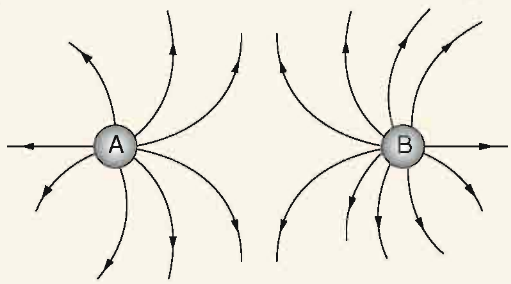


Fig. 5.46

   (a) Identify the charge on A and B.
   (b) Is the electric field produced by the point charge uniform? Explain your answer.
   (c) Mark the position of neutral point.

2. State three properties of electric lines of force.
3. Copy the figures and show how charges are distributed in each of the following cases (Fig. 5.47).

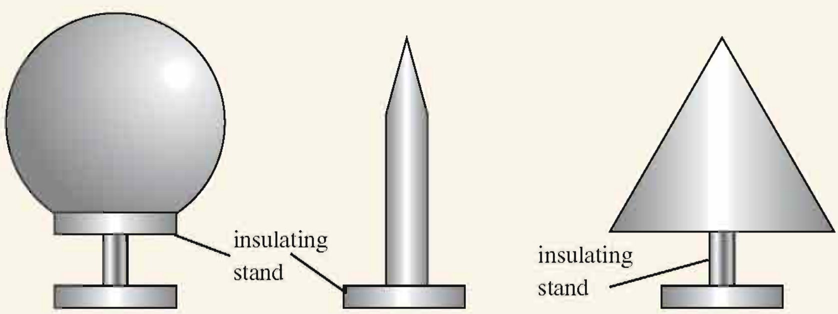


Fig. 5.47

4. Fig. 5.48 shows a thunder cloud which is negatively charged at its base.

   (a) Copy and complete the following in the diagram

      (i) the positive charges within the cloud.

      (ii) the sign of charge on the building. Explain your answer.

   (b) If the current developed during a thunder flash is 8 000 A which lasts for 0.2 s, calculate the quantity of charge that passes from the cloud to the ground during the 0.2 s.

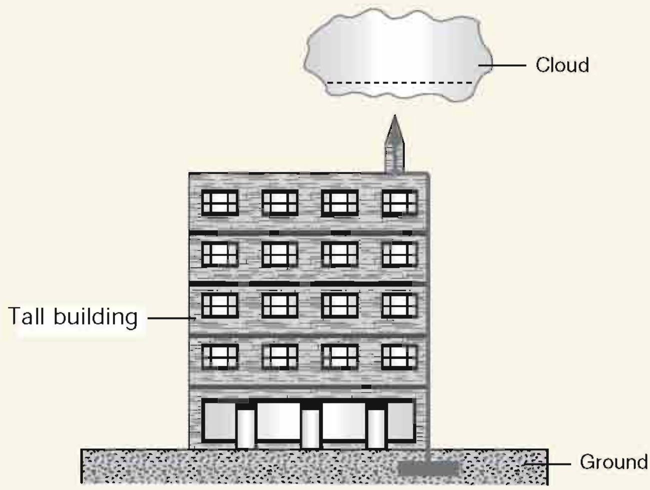


Fig. 5.48: Thunder arrestor

5. Fig.5.49 shows a graph of the relationship between the charge Q on each plate and the potential difference V between the plates of a capacitor. Explain how the graph could be used to calculate the capacitance of the capacitor.

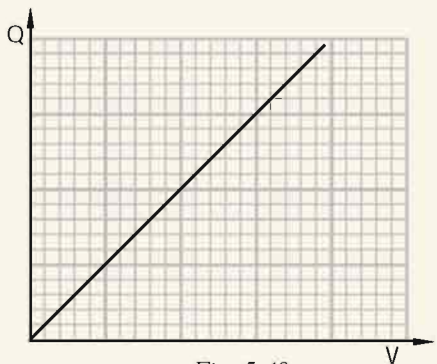


Fig. 5.49

6. The charge stored in a capacitor of capacitance 7 200 μF is 32.4 mC. Calculate the e.m.f of the battery charging the capacitor.

7. Fig. 5.50 shows the charged plates of a parallel plate air capacitor, when the distance of separation is *d*.

   (a) Copy and complete the diagram to show the electric field pattern in the space between the plates.

   (b) Without changing the area of overlap, suggest two ways by which you could increase the capacitance of the capacitor.

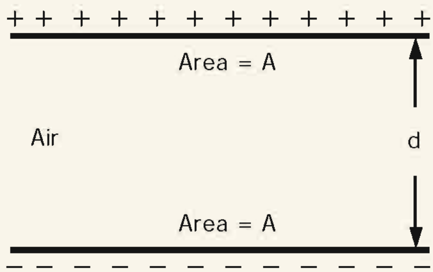


Fig. 5.50

8. (a) State how an electrolytic capacitor differs from other capacitors.

   (b) State where (i) an electrolytic capacitor (ii) a variable air capacitor could be used.

9. In the circuit shown in Fig. 5.51, calculate the charge on each plate of the capacitors shown.

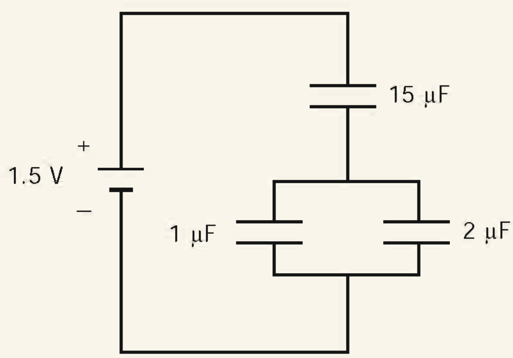


Fig. 5.51

UNIT 5 Magnetic field and electromagnetic Induction

Topics in the unit

Topic 6: Magnetic effect of an electric current

Topic 7: Electromagnetic Induction

Topic 8: Electric Power Transmission and house Installation

Key inquiry question

- How does Lenz's law relate to conservation of energy?
- Why does a current carrying conductor generate fields around it?
- How does an emf get induced in a moving wire that cuts magnetic field?
- Why are transformers important in the transmissions of electricity?

Learning outcomes

Knowledge and understanding

- Understand magnetic fields and electromagnetic induction

Skills

- Design and carry out investigations on electromagnetic induction, induced current mutual induction
- Apply the Biot-Savart law of magnetic fields
- Carry out practical investigations on generators, transformers, and magnetic field and magnetic induction,
- Interpret results in terms of laws of electromagnetic induction

Attitude and value

- Appreciate the need to conserve energy

TOPIC 6 Magnetic effect of an electric current

Topic outline

- Relationship between electric current and magnetism.
- The direction of a magnetic field.
- Magnetic field due to a current carrying solenoid.
- Simple electromagnet.
- Force on a current-carrying conductor in a magnetic field (motor effect).
- Simple d.c electric motor.
- Projects: Construction of:
    1. an electromagnet,
    2. an electric motor

Introduction

In 1819, Oersted observed that a compass needle deflected when brought near a current-carrying conductor. He also observed that direction on the compass needle depended on the relative position of the compass from the wire, and the direction of the current.

From Oersted's experiment, it was realised that there exists a relationship between an electric current and magnetism. In this topic we are going to study the magnetic effect of an electric current and some of its applications in technological development.

6.1 Magnetic field due to a straight current-carrying conductor

Activity 6.1: **To investigate the magnetic field pattern due to a straight current-carrying conductor**

(Work in groups)

Materials

- An electric circuit
- Iron filings
- Cardboard

- Source of current
- 7 plotting compasses

Steps

1. Set up the apparatus as shown in Fig. 6.1.

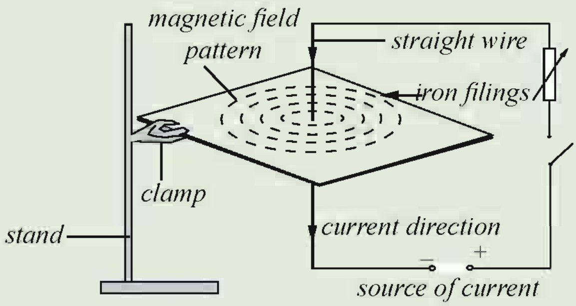


Fig. 6.1: Magnetic field pattern due to a straight current carrying conductor

You may use the variable resistor to vary the current, I.

2. Sprinkle iron filings on the card and close the switch. Tap the card gently. Draw the final pattern of the iron filings. Explain why the iron fillings form this pattern around the current carrying wire.
3. Repeat step 2 by placing 6 or 7 plotting compasses around the wire instead of iron filings as shown in Fig. 6.2.

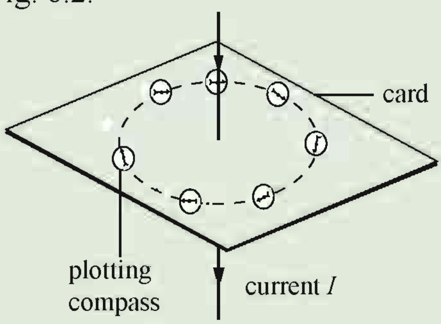


Fig.6.2

Observe the direction of the plotting compass.Sketch the line formed by the directions of the plotting compasses and indicate the direction of the field on that line. What is the shape and direction of the magnetic field around the currect carrying conductor.

4. Reverse the terminals and observe what happens. Describe how this affects the direction of the magnetic field.
5. Based on the two different directions you observed in step 3 and 4, describe the rules you can use to determine the direction of the field around the conductor.

When the card is tapped the iron filings settle in *concentric circles* round the wire.

In this activity, we can conclude that the current in the conductor has produced a magnetic field around it. *Thus, a magnetic field around a straight current-carrying conductor is a pattern of concentric circles around the conductor.*

By using the plotting compassess, we see that the direction of magnetic field around a current carrying conductor is a circular around the conductor.

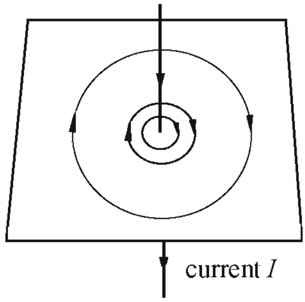


Fig.6.3: Direction of magnetic field.

When the current direction is reversed the compass needles point in the opposite direction. This shows that the direction of the field *reverses* when the current direction is reversed.

Rules for determining the direction of magnetic field

(a) Right hand grip rule (thumb rule)

Assume you are holding a conductor in your right hand with the thumb pointing in the direction of the current as shown in Fig. 6.4. The other fingers will point in the direction of the magnetic field due to the current in the wire.

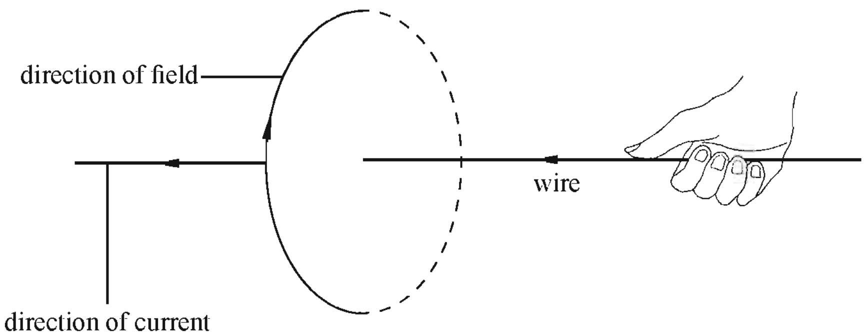


Fig. 6.4: Right hand grip rule

(b) Right handed corkscrew rule

Imagine you are holding and turning a screw in your right hand with the screw pointing in the direction of the current. Turn the screw clockwise so that it advances in the direction of the current. The clockwise rotation of the screw gives the direction of the field due to the current in the conductor as shown in Fig. 6.5.

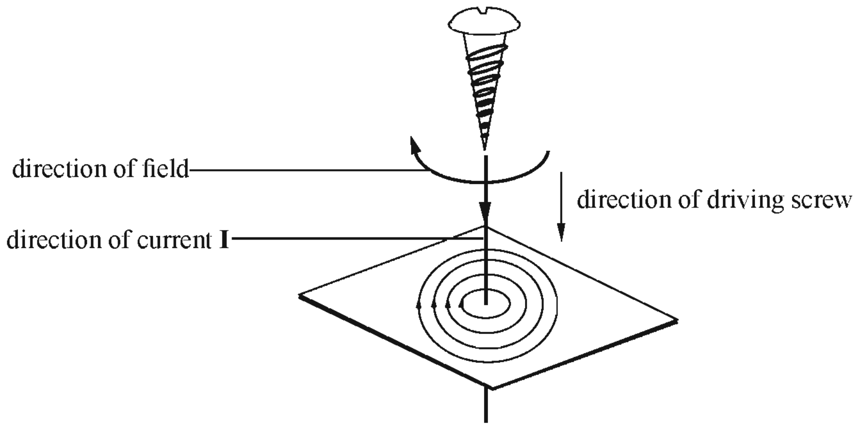


Fig. 6.5: The corkscrew rule

6.2 Magnetic field due to a current-carrying solenoid

Activity 6.2: **To investigate the magnetic field pattern due to a current carrying solenoid**

(Work in groups)

Materials

- A solenoid
- Iron filing
- A circuit
- Current source

Steps

1. Mount a solenoid on a rectangular piece of cardboard as shown in Fig. 6.6. Sprinkle some iron filings on the cardboard.

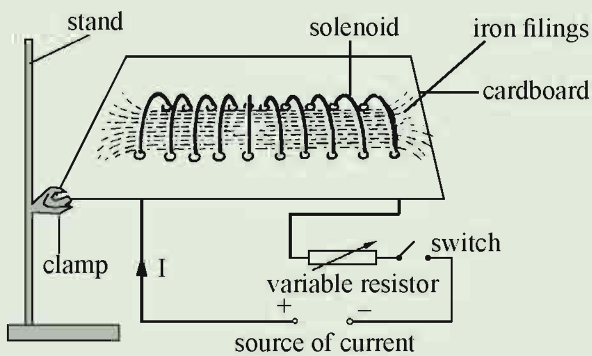


Fig. 6.6: Magnetic field due to a solenoid

2. Close the switch and tap the cardboard gently. Observe and draw the field pattern shown by the spread of the iron filings.

The iron filings arrange themselves as shown in Fig. 6.5(b).

3. Repeat the activity by placing a number of magnetic plotting compasses both inside and outside the solenoid. Draw the lines joining the directions of the plotting sketch.
4. Describe the magnetic field around a current carrying solenoid.

A solenoid is a long cylindrical coil made up of a number of turns of a closely packed wire.

The iron filings and plotting compasses show a similar pattern of the magnetic field around the solenoid (Fig 6.7). The direction of the field pattern is also indicated.

The activity shows that the solenoid behaves like a magnet with the N and S poles as indicated in Fig. 6.7.

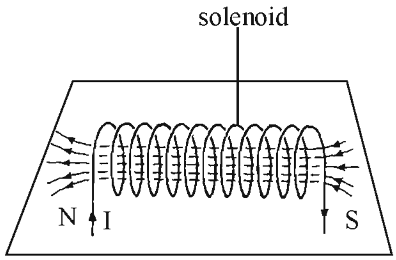


Fig. 6.5: Magnetic field due to a solenoid

View the coil from both ends in turn (Fig. 6.8(b)). If the direction of the current through the end being viewed is clockwise, then that end is found to be a south (S) pole. If the direction is anticlockwise the end is found to be a north (N) pole (Fig. 6.8).

anticlockwise *clockwise*

(a) *(b)*

Fig. 6.8: Polarity of a solenoid

6.3 Magnetic field around a current-carrying circular coil

Activity 6.3: **To investigate the magnetic field around a short circular coil carrying a current**

(Work in groups)

Materials

- A cardboard
- A short circular coil
- Iron filings

Steps

1. Mount a short circular coil on a cardboard and set up the circuit as shown. Sprinkle iron filings around it. Tap the cardboard, observe and draw the pattern formed.

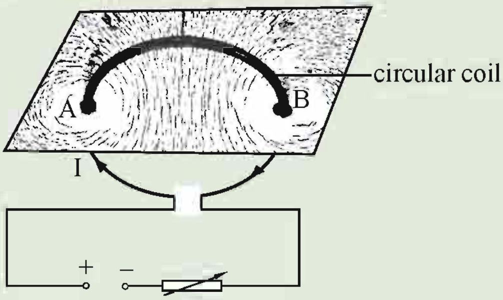


Fig. 6.9: Magnetic field due to a short coil.

2. Use plotting compasses to plot the field pattern due to the electric current flowing in the coil.

When viewed from above, it can be seen that at point A the current is *coming out of the cardboard* and at B the current is *going into the cardboard* Fig. 6.10. We use the symbol ⊙ to represent current coming out of paper and ⊗ to represent current going into the paper. Applying the right hand screw rule or the right hand grip rule at points A and B, the direction of the field in as shown in Fig. 6.10.

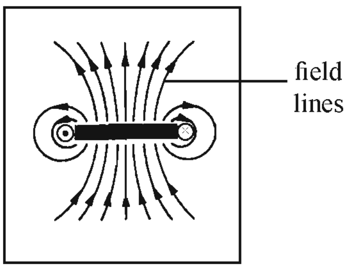


Fig. 6.10: Top view of magnetic field around the coil.

6.4 Charged particle in a magnetic field

A charged particle e.g. electron passing through a magnetic field follows a circular path as shown in figure 6.11.

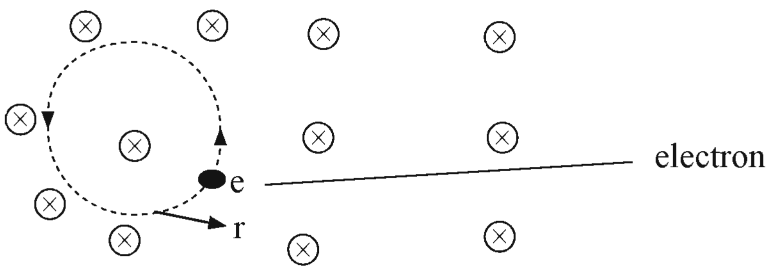


Fig. 6.11: Motion of a charged particle inside a magnetic field.

The deflection varies depending on the strength of the magnetic field

The centripetal force acting on the electron towards the centre of the circular path is given by

$$F_C = \frac{mV^2}{r}$$

Since the charge on the particle and the magnetic field are at a right angle, 90^0.

We get $F = qVB$

The Lorentz magnetic force supplies the centripetal force, so

$$qVB = \frac{mV^2}{r}$$

Making *r* the subject

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

where, q – Charge

B – magnetic field

m – Mass of charged particle

V – Velocity

r – cyclotron radius

6.5 Biot-Savart's law of magnetic field

Activity 6.4: **To investigate Biot-savart's law of magnetism**

(Work in groups)

Materials

- Internet
- Drawing on the board
- Reference books

Instructions

1. Predict what will happen if two wires carrying current in the same direction are brought close to each other.

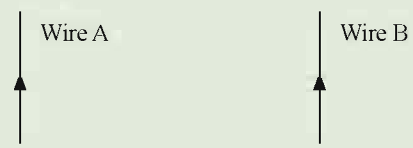


Fig. 6.12

2. Suggest what will happen when the currents in wires A and B are in opposite direction and the wires are brought near one another.
3. Now design and carry out an investigation to confirm or dissaprove your predictions in step1 and 2.
4. Using the results of your investigations, describe how the magnetic field around a current carrying conductor varies with distance from the conductor.
5. Research from internet about the Biot-Savart's law of magnetic.

The magnitude of the resultant magnetic field B at distance r from the conductor generated by a current flowing is determined by applying Biot-savart's law of magnetic field.

Biot-savart law states that

Magnetic field near a long straight conductor is directly proportional to the current in the conductor and inversely proportional to the square distance from the conductor

$$B \propto \frac{I}{r^2}$$

(a) For a straight conductor, see fig. 6.13

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

Where B – magnitude of magnetic field

μ_0 – Permeability of free space $4\pi \times 10^{-7}$ mA^{-1}

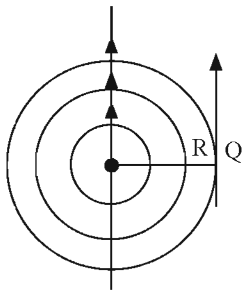


Fig. 6.13

(b) For a loop, magnetic field is given by

$$B = \frac{\mu_0 I}{4r}$$

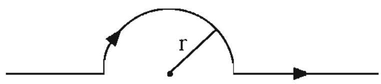


Fig. 6.14

where r is the radius of the loop carrying current

(c) For the solenoid, figure 6.15.

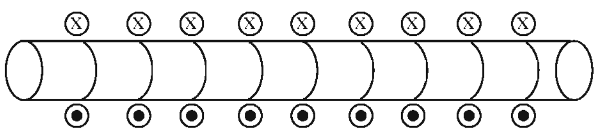


Fig. 6.15

At any point in a solenoid

$$B = \mu_0 nI$$

where n – number of turns per unit length

When two parallel straight current carrying conductors are close to each other as in Fig. 6.16 and the current is flowing in the same direction, the conductors attract one another.

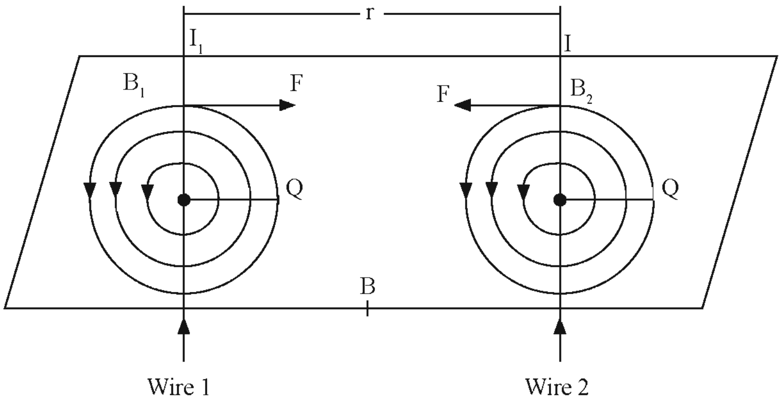


Fig. 6.16: Magnetic field

Force due to current I at a distance r is

$$B_1 = \frac{\mu_0 I_1}{2\pi r}$$

The field is uniform along wire 2 and perpendicular to it, so force F_2 it exerts on the wire 2

$$F = I\,l\,B\sin\theta \quad \text{since } \theta = 90$$

$$F_2 = I_2\,l B_1$$

From Newton's third law of motion $F_1 = -F_2$ and dividing l on both sides.

$$\frac{F}{l} = \frac{\mu_0 I_1 I_2}{2\pi r}$$

Example 6.1

A solenoid of length 2.0 m has radius 1 cm and a total of 100 turns, carries a current of 6A. Calculate magnitude of magnetic field inside the solenoid. If one electron was to move with a speed of 104 m/s along the axis of this current carrying solenoid.

$(\mu_0 = 4 \times 10^{-7}\ \text{mA}^{-1})$

Solution

$$B = \mu_o n I$$

$$= 4\pi \times 10^{-7} \times \frac{100}{2} \times 6$$

$$= 3.768 \times 10^{-4}\ \text{T} \quad \text{(T means Tesla)}$$

Example 6.2

A circular coil is of 100 turns and radius 1 m. If a current of 5A flows through it. Calculate the magnetic field in the coil from a distance of 2 m. (Take $\mu_0 = 4\pi \times 10^{-7}\ \text{mA}^{-1}$

Solution

$$B = \frac{\mu_0}{4\pi} \times \frac{2\pi n I}{r}$$

$$= \frac{4\pi \times 10^{-7}}{4\pi} \times \frac{2\pi \times \frac{100}{2} \times 5}{1}$$

$$= 10\pi \times 50 \times 10^{-7}\ \text{T}$$

$$= 500\pi \times 10^{-7}\ \text{T}$$

Exercise 6.1

Use $\mu_0 = 4\pi \times 10^{-7}$ mA^{-1} in this exercise

1. Fig. 6.14 shows a current-carrying conductor passing between two cardboards. Show the direction of the deflection of each compass on the cardboard.

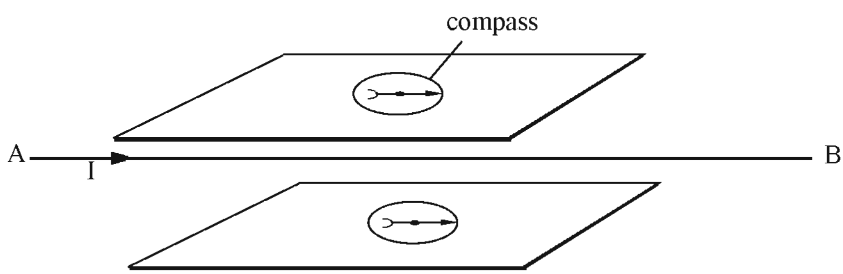


Fig. 6.14

2. State Biot-Savart law.
3. Draw the magnetic field around the following pairs of wires and describe the force between them.

   ⊗ ⊙ (a) ⊗ ⊗ (b) ⊙ ⊙ (c)

4. Calculate the magnetic field from a point from a rod of length 5 m if a current of 12 A flows through it from a distance of 2 m.
5. A circular coil has 200 turns and radius 3 m. If a current of 10 A flows through it, calculate the magnetic field in the coil from a distance of 1 m.

   (Take $\mu_0 = 4\pi \times 10^{-7}$ mA^{-1})

6.6 Force on a current-carrying conductor in a magnetic field (Motor effect)

Activity 6.5: **To demonstrate the force on a current-carrying conductor (motor effect)**

(Work in group)

Materials

- An electric circuit
- Strong magnetic

Steps

1. Arrange the apparatus as shown in Fig. 6.17(a). AB is a flexible wire loosely held between the poles of strong magnets.

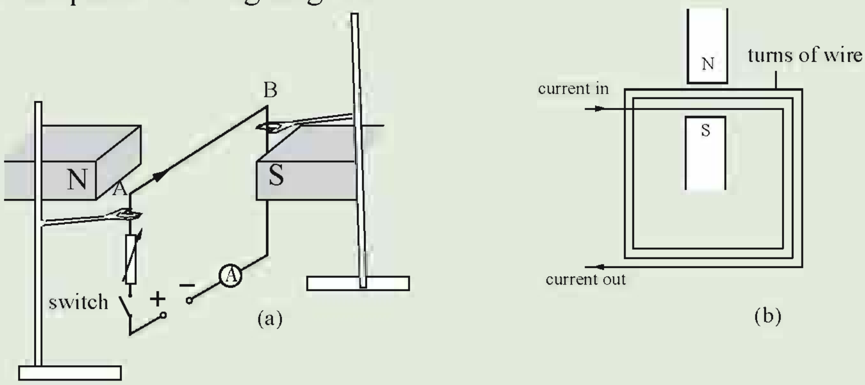


Fig. 6.17: Electric motor effect

2. Close the switch. Observe and explain what happens to the wire.
3. Repeat the activity with a larger current. Observe and explain what happens to the wire.
4. Repeat the activity using stronger magnets but with the same initial current. Observe and explain what happens to the wire.
5. Repeat the activity using two or more turns of wire in the magnetic field carrying the same current in the same direction as shown in Fig. 6.17(b).
6. Repeat the activity with the circuit connection to the battery interchanged and observe what happens.
7. Describe a rule that can be used to determine the direction of the force experienced by a current carrying conductor inside a magnetic field.

The results of the above activity show that a current-carrying conductor placed in a magnetic field experiences a force. This is called the motor effect. The force on the wire *increased* when:

1. the current was increased.
2. stronger magnets were used.
3. the number of turns of the wire in the magnetic field was increased.

When the direction of current is reversed, the wire moves in the opposite direction. When the activity is repeated with the flexible wire AB kept at an angle less than 90° to the magnetic field, the force on the conductor is found to decrease.

The rule of determining the direction of force on a current carrying conductor was proposed by a physicist called *Fleming* using three fingers of the left hand.

The rule states that *when the thumb and the first two fingers of the left hand are held at right angles to each other, the* **F***irst finger points in the direction of the* **F***ield, the se***C***ond finger points in the direction of the* **C***urrent and the* **T***humb points in the direction of the* **T***hrust (or force) on the conductor (Fig. 6.18).*

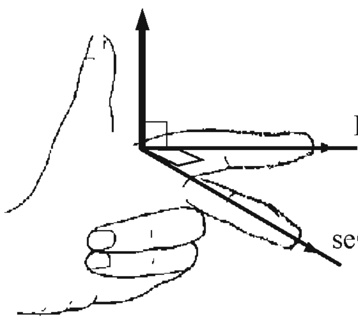


Fig 6.18: Fleming's left hand rule

6.7 Applications of the electric motor effect

Activity 6.6: **To describe the applications of motor effect**

(Work in group)

Materials

- Model of an electric motor or
- Diagram of an electric motor drawn on a manilla paper

Steps

You are provided with a model or a diagram of a simple electric motor by your teacher. (Fig. 6.19).

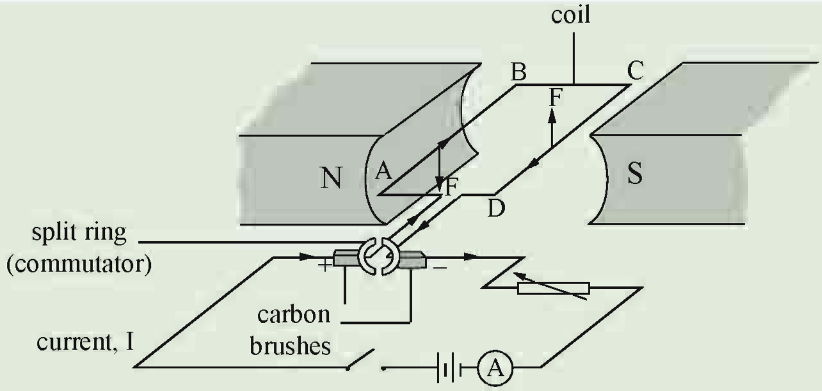


Fig. 6.19: Simple d.c motor.

1. Describe how the motor works by explaining clearly
   (a) The direction of rotation of sides AB and DC in each half cycle.
   (b) The purpose of the commutators and why they are split into 2 halves.
   (c) The purpose of the carbon brushes.
2. Describe how the speed and the force of the rating coil can be incresed.
3. Let one of your group members make a presentation of your discussion to the rest of the class.

Simple d.c electric motor

An electric motor is a device which converts *electrical energy* to *mechanical energy.* Examples of devices which use electric motors include electric drill, vacuum cleaner, electric shaving machine, electric bell, electric fan etc. A simple electric motor consists of a rectangular coil of wire placed between the poles of a strong magnet as shown in Fig. 6.19 in the activity.

The end of each wire is connected to a section of a split ring called the *commutator*. The commutator rotates with the coil. Two *carbon brushes* are fixed just by touching the commutators. Current enters the coil through the brushes.

According to Fleming's left hand rule, wire AB experiences a force downwards while wire CD experiences an upward force. These two equal forces in opposite directions cause the loop ABCD to *rotate* in anticlockwise direction. The commutator reverses the current flow in the coil every half-cycle. This ensures that the coil continues to rotate in the same direction. The motor is found to work faster when

1. the current in the coil is increased.
2. a stronger magnet is used.
3. more turns of the coil of the wire are used.

4. the area of the coil in magnetic field is increased.
5. many coils are used with more split ring parts in many planes.

The moving coil loudspeaker

The moving coil loudspeaker works on the same principle as the earpiece. *It converts electrical energy to sound energy.*

Fig. 6.20 shows the different parts of a moving coil loudspeaker. The turns of the cylindrical coil (voice coil) are at right angles to the magnetic field between the ring pole and the central pole. The coil experiences a force in accordance with Fleming's left hand rule, when a current flows through it. A varying force on the coil (in response to the varying current) causes the paper cone connected to it to move thus producing sound waves which travel through the surrounding air to the ear of the listener.

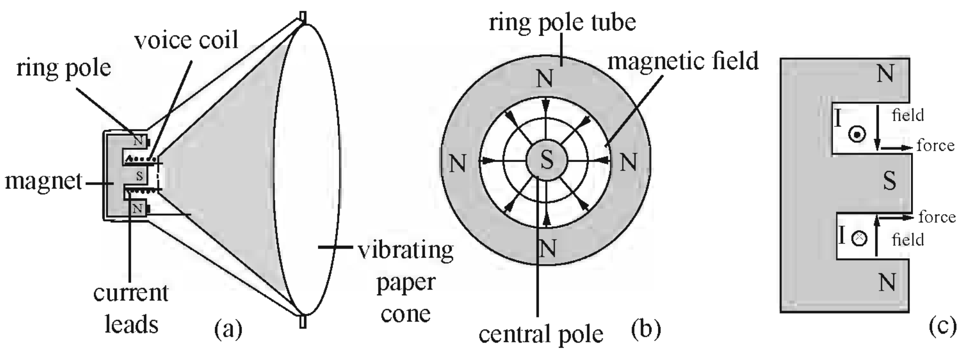


Fig. 6.20: The moving coil loud speaker

Exercise 6.2

1. The three diagrams of Fig. 6.21 show a wire carrying a current, I, in a magnetic field. Copy each diagram and draw an arrow to show the direction of the force F, experienced by the wire.

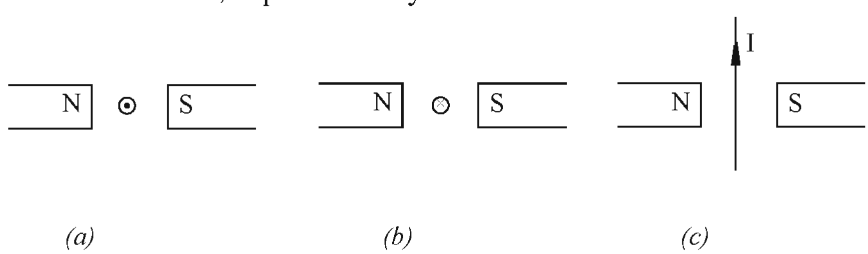


Fig. 6.21

2. Fig. 6.22 shows a loose wire XY placed between the poles of two magnets.From your knowledge of magnetic effect of electric current, suggest a method of making the wire XY taut.

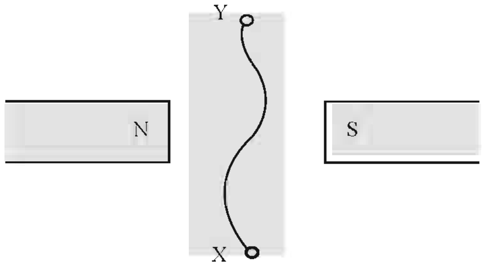


Fig. 6.22

3. (a) State and explain what happens to the conductor PQ when the switch is closed (Fig. 6.23).

   (b) Suggest two methods by which the effect you have explained in part (a) can be increased.

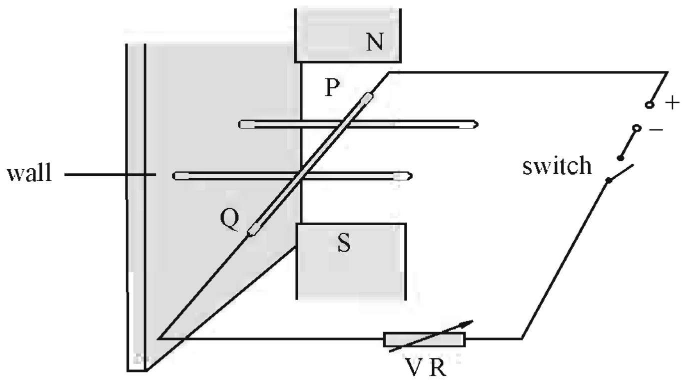


Fig. 6.23

Project 6.1: Construction of an electric motor

Suggested materials:

2 ceramic magnets, an empty match box or a wooden block of the same size, a thick copper wire or a thin metal rod where sellotape is wrapped round one end, about 1-1.5 m insulated copper wire (S.W.G 26/28) where the insulation has been removed from each end (the bare ends to act as *commutators*), a wooden base with 2 vertical supports where the 2 ceramic magnets can be fixed, 2 rings cut-off from a narrow rubber tubing which can fit exactly into the thick copper wire or the thin metal rod, 2 optical pins pierced through, 2 pieces of cork which can act as *brushes* and also as leads to the power supply (3V battery or low voltage supply), 2 thick wires with a dent in the middle (Fig. 6.23) suitably supported as pivots for the coil to rotate freely.

Assembly

- Pierce the thick copper wire or the thin metal rod through the match box and wind about 15 turns of the copper wire around the match box. This is the *coil of motor.*
- Slip the 2 rubber rings onto the end with sellotape. The bare ends of copper wire should pass through the rubber rings so that it is held lightly against the sellotape on the opposite sides of the rod.
- Support the 2 optical pins so that they just touch each end of the bare copper wire.
- Support the match box and rod through it on the 2 dents.
- Slide this assembly in between the 2 ceramic magnets with opposite poles facing each other (Fig. 6.24).

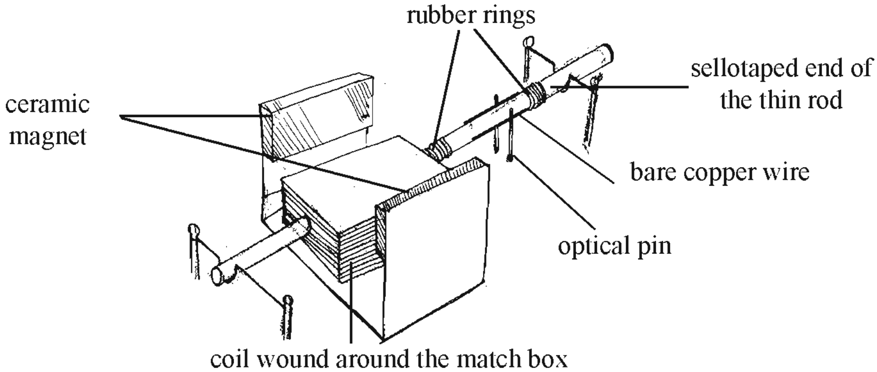


Fig. 6.24: Construction of an electric motor.

- Connect the dc power supply to the ends of the optical pins (underneath) and adjust the plane of the coil to be horizontal, i.e parallel to the magnetic field . Give a slight push to the coil and see the effect.

Topic Summary

- A current-carrying conductor has a magnetic field associated with it.
- The direction of the magnetic field pattern around a current-carrying conductor can be determined using the *right-hand grip rule* or *cork-screw rule*.
- The magnetic field around a current-carrying conductor consists of concentric circles around the conductor.
- The magnetic field due to a solenoid resembles that of a bar magnet. The polarities of the ends of the solenoid can be determined by the direction of current as observed from that end. Clockwise is south (S) and anticlockwise is north (N).
- An electromagnet is a coil of a conducting wire wound on a soft iron core. The strength of the electromagnet is proportional to the size of current in the wire and the number of turns per unit length of the iron core.

- When a current-carrying conductor is placed in a magnetic field it experiences a force. The force experienced is perpendicular to the plane of the field and the current.
- Fleming's left hand rule states that when the thumb, first finger and second finger are held mutually perpendicular with the first finger pointing in the direction of the field while the second finger points in the direction of the current in a conductor then the thumb points in the direction of thrust/force (or motion) experienced by the conductor in the magnetic field.
- An electric motor is a device which uses electrical energy to do work. It uses the principle that a current-carrying conductor in a magnetic field experiences a force. This principle is called the *electric motor effect.*
- The electric bell and the telephone receiver make use of electromagnets.
- A moving coil loud speaker use the electric motor effect.

Topic Test 6

1. Draw the magnetic field pattern due to two isolated straight conductors carrying a current as shown in Fig. 6.25(a) and (b).

Fig. 6.25

2. Mercury is a good conductor of electricity. Fig. 6.26 below shows a wire freely pivoted at point P and just touching the mercury in the bowl. Study the diagram and answer the questions that follow.

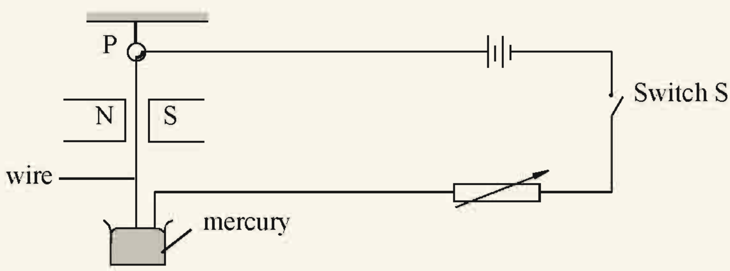


Fig. 6.26

(a) Copy the diagram and on it show the magnetic field pattern when the switch is open.

(b) What will happen to the wire when the switch S is closed?

(c) Describe fully the state of motion of wire when the switch remains closed.

(d) Why should the above experiment be conducted in a fume chamber?

3. Draw and label a diagram of a moving coil loudspeaker. Sketch a front view of the loudspeaker and draw the magnetic field associated with the loudspeaker. Describe how the loudspeaker works.

4. Draw a diagram of a current-carrying solenoid showing clearly the direction of the current in and out of the solenoid. Add the magnetic field pattern associated with the solenoid.

How does the strength of the field depend on

(a) the current in the solenoid?

(b) the number of turns per unit length of the solenoid?

5. Fig. 6.27 below represents a simple electric motor. Study the diagram then answer the questions that follow.

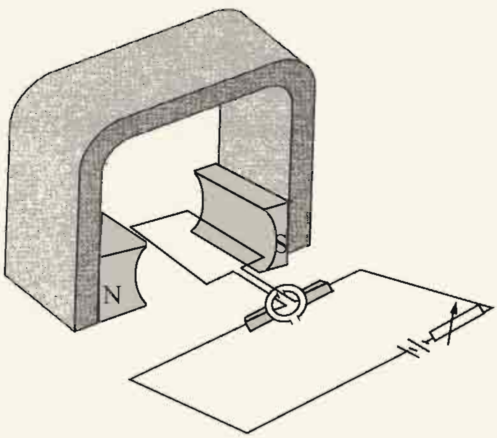


Fig. 6.27

(a) Copy the diagram and label it to show the brushes, commutator, variable resistor, cell and the coil.

(b) Indicate on your diagram the direction of rotation of the coil.

(c) Briefly describe and explain how the motor works specifying clearly the role of the brushes and the commutator.

(d) When viewed from the front the motor can be represented by Fig. 6.28 below. Copy the diagram and draw the magnetic field pattern between the two poles of the magnet.

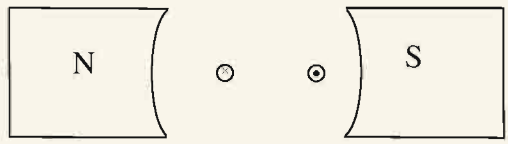


Fig. 6.28

6. Calculate the magnetic field from a point 5 m from a rod of length 10 m if a current of 5A flows through the rod.

TOPIC 7 Electromagnetic Induction

Topic outline

- Demonstrate electromagnetic induction
- Factors affecting the magnitude of induced e,f
- Laws of electromagnetic induction
- Structure and working of transformers
- Types of transformers
- Transformers equation
- Efficiency of a transformer
- Power losses in a real transformer
- Applications of transformers.
- Alternating current generator
- Other application of electromagnetic induction

Introduction

In 1819, Hans Oersted discovered that whenever an electric current flows through a conductor, a magnetic field is produced around it. If such a conductor is placed in a magnetic field, it experiences a magnetic force (motor effect). Can the reverse effect hold true? That is, by moving a coil in a magnetic field, can an electric current be generated? This question was answered by Michael Faraday and Joseph Henry in the year 1831. The two scientists, although working independently, were able to show that an e.m.f can be generated. This method of generating e.m.f is called *electromagnetic induction*. The generated e.m.f is called *induction e.m.f* and hence induced electric current flows in a ciruit. In this unit, we will discuss this concept and apply it in making some devices.

7.1 Demonstrations of electromagnetic induction

The induced e.m.f can be produced in two ways.

(a) Relative movement (generator effect)

The following Activities will help us to understand electromagnetic induction.

Activity 7.1: **To induce an electromotive force in a straight conductor (wire)**

(Work in groups)

Materials

- U-shaped magnet
- Copper wire (Conductor)
- Centre-zero galvanometer

Steps

1. Connect a copper wire XY to a sensitive centre zero galvanometer (Fig. 7.1) Centre zero galvanometer

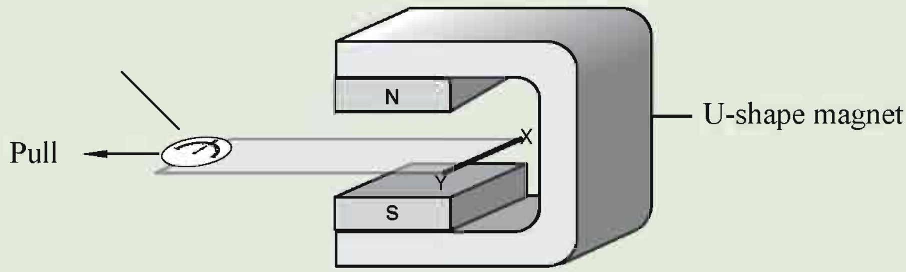


Fig. 7.1: A conductor in between the poles of a U-shaped magnet

2. Place a conductor in between the poles of a magnet as shown in Fig. 7.1 and observe the galvanometer reading when the wire is stationary.
3. Pull the conductor horizontally away from the poles and stop. Observe and explain why happens to the galvanometer pointer deflects.
4. Re-introduce the wire in between the poles of the magnet and stop. Explain why the galvanometer pointer deflects in the direction opposite to that in step 3.
5. Repeat the activity, keeping the wire stationary and moving the magnet. Explain why the galvanometer pointer deflects.
6. Repeat the activity by first moving the wire vertically up and down and then repeat by moving the magnet. Explain why the galvanometer pointer does not deflect.

Consider straight conductor XY connected to a galvanometer and placed in a magnetic field. When the wire is stationary, the pointer does not move. When the wire is being moved out, the pointer shows a deflection in one side (Fig. 7.2 (a)), but returns to the zero position once the wire stops (Fig. 7.2 (b)).

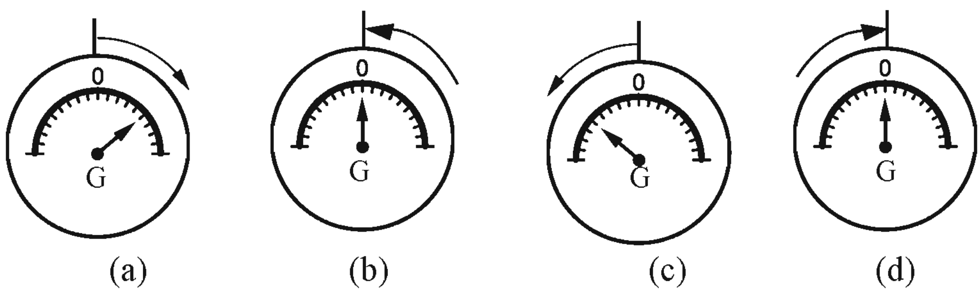


Fig. 7.2: Deflection on a glavanometer

When the conductor is re-introduced in between the poles, the pointer deflects but in the opposite direction (Fig. 7.2 (c)). However, when the conductor stops, the pointer once again returns to the zero position (Fig. 7.2 (d)).

Similar effects are observed when the magnet is moved instead of the conductor. However, no deflection is observed when the wire or the magnet is moved vertically up or down.

From this activity, we can conclude that whenever there is relative motion between a conductor and a magnet, an e.m.f is generated in the conductor. The generated e.m.f. is called induced e.m.f. If the conductor forms a part of circuit in Fig. 7.3 where it is connected to a galvanometer, the e.m.f. produces a current. The current produced is called induced current. This relative motion is such that the wire 'cuts' the magnetic field lines of force (Fig. 7.3).

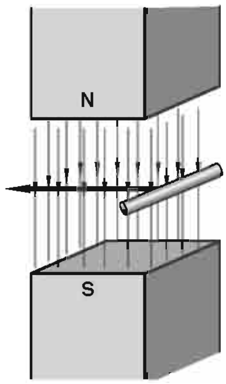


Fig. 7.3: A conductor cutting magnetic field lines of force

This phenomenon we are talking about is called electromagnetic induction.

Activity 7.2: **To induce an electromotive force in a coil using a magnet.**

(Work in pairs)

Materials

- Insulated copper wire
- Bar magnet
- Galvanometer
- Connecting wires

Steps

1. Make a coil using an insulated copper wire.
2. Connect the ends of the coil to a sensitive centre-zero galvanometer. Write down your observations.
3. Introduce a bar magnet into the coil and stop (Fig. 7.4). Explain why the galvanometer pointer deflects.

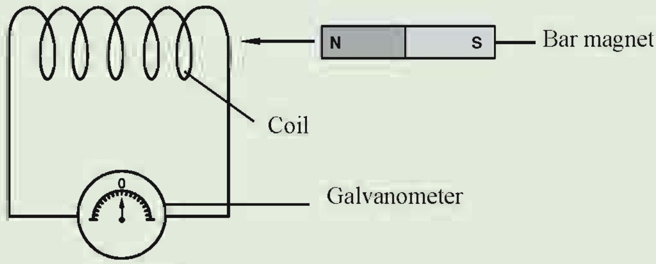


Fig. 7.6: Moving a magnet into a coil

4. Withdraw the magnet from the coil and stop. Write down your observations. Why does the galvanometer deflect in the opposite direction.
5. Repeat the activity by moving the coil and keeping the magnet stationary. Observe and explain what happens to the pointer of the galvanometer in each case.
6. Move both the coil and the magnet in the same direction at the same speed. Explain why there is no deflection by the point.

When the magnet is introduced into the coil, the pointer of the galvanometer shows a deflection in one side but returns to the zero position when the magnet is brought to rest.

When the magnet is withdrawn from the coil, the pointer deflects but in the opposite direction. However, when the magnet stops, the pointer once again returns to the zero position.

Similar effects are observed when the coil moves instead of the magnet.

No deflection is observed when both the coil and the magnet are moved at the same speed in the same direction.

From this activity, we can conclude that an electromotive force is induced whenever there is relative motion between the coil and the magnet hence a current flows in the coil.

(b) Changing a magnetic field (transformer effect)

Activity 7.3: **To induce an electromotive force in a coil using another coil**

(Work in pairs)

Materials

- Insulated copper wire
- Galvanometer
- Connecting wires
- Source of current

Steps:

1. Make two coils using the insulated copper wire. Connect the coils as shown in Fig. 7.5. Keep the coils close together.

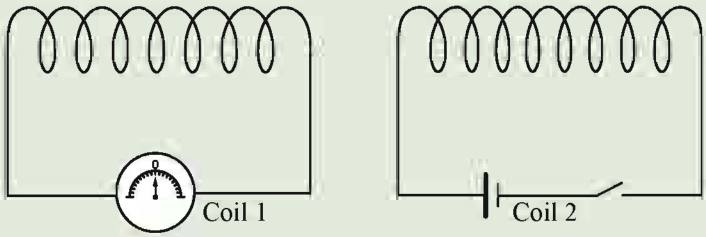


Fig. 7.5: Electromagnetic induction using two coils

2. Swiftly close the switch in coil 2. Explain why pointer of the galvanometer connected to coil deflects yet the two coils are not in contact.
3. Open the switch swiftly. Explain why the galvanometer pointer deflects in the opposite direction the that observed in step 2.

When the switch is closed, the pointer of the galvanometer momentarily deflects to one side but returns to the zero position when the switch is left closed. When the switch is opened, the pointer momentarily deflects again but in the opposite direction. However, when the switch is left open, the pointer once again returns to the zero position.

From this activity, we can conclude that an e.m.f is induced in coil 1 the moment the switch in coil 2 is closed or opened.

Electromagnetic induction is as a result of one of those actions-at-a-distance effects. Michael Faraday explained this action using a model based on magnetic field lines of force. He explained that an electromotive force is induced in a conductor which is a part of a closed loop or circuit when there is a change in the number of magnetic field lines (also known as the strength of magnetic field B) passing through this loop or when the conductor 'cuts' the field lines.

Consider a coil moving away from a magnet as shown in Fig. 7.6.

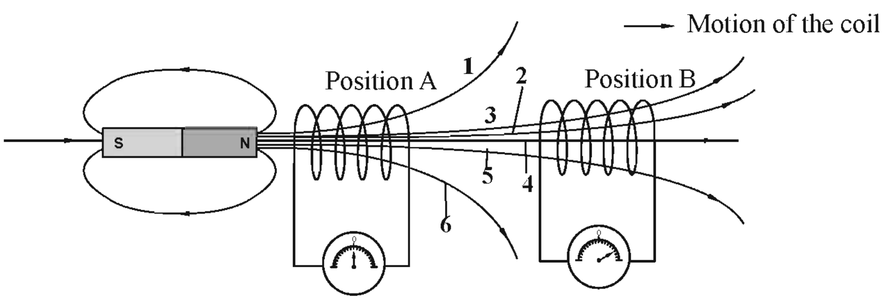
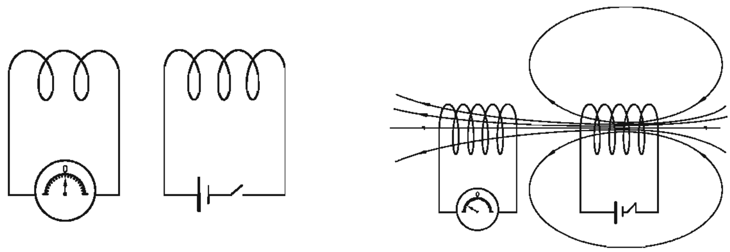


Fig. 7.6: Electromagnetic induction using a magnetic and a coil

The number of magnetic field lines linking or threading the coil decreases from 6 to 4 as the coil is moved from position A to position B. We can also say that the coil cuts two lines as it moves from position A to position B. Similar reasoning may be applied when the magnet is moved away or towards the coil.

In case of switching on and off of the circuit, the fields builds up to a certain strength and reduces to zero respectively as shown in Fig. 7.7.



Number of field lines linking the coil is zero

Number of field lines linking the coil is 4

Fig. 7.7: Building the magnetic field

7.2 Factors affecting the magnitude of emf induced

Activity 7.4: **To investigate factors affecting the magnitude of the induced e.m.f. in a coil**

(Work in groups)

Materials:

- Insulted copper wire
- Galvanometer
- Iron rod
- Bar magnet
- Connecting wires
- Ceramic magnet

Steps

1. Make a coil of a few turns using the insulated copper wire. Connect the coil to a centre-zero galvanometer as shown in Fig. 7.8.

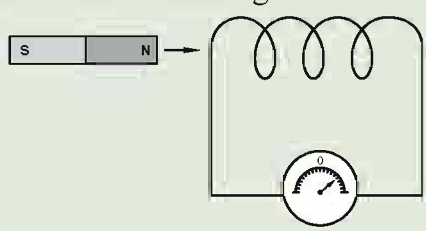


Fig. 7.8: Moving a magnet into a coil at different speed

2. Use the step up and where necessary adjust it accordingly to investigate how the magnitude of induced emf varies with
   (a) the speed at which the magnet approaches the coil.
   (b) number of turns of the coil.
   (c) strength of magnetic field.
   (d) presence of soft iron coil.

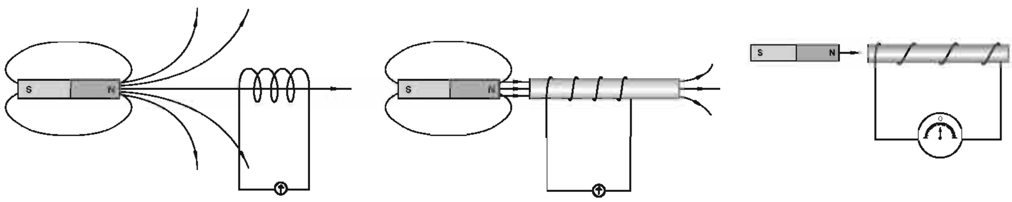
3. Write a brief summary of the results of your investigation.
4. Present your findings to the rest of the class.

The magnitude of the induced electromotive force depends on a number of factors. Before we discuss these factors, we recommend that you refresh your knowledge of quantities and measurements associated with magnetism that we have summarised in Appendix 1 at the end of this book.

When the magnet is slowly introduced into a coil, the induced e.m.f (ε) is less than when the magnet is moved quickly. Same effect will be observed when the coil is moved slowly or quickly towards the magnet.

When a stronger magnet is used, the induced electromotive force increases, . When a coil with more turns is used, the induced emf is found to increase. The induced electromotive force is found to increase when a soft iron core is used.

Fig. 7.9 (a) shows one line of force linking the coils while in (b) there are three lines of force. The soft iron core concentrates the flux lines onto the coil producing a higher rate of change of flux when there is relative movement.



(a) (b) (c)

Fig. 7.9: Inducing an e.m.f using a coil wound on a soft iron core

We can conclude that, *the magnitude of the induced emf is directly proportional to:*

- the strength of magnetic field i.e the stronger the magnet the higher the induced emf.
- the number of turns in the coil i.e. the more turns the higher the induced emf.
- the induced emf is much higher in the presence of a soft iron core.
- Area of the coil.
- The rate (speed) of cutting the magnetic flux.

7.3 Laws of electromagnetic induction

Activity 7.5: **To state the laws of electromagnetic induction**

(Work in pairs)

Materials

- Magnet
- Centre-zero-galvanometer
- Insulated copper wire
- Connecting wires

Steps

1. Conduct a research from the Internet and reference books on the following laws of electromagnetic induction:
   (a) Lenz's law (b) Fleming's right hand rule
   (c) Faraday's law
2. Repeat activity 7.2 steps 3 and 4. Explain how Lenz's law is confirmed in the observation you make.
3. Relook at the observations you made in activity 7.4 steps 2 to 6. Explain how each observation confirms the Farady's law of electromagnetic induction.
4. Make a presentation to the class.

7.3.1 Lenz's law

When an electromotive force is induced in a circuit, a current flows in the circuit. What is the direction of the induced current?

Consider a magnet moving towards or away from a coil as shown in Fig. 7.10 (a) and (b).

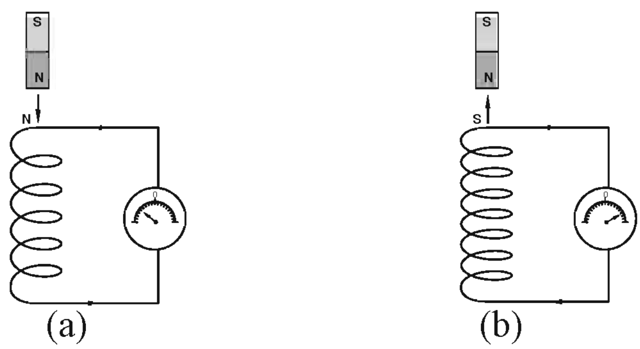


Fig. 7.10: Direction of the induced electromotive force

When a north pole is moved towards a coil, the current flows in such a way as to oppose the introduction of the north pole. A north pole (N) is therefore induced at the top end of the coil to repel the incoming north pole of the magnet. Similarly a south pole is induced at the top end of the coil to resist the withdrawal of north pole of the magnet.

The direction of the induced current can be determined using a law that was developed by a German scientist called Lenz.

Lenz's law states that *the direction of the induced current is such that it opposes the change producing it.*

7.3.2 Fleming's right hand rule

In case of straight conductors moving in a magnetic field, Fleming's right hand rule gives the relationships between the directions of the field motion and induced current.

It states that,

If the thumb and first two fingers of the right hand are mutually perpendicular to each other, the First finger pointing in the direction of the Field and the thuMb in the direction of Motion of the conductor, then the seCond finger points in the direction of the induced Current see Fig. 7.11.

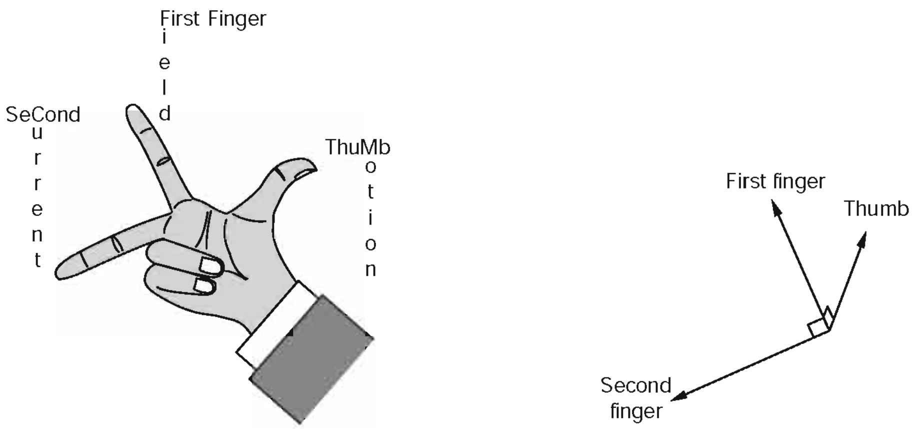


Fig. 7.11: Fleming's right hand rule

7.3.3 Faraday's law

The factors affecting the magnitude of the induced electromotive force were summarised by Michael Faraday in what is known as **Faraday's law of electromagnetic induction.**

The law states that; *the electromotive force induced in a conductor is directly proportional to the rate at of change of the magnetic flux linked to the conductor*

Exercise 7.1

1. Describe an experiment to illustrate electromagnetic induction.
2. State the two laws of electromagnetic induction.
3. Describe an experiment to demonstrate Faraday's law of electromagnetic induction.

4. A long bar magnet is pushed into a coil with many turns as shown in Fig. 7.12.

(a) What happens to the needle of the centre-zero-galvanometer when the magnet;

(i) slowly enters the coil,

(ii) remains at rest inside the coil,

(iii) is rapidly withdrawn.

(b) Explain

(i) why the magnet has to be long.

(ii) why the coil has to have many turns.

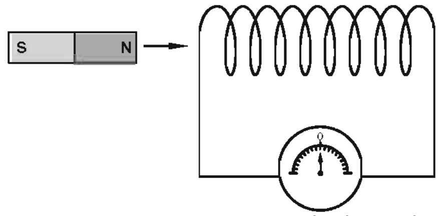


Fig. 7.12: Bar magnet pushed into the coil

5. Explain the following terms:

(a) Electromagnetic induction.

(b) Induced electromotive force.

(c) Induced current.

6. Explain how to determine the direction of the induced current in a coil, when a magnet moves into the coil.

7. Describe energy conversions during the process of electromagnetic induction in:

(a) A coil using a bar magnet.

(b) A coil using another coil carrying a current.

8. Two coils are placed near each other as shown in Fig. 7.13.

(a) What happens to the needle of the galvanometer

(i) On closing the switch?

(ii) If the switch is kept closed?

(iii) On opening the switch?

(b) Give three possible ways of increasing the deflection in the galvanometer.

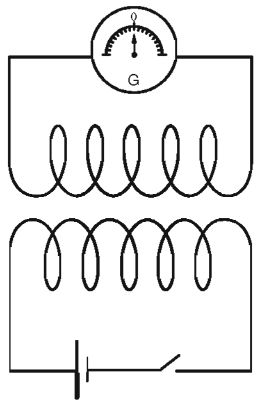


Fig. 7.13

9. Fig. 7.14 shows a straight copper wire between the poles of a magnet.

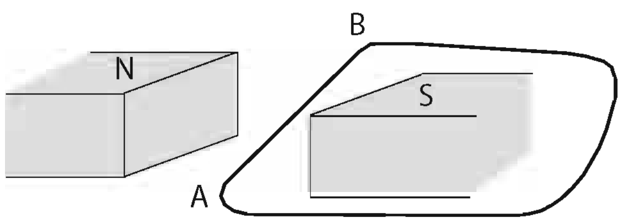


Fig. 7.14: Conductor-carrying current in a magnetic field

(a) If the wire AB is abruptly moved upwards in which direction will current be induced in it?

(b) What is the effect of

(i) reversing the direction of movement of wire?

(ii) reversing the magnetic field?

(iii) reversing the field and direction of movement of wire at the same time?

7.4 Transformers

7.4.1 Structure and working of a transformer

Activity 7.6: **To describe the structure and working of a transformers**

(Work in groups)

Materials

- Internet
- Reference books
- Transformer in the school or near your school

Steps

1. Using a simple drawing, discuss the architecture of a transformer and how it functions.
2. Explain how the stepping up or down of voltage is achieved by the transformer yet without contradicting the principle of conservation of energy between the input and output coils.
3. By making reference to your observations in activity 7.3, explain how a transformer works.
4. Describe how energy lossess in a transformer are reduced.
5. Present your report to the whole class through your secretary.

A transformer is an electric device that transfers electrical energy from one circuit to another by electromagnetic induction. In transferring this energy, a transformer steps up or steps down the voltage or electromotive force from the source.

A simple transformer consists of two coils insulated from each other and wound on the same soft-iron core. One coil contains a few turns of thick wire and the other coil contains many turns of thin wire. The coil that is connected to *a.c* mains is called the *primary coil (p)* while the one through which the stepped up or stepped down electrical current output is delivered to the outer circuit is called the *secondary coil (s)*.

Fig 7.15 shows the structure of a transformer in which P is the primary coil and S is the secondary coil.

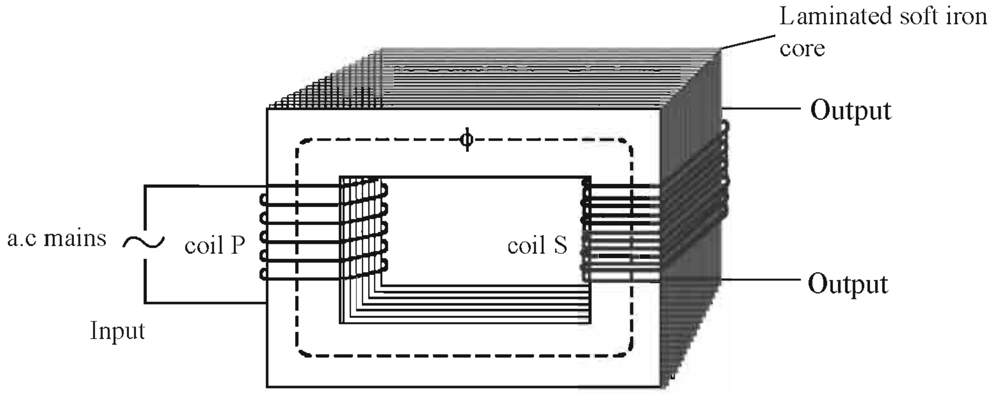


Fig. 7.15: The structure of a transformer

In Activity 7.3, you must have observed that by switching the current on and off in one coil, an electromotive force is induced in another coil. The circuit that induces the electromotive force is called the *primary circuit*, while the circuit where the electromotive force is induced is called the *secondary circuit*. Although the two coils are not connected, changes in current in the primary circuit induces an electromotive force in the secondary circuit.

This effect is called **mutual induction**. Mutual induction occurs on switching the current on and off in the primary circuit. The switching on and off of the current can also be achieved by replacing the battery and the switch with an a.c power supply as shown in Fig. 7.16 (a). Fig. 7.16 (b) shows how the induced current varies with time.

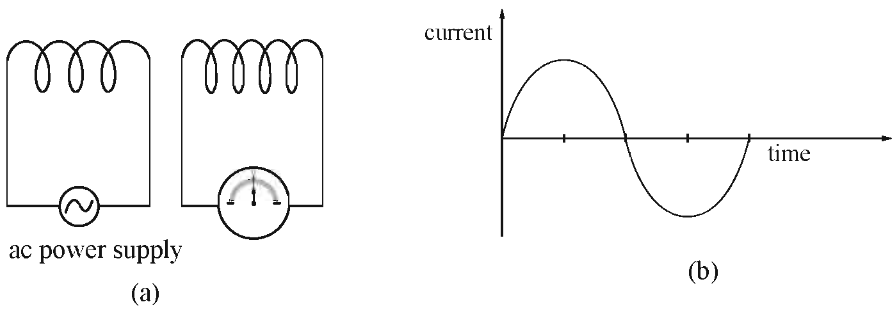


Fig. 7.16: Inducing a current by mutual induction

The mutual induction is more pronounced when the two coils are wound round a soft iron core. This was shown by Michael Faraday who used a soft iron ring as shown in Fig. 7.17.

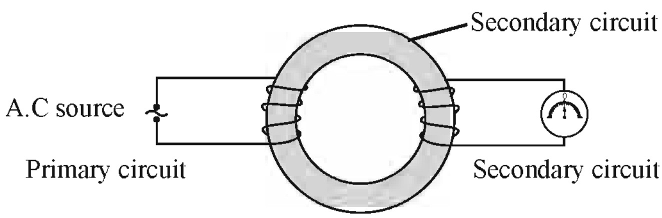


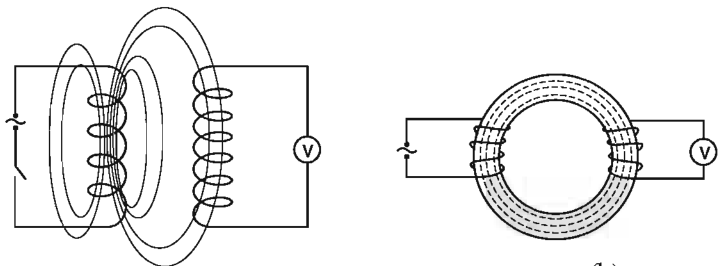
Fig. 7.17: Faraday's ring

The magnitude of e.m.f induced in the secondary coils also depends on the ratio of the number of turns of secondary to primary coils.

Explaining mutual induction

An electric current creates a magnetic field around the conductor through which it flows. When the current is switched on and off in the primary coil, the strength of the field (magnetic flux) keeps changing from zero to maximum and back to zero (alternating current does this automatically without being switched on and off as it fluctuates from zero to maximum). The change in magnetic flux induces a current in the secondary coil in a way that this current tends to oppose the current in the primary coil, and also fluctuates from zero to maximum. Thus, an a.c input in the primary coil induces an a.c output in the secondary coil (Fig. 7.18 (a). Thus, the change in the number of magnetic field lines threading the primary coil induces an electromotive force in the secondary coil in an opposite direction in accordance with Lenz's law as shown on Fig. 7.18 (a)).

Soft iron core increases the induced e.m.f because it can easily be magnetised and easily be demagnetised. Soft iron also helps to concentrate the magnetic field lines in the secondary coil (Fig. 7.18 (b)). The induced electromotive force in the secondary circuit has the same frequency as the electromotive force in the primary circuit.



(a) (b)

Fig. 7.18: Effects of soft iron core on the number of field lines threading the secondary coil

7.4.2 Types of transformers

Activity 7.7: **To describe types of transformer and their uses**

(Work in groups)

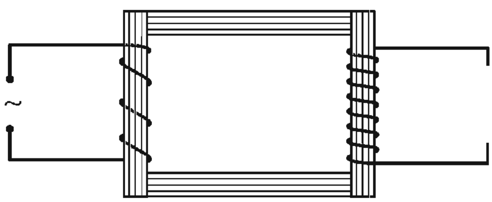
Materials

- A transformer within or near the school compound
- Internet
- Reference books

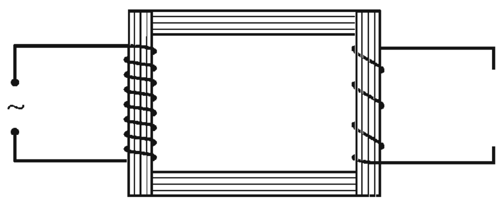
Steps

1. Identify a transformer in or near your school. Move close to it. What type of transformer it is? How many types do you know? Name them and sketch their symbols.
2. Describe some causes of transformer failures..
3. Now do a research on types and uses of transformers.
4. Discuss your findings with your group members.

There are two types of transformers, namely, the *step-up* and the *step-down transformers*. In a step-up transformer, the number of turns in the secondary coil N_s is more than the number of turns in the primary coil N_p (Fig. 7.19 (a)), while in a step-down transformer, the number of turns in the secondary coil is less than the number of turns in the primary coil (Fig.7.19 (b)). Fig. 7.19 (c) shows a commercial step-down transformer.



(a) Step-up transformer



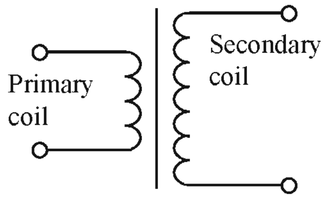
(b) Step-down transformer

(c) A commercial step-down transformer

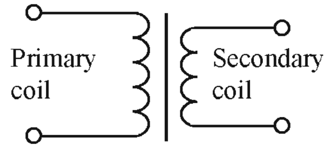
Fig. 7.19: Types of transformers

The terms, step-up and step-down, apply to output voltages of the transformer. When an alternating electromotive force is applied to the primary coil, a changing magnetic field is produced. The soft iron core links this field to the secondary coil. This alternating field produces an alternating electromotive force in the secondary coil through mutual induction.

Fig. 7.20 shows the circuit symbols for the step-up and step-down of transformers.



(a) Step-up transformer



(b) Step-down transformer

Fig. 7.20: Circuit symbols for transformers

A transformer may have more than one secondary coil. Fig. 7.21 shows a transformer with two coils in the secondary circuit. Such transformers can step-up and step-down voltages simultaneously.

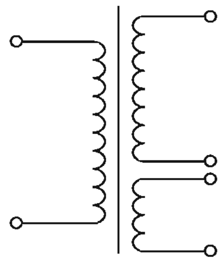


Fig. 7.21: A transformer with two coils in the secondary circuit

7.4.3 Transformer equations

Activity 7.8: **To investigate the relationship between number of coils and the induced e.m.f**

(Work in groups)

Materials

- Connecting wires
- Galvanometer
- Switch
- Insulated copper wire
- Source of current

Steps

1. Make two coils (one with more turns than the other) using the insulated copper wire.
2. Connect one coils to the galvanometer and the other coil to the source of current and the switch as shown in Fig. 7.22.

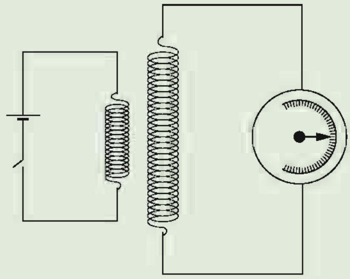


Fig. 7.22: Transformer connected to a galvanometer

3. Bring the two coils close to each other.
4. Close the switch. What do you notice on the pointer of the galvanometer? Record down the reading indicated by the galvanometer.
5. Repeat stops 1 to 4 with the galvanometer on the coil with lesser turns.
6. Compare the reading obtained in steps 4 and 5. Which one is larger? Explain.
7. Now discuss in your groups the relationship between the number of turns of the coil and the magnitude of the emf produced.

Table 7.1 shows the results obtained in a similar activity.

Table 7.1

Primary e.m.f (ε_p) (V)	Turns in the primary coil N_p	Turns in the Secondary coil N_s	$\frac{N_S}{N_P}$	Deflection of the galvanometer
1.5	10	5	0.5	Small
1.5	20	5	0.25	Smaller
1.5	30	5	0.17	Smaller
1.5	10	10	10	High
1.5	10	20	2.0	Higher
1.5	10	30	3.0	Higher

From the activity, we can conclude that the magnitude of the induced electromotive force in the secondary circuit is directly proportional to the ratio of the number of turns of coils used.

Let V_P and V_S represent the voltage in the primary coil and secondary coils respectively.

N_P and N_S represent the number of coils in the primary and secondary coils respectively.

Electromotive force induced in the secondary circuit (ε_s) α $\frac{\text{Number of turns in secondary coil, } N_S}{\text{Number of turns in primary coil, } N_p}$

$$\text{i.e } \varepsilon_s \, \alpha \, \frac{N_s}{N_p}$$

When the experiment is done using an a.c power supply, it can be shown that

$$\frac{\text{Secondary e.m.f}, V_s}{\text{Primary e.m.f}, V_p} = \frac{\text{Number of turns in secondary coil}, N_S}{\text{Number of turns in primary coil}, N_p}$$

$$\frac{V_s}{V_p} = \frac{N_s}{N_p}$$

In an ideal case (no power loss), the electric power (P = VI) in the primary coil is equal to that in the secondary. Thus, when the voltage is stepped up, the current is stepped down and vice versa.

Hence in such a case,

$$\frac{I_s}{I_p} = \frac{N_p}{N_s}$$

Noted that, the e.m.f induced in the secondary coil is maximum when the two coils are close together and when wound on a soft iron core.

When the emf in the transformer is maximized, it is transmitted to different places through cables. Among the many risks involves when transmitting high voltage include electric shock incase the poles collapse and fire outbreak on structures and vegetation.

7.4.4 Efficiency of a transformer

As mentioned earlier, a transformer transfers electrical energy from one circuit to the other. The energy per second, supplied to the primary coil is called the power input, while the energy obtained per second from the secondary coil is the power output. In an ideal transformer, the power output is equal to power input. The term efficiency is used to indicate how effective a transformer is in transferring the input energy to output energy.

The efficiency of a transformer is the ratio of the power output to power input expressed as a percentage.

$$\text{Efficiency} = \frac{\text{power output}}{\text{power input}} \times 100\%$$

The term *efficiency* is used to indicate how effective a transformer is in transferring the input energy to output energy.

Well designed practical transformers often have efficiency as high as 98%.

For an ideal transformer power output = power input (efficiency 100%)

$$\text{Efficiency} = \frac{\text{power output}}{\text{power input}} \times 100\% = 100\%$$

power input $= V_p I_p$; power output $= V_s I_s$

$$V_p I_p = V_s I_s;$$

$$\therefore \quad \frac{V_s}{V_p} = \frac{I_p}{I_s} \quad \text{.....................} (2)$$

Where I_p and I_s are the current in primary coil and in secondary coil respectively. Hence from the equation (1) & (2) we obtain:

$$\frac{V_s}{V_p} = \frac{I_P}{I_S} = \frac{N_s}{N_p}$$

And $N_pI_p = N_sI_s$ .... (3)

Equations 2 and 3 can be used to calculate the current in transformers coils.

Be Safe!
Note that a transformer can be disastrous if tampered with. It can cause fire on premises and surrounding vegetation. Do not tamper with a transformer in your places.

Example 7.1

An alternating electromotive force of 240 V is applied to a step-up transformer having 200 turns on its primary coil and 4 000 turns on its secondary coil. The secondary current is 0.2 A. Calculate the

(a) (i) Secondary electromotive force. (ii) Primary current.
(iii) Power input. (iv) Efficiency.
(b) Comment on the answer to (iv).

Solution

(a) (i) $\frac{V_s}{V_p} = \frac{N_s}{N_p}$

$$V_s = \frac{V_p \times N_s}{N_p}$$

$$= \frac{240 \times 4\,000}{200}$$

$$= 4\,800 \text{ V}$$

(ii) $\frac{I_s}{I_p} = \frac{N_p}{N_s}$

$$I_p = \frac{N_s \times I_s}{N_p}$$

$$= \frac{4\,000 \times 0.2}{200}$$

$$= 4.0 \text{ A}$$

(iii) Power input $= I_p \times V_p$

$$= 4 \times 240$$

$$= 960 \text{ W}$$

(iv) efficiency $= \frac{\text{Power output}}{\text{Power input}} \times 100\%$

$$= \frac{I_S \times V_S}{960} \times 100\%$$

$$= \frac{0.2 \times 4800}{960} \times 100\%$$

$$= 100\%$$

(b) Since the efficiency of this transformer is 100%, then it is an ideal transformer.

Example 7.2

A step-down transformer is connected to a 240 V alternating current power supply. The primary coil has 1000 turns. How many turns should the secondary coil have so as to operate a 12 V alternating current toy car?

Solution

$$\frac{V_s}{V_p} = \frac{N_s}{N_p} \Leftrightarrow \frac{12}{240} = \frac{N_s}{1000} \Rightarrow N_s = 50 \text{ turns}$$

Example 7.3

A transformer has an input coil of 60 turns. When this coil connected to a 240 V source, the output voltage is found to be 4 800 V. The output power is 3 600 W.

(a) Calculate the number of turns in the output coil.

(b) If the efficiency of the transformer is 80%, calculate the

(i) output current

(ii) input current.

Solution

(a) $N_p = 60$; $V_p = 240$ V; $V_s = 4800$ V; $N_s = ?$

$$\frac{V_s}{V_p} = \frac{N_s}{N_p} \Rightarrow \frac{4\,800}{240} = \frac{N_s}{60} \quad N_s = \frac{4\,800 \times 60}{240}$$

$$= 1\,200 \text{ turns}$$

(b) (i) $P_o = V_s I_s$

$$3\,600 = 4\,800\, I_s \Rightarrow I_s = \frac{3\,600}{4\,800}$$

$$= 0.75 \text{ A}$$

(ii) $$\text{Efficiency (E)} = \frac{P_o}{P_i} \times 100\% = \frac{V_s I_s}{V_p I_p} \times 100\%$$

$$80 = \frac{4\,800 \times 0.75}{240 \times I_p} \times 100\%$$

$$= \frac{360\,000}{240 I_p} \times 100\%$$

$$I_p = \frac{360\,000}{240 \times 80} = 18.75 \text{ A}$$

Example 7.4

An ideal transformer is used to operate a 16 V, 48 W lamp from a 240 V mains supply. Its primary coil has 450 turns.

(a) Draw a well labelled sketch of the transformer.

(b) How many turns does the transformer have in its secondary coil?

(c) How much current is flowing in the primary coil?

Solution

(a)

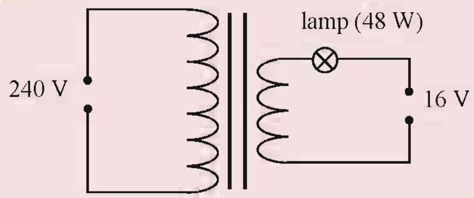


Fig. 7.23

(b) $N_p = 450; V_p = 240\text{ V}; \ V_s = 16\text{ V}; N_s = ?$

$$\frac{V_s}{V_p} = \frac{N_s}{N_p} \Rightarrow \frac{16}{240} = \frac{N_s}{450}$$

$$N_s = \frac{450 \times 16}{240}$$

$$= 30 \text{ turns}$$

The current flowing in the mains is given by.

$$Is = \frac{P}{V} = \frac{48\text{ W}}{16\text{ V}} = 3\text{A}$$

(c) For an ideal transformer, $\frac{N_s}{N_p} = \frac{I_p}{I_s} \Rightarrow \frac{30}{240} = \frac{I_p}{I_s}$.

Hence $I_p = \frac{30 \times 3\text{ A}}{450} = 0.2\text{ A}$

7.4.5 Power losses in a real transformer

Activity 7.9: **To find out the factors that contribute to power losses in a transformer**

(Work in groups)

Materials

- Internet
- Reference books

Steps

1. In groups, suggest and explain some of the factors that contribute to power loss in a transformer.

2. Now conduct a research from the internet and reference books on factors that contribute to the loss of power in a transformer. Compare them with the ones you suggested in step 1. How right were you?
3. In your research, also find out the application of transformers.
4. Give a presentation on your finding to the whole class through your group secretary.

The energy supplied in the primary circuit of a transformer is lost in a number of ways. The following factors contribute to the overall power loss and therefore affects the efficiency of a real transformer.

1. Resistance of the coils

As the current flows in the coils, the wires heat up and energy is lost in form of heat.

$$\text{Energy lost} = I^2 \times R \times t$$

This method of losing energy is called *joule-heating*.

To *minimise energy loss* in this way, *thick copper wires of low resistance are used* where large currents are to be carried.

2. Eddy currents

When the magnetic field changes, small amount of current called *eddy currents*, are induced in the core of the transformer. This heats up the core and *energy is lost in form of heat.*

To *minimise this loss of energy*, *the core is laminated and insulated between the laminations*. This reduces the magnitude of the eddy currents.

3. Hysteresis losses

The magnetisation and demagnetisation of the core by the alternating magnetic field requires energy. This energy heats up the core and is lost as heat energy. This method of losing energy is called *hysteresis loss*.

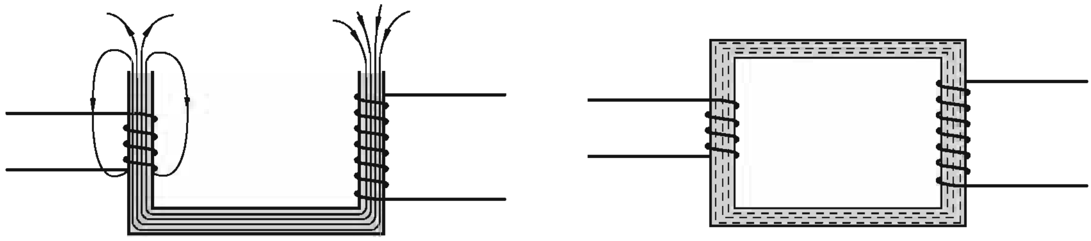
To *minimise this loss of energy*, the *core is made of a soft magnetic material that is easy to magnetise* and demagnetise e.g. soft iron.

4. Flux or magnetic leakage

Not all the magnetic field lines of force due to the primary coil may link the secondary coil resulting in what is called *flux leakage as shown on* Fig. 7.24 (a)).

To *reduce this loss*, the *core is designed in such a way that almost all the magnetic effect due to the primary coil is transferred to the secondary* coil e.g. using a loop.

(Fig. 7.24 (b)).



(a) Incomplete core (b) Complete core (loop)

Fig. 7.24: Magnetic or flux leakage

Since it is not possible to completely reduce energy losses in transformers, very large transformers are *oil-cooled* to reduce *overheating otherwise* they have the potential to cause massive destruction to the surroundings.

7.4.6 Applications of transformers

1. **Transformers are used in electric power transmission Grid systems to step-up or down voltage and current.**

Electric power is usually transmitted over long distances at very high voltage e.g 11 000 V and at low current to minimize power loss due to internal heating (I^2R).

Transformers are used to step-up voltage at the power station and step-down e.g 240 V for use in a home.

2. **Transformers are used in electric welding**

Electrical welding machines use electricity at high current to melt metals.

For example, a transformer with 800 turns in the secondary coil and only 5 turns as primary, steps-up current in the ratio of 160:1. In a perfect transformer (step-up), the current is stepped up in the same ratio. A current of 1 A in the primary might give a current of 160 A in the secondary. This large current heats the metal until it melts. The current can be used to weld two metals together.

Exercise 7.2

1. **(a)** Name two type of transformers.
   (b) Explain the structure of each type of transformer.
   (c) Describe the working principle of transformers.

2. A student designed a transformer to supply a current of 10 A at a potential difference of 60 V. If the efficiency of the transformer is 80% the mains supply voltage is 250 V, calculate

   (a) The power supplied to the transformer.

   (b) The current in the primary coil.

3. Describe the energy changes in a transformer.

4. Give two factors that affect the efficiency of a transformer.

5. Fig. 7.25 shows a transformer with 400 turns in the primary coil and 1000 turns in the secondary coil.

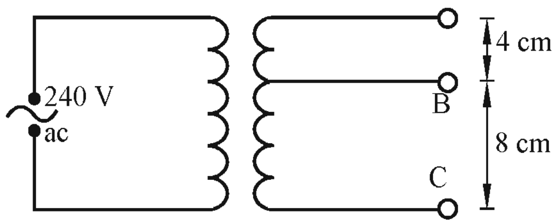


Fig. 7.25

   (a) What type of transformer is it?

   (b) Find the potential difference across BC.

   (c) What assumption(s) have you made?

6. A transformer is used to operate a 9 V ac shaving machine (Fig. 7.26).

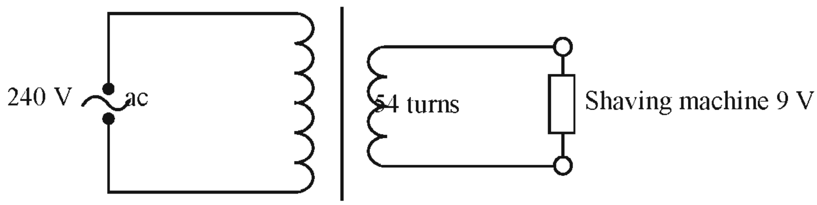


Fig. 7.26

   (a) Explain why the primary coils should be made of thicker wire than that of the secondary coils.

   (b) How many turns are there in the primary coil?

   (c) Explain what would happen to the transformer if a 240 V dc power supply is used instead of 240 V mains.

   (d) What happens to the primary current when the machine is being used?

7. A step-down transformer has a primary coil with 800 turns and secondary coil with 100 turns. The primary coil is connected to 240 V supply.

   (a) Find the voltage output.

   (b) If the transformer has a primary current of 0.10 A and of secondary 0.72 A, calculate its efficiency.

7.5 Other applications of electromagnetic induction

Activity 7.10: **To observe and describe the applications of electromagnetic induction**

(Work in groups)

Materials

- Model of a.c generator
- Diagram of an a.c. generator drawn on manila paper

Steps

1. With the help of a.c generator or diagram model provided by your teacher, describe the working of an a.c generator.

   In the description, explain clearly

   (a) the purpose of the slip rings and carbon brushes.

   (b) how the inversion of the signal is achieved in the generation. Sketch the output signal.

   (c) how the voltage output in an operational a.c. generator is increased.
2. With a well labelled diagram, explain how the concept of electromagnetic induction is applied in the working of a microphone.
3. Let one of your group members make presentation.

(a) Alternating current (a.c) generator

Structure of a simple a.c generator

Fig. 7.27 shows a diagram of a simple a.c generator.

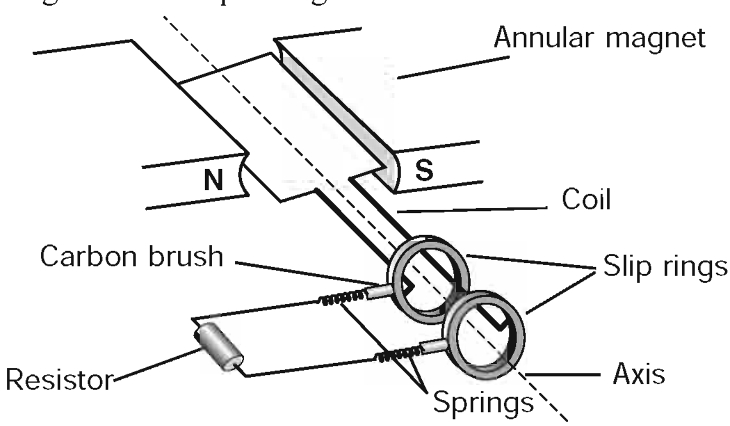
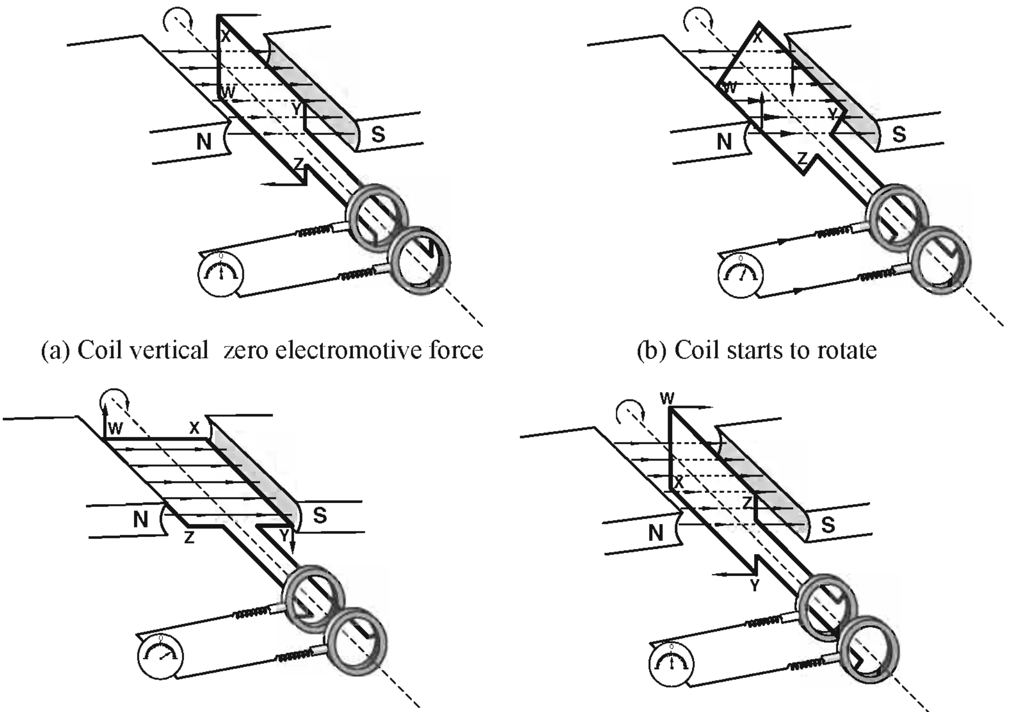


Fig. 7.27: A simple ac generator

The generator consists of a rectangular coil of conductor wire whose ends are connected to two slip rings. The slip rings make contact with carbon brushes which connect them to an external circuit. Two light springs are used to make the carbon brush press lightly on the slip rings thus making a good contact between the carbon brushes and the slip rings. The coil is placed in between two poles of a permanent magnet. The poles are annular in shape so as to concentrate the magnetic field lines on the coil.

Working of simple a.c generator

When the coil is rotated about its axis, an electromotive force is induced depending on the position of the coil. Let us start with the coil in a vertical position as shown in Fig. 7.28 (a). In this vertical position the wires XY and WZ are moving along the magnetic field lines. The wires are therefore not cutting the magnetic field lines resulting in no electromotive force being produced (Fig. 7.28(a)). As the coil is rotated from this position, it starts to cut across the magnetic field lines of force and an electromotive force is induced (Fig. 7.28 (b)). During the first quarter of rotation, the induced e.m.f increases from zero to a maximum value (peak value) when the coil becomes horizontal Fig. 7.28(c)). During the second quarter of rotation the induced electromotive force reduces and reaches zero again when the coil is in vertical position (Fig. 7.28(d)).



(a) Coil vertical zero electromotive force

(b) Coil starts to rotate

(c) Coil horizontal electromotive force is maximum

(d) Coil vertical zero electromotive force

Fig. 7.28: Working of a simple generator

The induced e.m.f sets up a potential difference between the ends of the coil which are connected to the two slip rings mounted on the axle on which the coil rotates. This potential difference drives the current in the external circuit. This process is repeated in the third and fourth quarter of rotation. However, the direction of the current in the coil changes. The direction of the induced current can be determined by Fleming's right hand rule. In the first half of rotation the side XY is moving down. The current therefore flows from X to Y and from Z to W. During the second half of rotation, XY is moving up and so the current flows from Y to X and from W to Z (Fig. 7.29).

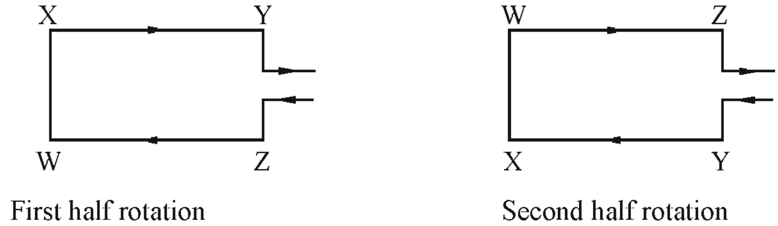


Fig. 7.29: Set-up showing the rotation of coil

The current changes direction after every half a rotation (cycle). Fig. 7.30 shows how the current in the external circuit changes with the position of the coil. The coil produces an electromotive force that changes in a manner similar to a sine curve.

This shows that the cutting of the magnetic lines of force is greatest whenever the coil passes through its horizontal position. In this position, the induced electromotive force is maximum. The current flows in the circuit, first in one direction and then in the opposite direction. A current that flows back and forth in a circuit is called an *alternating current*. The number of cycles it completes in one second is known as the *frequency of the alternating current* and is measured in hertz (Hz).

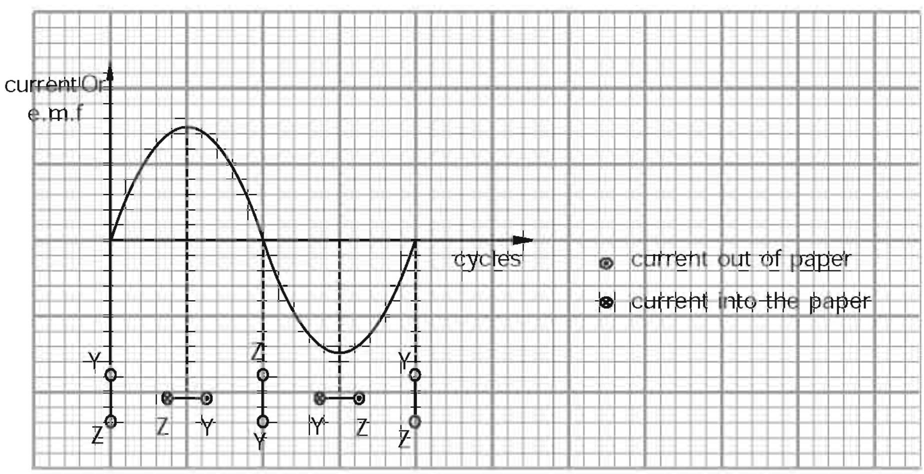


Fig. 7.30: Variation of current or e.m.f with coil positions

(b) Induction coil

An induction coil consists of two coils (secondary and primary coils) with one wound over the other around a soft iron core. The secondary coil has a greater number of turns (Fig. 7.31).

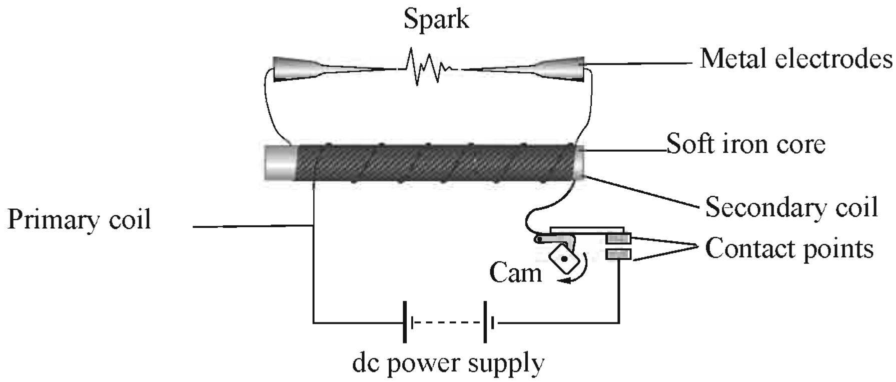


Fig. 7.31: Induction coil

An induction coil works like a step-up transformer but with a d.c power supply. The direct current in the primary coil is switched on and off by a rotating cam. The current in the primary coil produces a changing magnetic field which in turn induces an electromotive force in the secondary coil.

Due to the large number of turns in the secondary coil and the rapid change of current in the primary coil, a large potential difference is induced between the metal electrodes. This large potential difference causes a spark between the metal electrodes. This spark may be used in many ways. For example, the spark produced is used in igniting the petrol-air mixture inside a car's engine.

(c) Moving coil microphone

A moving coil microphone is a device for changing sound energy into electrical energy. It consists of a diaphragm with a light coil connected to it. This coil is placed in between two poles of a strong cylindrical pot magnet as shown on Fig. 7.32.

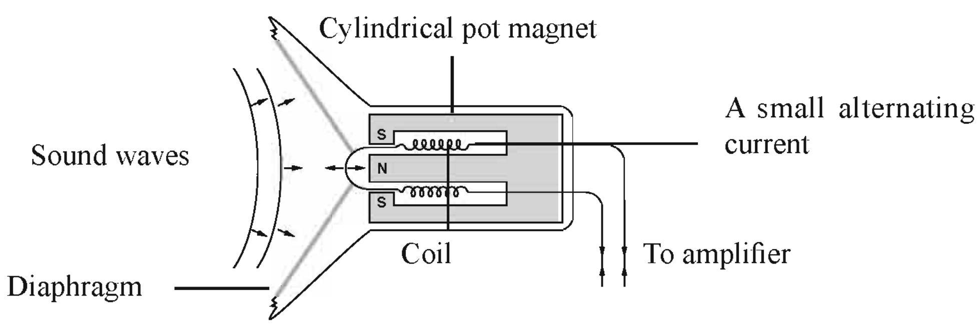


Fig. 7.32: A moving coil microphone

When a person speaks in front of a microphone, the sound energy set the diaphragm into vibration. This moves the coil back and forth between the poles of the magnet. A small alternating current is induced in the coil. When this alternating current is made larger (amplified), it operates a loudspeaker.

Exercise 7.3

1. Explain the function of each of the following in an ac generator:
   (a) rectangular coil,
   (b) slip-rings,
   (c) carbon brushes.
2. What is the main difference in the features of an ac and dc generator?
3. State the conditions necessary for the production of an electromotive force in a conductor.
4. The end view of a coil placed horizontally in between the poles of a magnet is shown in Fig. 7.33. The coil is rotated in an anti-clockwise direction about its axis.
   (a) Copy the diagram and indicate the direction of the
      (i) magnetic field,
      (ii) induced current.
   (b) Redraw the diagram to show the position of the coil when the current is:
      (i) maximum,
      (ii) zero.
   (c) Starting with the coil at the horizontal position:
      (i) Sketch a graph to show the variation of the induced e.m.f with time for one revolution of the coil.
      (ii) Mark on the graph where the coil is horizontal and vertical.
      (iii) On the same axes sketch the graph you would expect when the coil is rotated at twice the speed.

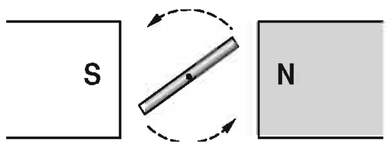


Fig. 7.33

5. A rectangular coil is rotating as shown in Fig. 7.34.
   (a) What type of generator is represented by the set-up?
   (b) Describe the production of an electromotive force by this device.
   (c) What is the direction of the induced current in the coil?

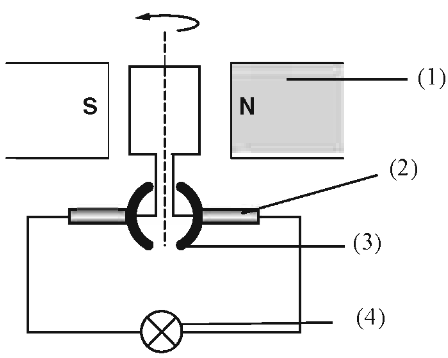


Fig. 7.34

(d) Name the parts 1 to 4.

(e) What is the function of the part labelled 3?

(f) State 4 ways by which the induced current may be increased.

(g) Which of the terminals is negative if the coil is rotated in a clockwise direction?

(h) State the energy changes that occur as the coil is rotated.

6. With a well labelled diagram, describe how moving coil microphone works.

Project work 7.1: Construction of a simple transformer

Materials needed

- Dry cells
- Bulb
- Insulated copper wires
- Masking tape or a cloth tape
- Soft iron sheets or blades,
- Connecting wires
- Sheets of paper

Assembly

- Make a complete soft iron core by packing a number of soft iron blades together. Use sheets of paper to separate the soft iron blades. (Fig. 7.35).

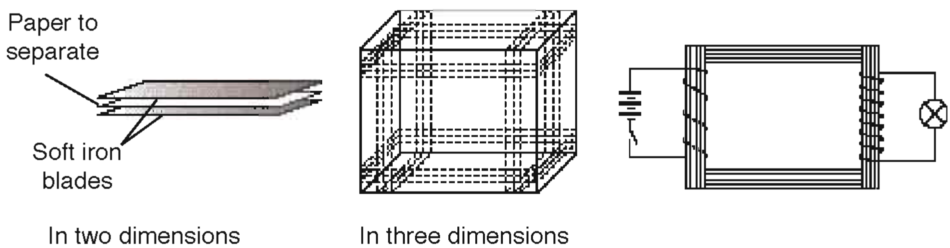


Fig. 7.35: A simple transformer

- Use the masking tape to hold the bundles of soft iron blades together. Make 20 turns of the primary coil and 40 turns of the secondary coil. Connect the ends of the primary coil to three dry cells in series with a switch. To the ends of the secondary coil, connect a small bulb.
- Switch the circuits on and off rapidly and note what happens to the bulb.

Topic summary

- If a conductor cuts magnetic field lines, an electromotive force is induced. This process of producing electricity is called electromagnetic induction.
- The magnitude of the induced electromotive force is given by the Faraday's law of electromagnetic induction.
- The direction of the induced electromotive force is determined by Lenz's law.
- The magnitude of the induced electromotive force is affected by the rate of change of magnetic field, strength of the magnet, the number of turns of the coil and the material used for the core.
- Fleming's right hand rule is used to show the direction of the induced current in a straight conductor cutting the magnetic field.
- A generator converts mechanical energy to electrical energy.
- Slip rings in an a.c generator reverses the direction of the induced current in the external circuit.
- Split rings or commutator help to maintain the flow of the current in one direction in the external circuit of a d.c generator.
- In both the d.c and a.c generators, the induced electromotive force is maximum when the coil is moving in a direction perpendicular to the direction of the field. It is zero when moving parallel to the direction of the field.
- A transformer is an electrical device that transfers electrical energy between two or more circuits through electromagnetic induction.
- In a step down transformer, there are more primary turns than secondary turns.
- In a step up transformer, there are more secondary turns than primary turns.
- Power loses in transformers occurs through due to resistance of the coils, eddy currents, hysteresis and magnetic flux leakage.
- In transformers; $\frac{N_s}{N_p} = \frac{V_s}{V_p}$
- For an ideal transformer, $\frac{I_p}{I_s} = \frac{N_s}{N_p}$

- The efficiency of am ideal transformer may be calculated from:

$$\text{Efficiency} = \frac{\text{Power output}}{\text{Power input}} \times 100\%$$

- Power losses in a transformer occur due to resistance in the coils, eddy currents, hysteriss losses and magnetic flux leakage.
- Electricity is transmitted through cables at high voltage and lower current from power stations to the consumers.
- Power loss in transmission cables occurs due to resistance in the loss. It is minimised by using thick wires of good conducting material and trnasmission at high and low current.
- Dangers associated with power transmission include risk of shock to people living near the lines.

Topic Test 7

1. (a) What do you understand by the term electromagnetic induction?

   (b) State the applications of electromagnetic induction.

2. You have been provided with the following apparatus: a straight conductor, connecting wires, a horse-shoe magnet and a centre-zero-galvanometer. Describe an experiment to illustrate electromagnetic induction.

3. The following apparatus may be used to perform an experiment to demonstrate one of the factors that affect the magnitude of the induced electromotive force; two identical coils, rheostat, dry cells, a switch, connecting wires, a centre-zero-galvanometer.

   (a) Draw the set-up that you need to assemble to perform the experiment.

   (b) Describe how the experiment is to be carried out.

   (c) State the expected results.

4. Fig. 7.36 shows a trolley carrying a magnet moving at a high speed towards the coil. The trolley enters and passes through the coil.

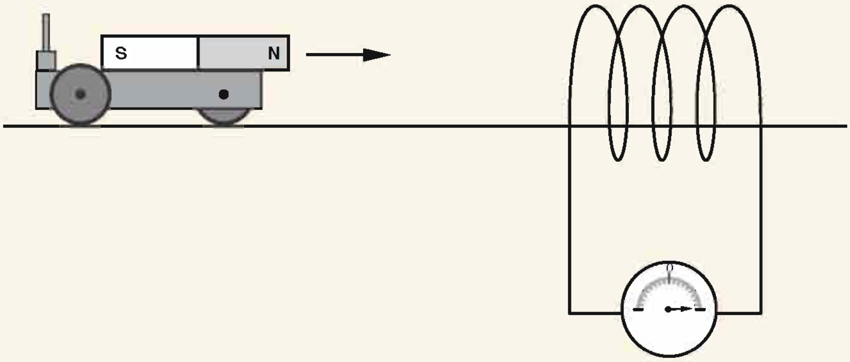


Fig. 7.36: A trolley with a magnetic moving into a coil

(a) Explain what happens to the needle of the galvanometer when the trolley
   (i) approaches the coil.
   (ii) is moving inside the coil.
   (iii) is moving away from the coil.
   (iv) and the coil are made to move at the same speed in the same direction.

(b) State the energy changes that occur as the trolley enters and leaves the coil.

5. (a) State Fleming's right hand rule.
   (b) Fig. 7.38. shows a conductor moving in a region of a uniform magnetic field.
      (i) State the direction of the magnetic field.
      (ii) What is the direction of the induced current?
      (iii) Give three ways of increasing the magnitude of induced current.

6. (a) Explain the working of a simple a.c generator.
   (b) What changes would you make in the a.c generator in order to produce a larger electromotive force?

7. Fig. 7.37 shows a simple generator.

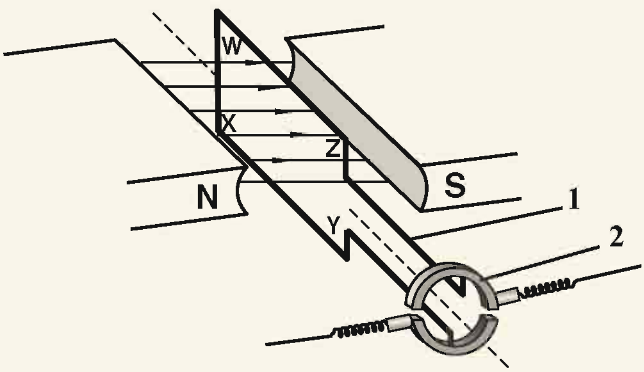


Fig. 7.37: A simple generator

(a) What is the function of the annular magnets?

(b) Name the type of the generator.

(c) What is the function of the parts labelled 1 and 2?

(d) Explain how the electromotive force is induced in the coil. Sketch the output graph of p.d against time.

(e) Sketch the variation of the voltage from a.c. generator and use it to define the term peak value and period.

8. Use the words provided below to fill in the blank spaces.

position, mechanical, dc, current, ac, direction, electrical

A generator is a device that converts ______ energy to ______ energy. There are two types of generators commonly the ac and dc generators. A ______ generator produces alternating voltage while ______ generator produces direct voltage in both types of generators, the direction of the ______ induced in the coil depend upon the ______ of the coil and the ______ in which the coil is moved.

9. Fig 7.38 shows a wire placed in a uniform magnetic field. If the force acting on the wire is into the paper.

(a) Indicate on the diagram the direction of the current through the wire.

(b) Explain what happens when the battery terminates connected to wire AB are reversed.

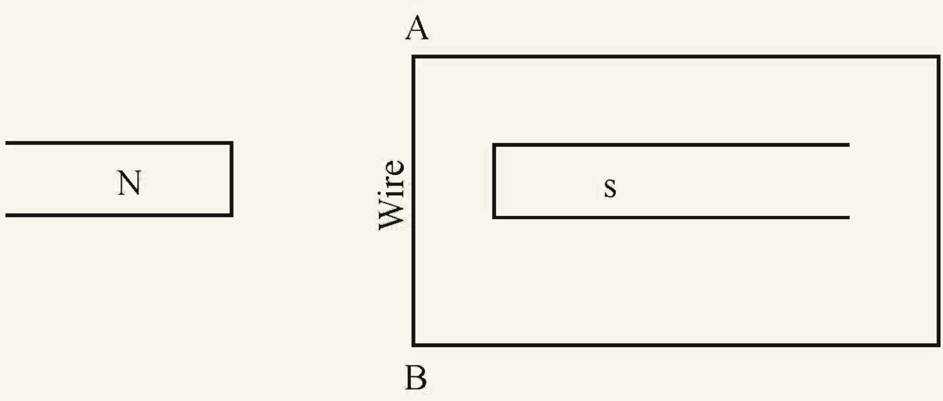


Fig. 7.38

10. **(a)** A cable connected to a centre-zero galvanometer G as shown in Fig. 7.39.

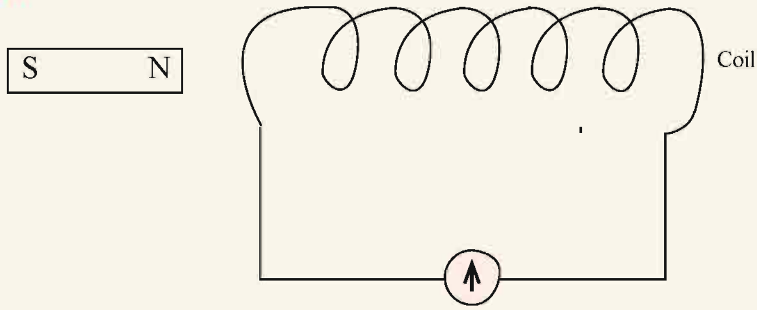


Fig. 7. 39

(i) State what is observed when the N-pole of a bar magnet is moved towards the coil.

(ii) State two ways in which the effect observation (a) (i) can be increased.

(b) With aid of a labelled diagram describe how a simple a.c generator works.

11. **(a)** Explain the term mutual induction.

(b) Why is a complete core (loop) used in transformers?

(c) Distinguish between step-up and step-down transformers.

(d) Explain why a transformer will only work with an alternating voltage.

12. A transformer has 400 turns in the primary winding and 10 turns in the secondary winding. The primary electromotive force is 250 V and the primary current is 2.0 A. Calculate:

(a) the secondary voltage.

(b) the secondary current assuming 100% efficiency.

(c) describe two features in a transformer design which help to achieve high efficiency.

13. Explain two environmental impacts of generating and transmission of electric power.

14. The secondary circuit of a transformer is connected to a bulb rated at 12 V, 40 W. The primary circuit has 5000 turns on the primary and the secondary has 250 turns. If the bulb is operating normally, find:

(a) The input voltage to the transformer.

(b) The current flowing through the bulb

(c) The power taken from the supply if the efficiency of the transformer is 90%.

15. A power station has an output of 100 kW at a p.d. of 800 V. The voltage is stepped up to 33 kV by transformer T_1 and transmitted along a grid of resistance 0.85 kΩ.

It is then stepped down to a pd. of 500 V by transformer T_2 at the end of the grid for use in a light industry. Given that the efficiency of T_1 is 95% and that of T_2 is equal to 90%, calculate to 2 decimal places the:

(a) power output of T_1

(b) current in the grid

(c) power loss in the grid

(d) input voltage of T_2

(e) maximum power and current available for use in the industry.

TOPIC 8

Electric Power Transmission and house Installation

Topic outline

- Introduction
- Electric power transmission
- Environmental impact of power generation and transmission
- Household electrical installation
- Electrical appliances
- Types of electrical cables
- Household wiring
- Dangers of electricity

Introduction

After electricity is produced at power plants, it has to get to the customers that use it. Many countries have a National Grid with power lines that transmit electricity from power stations to homes, towns and industries. In this unit, we will analyse in details how electrical power is transmitted.

8.1 Electric power transmission

8.1.1 The grid power transmission system

Activity 8.1: To describe the transmission of electrical power

Materials

- Cables of different thickness made of different metals (e.g copper, aluminium steel etc)
- Reference books
- Internet

Steps

1. Are there any overhead power transmission cables near your school? If so, tell your classmates the materials used to make the overhead wires you have identified.
2. Observe the cables provided to you. By giving appropriate reason, identify which one is suitable for the transmission of electricity. Which cable would contribute to loss of more electric energy than the other? Explain.
3. Describe briefly how electricity is transmitted from the power generating station all the way into a house or industry far away from the station.
4. Now, conduct a research from the Internet and reference books on transmission of electrical power. In your research, find out:
   (a) Ways in which electrical power transmitted is lost during transmission and how to minimise it.
   (b) How electricity is transmitted and the dangers it exposes to the people in the surrounding.
5. Share your report on your findings to the whole class.

The electrical energy generated at a power station is delivered to consumers through cables. It is distributed to consumers all over the country through the *National Grid System* which consists of a network of transmission cables carried over through structures called *pylons*.

Fig. 8.1 shows pylons and cables carrying electricity from a generating station to the consumers.

Fig. 8.1: Pylons and electricity transmission cables

Electrical power is generated at a relatively high current (e.g at 100 A and 25 kV), its voltage is immediately stepped up using a *step-up transformer* at the generating station, automatically stepping down its current for transmission through the grid (e.g. at 6.25 A and 400 kV). On reaching the consumer, the voltage is stepped down to a low value e.g. 240 V for use in a home by a *step-down transformer* placed near the home.

Fig. 8.2 shows a section of a typical National Grid System from the power generating station to the factories, towns and villages.

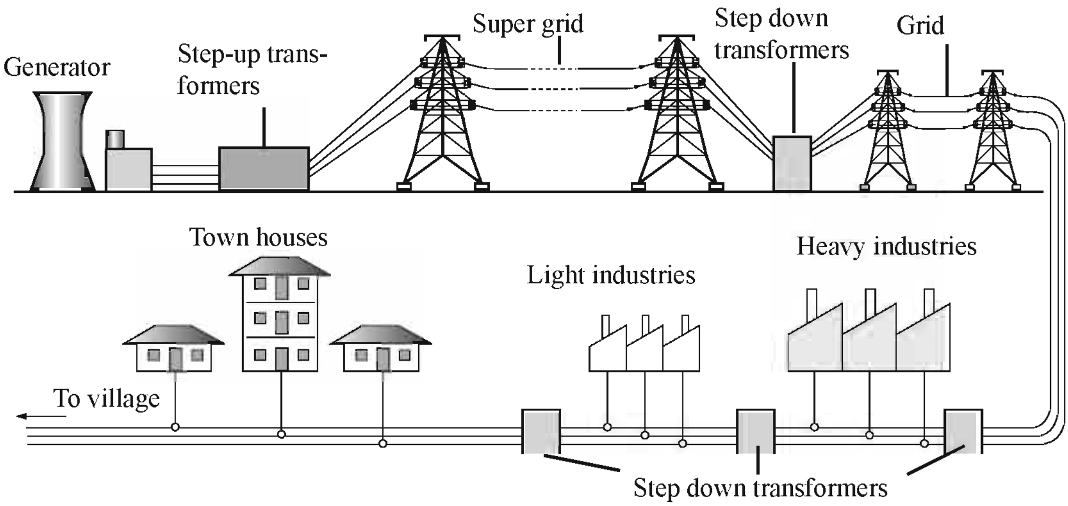


Fig. 8.2: The National Grid System

8.1.2 Power loss in transmission cables

Due to *electrical resistance* (R) of the transmitting cables, some electric power (Given by $P = I^2R$) is *lost in form of heat* in the transmission cables.

Remember, the electrical resistance of a wire (conductor) is directly proportional to its length and inversely proportional to its cross-sectional area (A), that is;

$$(R \propto \rho \frac{1}{A}).$$

This means that a long thin wire has high electrical resistance than a short thick wire. As such, a very high quantity of electric power would be lost if electric power is transmitted at high current and through thin wires in the National Grid.

To reduce power loss in transmission cables, the following conditions should be considered

1. Very thick transmission wires are used.
2. The transmission wires are made of metals like copper that are very good conductors of electricity hence have very low electrical resistance.
3. Electric current is transmitted at very high voltage and very low current.

8.1.3 Advantages of a.c over d.c. power transmission

1. An a.c. voltage can easily and cheaply be stepped up or down from one voltage value to another by a transformer while d.c power cannot.

2. An a.c. voltage can be transmitted over long distances at high voltage and low current with minimum power loss, while d.c. cannot be transmitted over a long distance even at high voltage and low current because a lot of electrical power will be wasted as internal energy warms the transmission cable.

8.1.4 Dangers of high voltage transmission

Activity 8.2: **To find out the dangers of high voltage transmission**

(Work in groups)

Materials

- Internet
- Reference books

Steps

1. Suggest some of the dangers of high voltage transmissions.
2. Cancer has become the world's number one killer, dethroning HIV and AIDS. Conduct research from reference books, magazines journals and Internet to find out whether living near high voltage transmission line is one of the causes of cancer.
3. Give summarized report on your finding through your group secretary.

Due to the high voltages in the transmission cables, a strong electric field is setup between the cables and the earth. Air, an insulator under normal conditions, may start to conduct electricity especially on rainy days. People or animals in the vicinity may get electrocuted. To minimise this danger, transmission cables carrying high voltages are supported high above the ground by *pylons*. When the cables enter towns and cities, they are buried underground.

Caution
Avoid touching loosely hanging electric cables. You will be electrocuted.

8.1.4 Danger of living and working near high voltage power lines

Living near high-voltage power lines and towers exposes one to the electrical and magnetic radiation produced by these high-voltage wires. Long-term exposure is likely to cause some health problems. It is worth noting that there is alot of uncertainity and debate about some of the health impacts.

Some health impacts include:

1. Risk of electric shock

There is high risk of electric shock involved when transmitting high-voltage power. For example, if the pole collapses or cables hang too low, they can give electric shock to human beings and animals when they come into contact. This may result in death.

2. Risk of fire

When the high-voltage cables fall on structures and vegetation they cause fire. This can lead to massive destruction of property and plants.

3. Childhood leukemia

A research conducted in 1979 indicates that children living near high voltage power lines and towers are at high risks of suffering from leukemia than their counterparts who live far away. However, no evidence has been provided to establish a direct connection between childhood leukemia and electromagnetic fields produced by high-voltage power lines.

4. Other cancers

Long exposure to electromagnetic field radiation from high-voltage power lines and towers, may result in incidences of cancer. Research has indicated that people who live within a 50 m radius of power lines have twice the chance of developing cancer compared to those who are 500 m away.

5. Depression

A research conducted on the psychological effect of living close to high-voltage power lines shows exposure to extremely low frequency electromagnetic fields might contribute to the number of depression-related suicides in people living close to high-voltage power sources.

In addition, many researchers have discovered a link between people living near high-voltage power lines and a number of health concerns, including brain cancer, miscarriage, breast cancer, birth defects, fatigue, hormonal imbalance, decreased libido, sleeping disorder, heart disease and so on.

8.1.5 Environmental impact of power generation and transmission

Activity 8.3: **To find out the environmental impact of power generation and transmission**

(Work in groups)

Materials

- Reference books
- Internet

Step

1. Brain storm among yourselves what impacts power generation and transmission has on the environment.

2. Conduct a research from the internet and reference books to verify your suggestions.

3. Organise a class debate to discuss these impacts.

Generation and transmission of power have both positive and negative impacts on the environment. Before a power plant is constructed, one has to know the environmental and health consequences of electricity generation and transmission.

Electric power is generated through sources like *hydroelectric, nuclear reactions, fossil fuels, solar, geothermal energy and biomass.*

Hydroelectric power is one of the most commonly generated power in the world. This method of power generation is cheaper, has low operating costs, compared to other methods of generating electricity like electricity from fossil fuels or nuclear energy.

Some of the negative impact of hydroelectric power generation and transmission on the environment are:

- Displacement of people living around the place where a dam has to be constructed.
- Releasing carbon dioxide during construction and flooding of the reservoir.
- Disrupting the aquatic ecosystems and animal life.
- Can be catastrophic if the dam wall collapses e.g can cause flooding.
- The dam becomes a breeding site of mosquitoes which carry and transmit malaria.

Environmental impact from the generation and transmission of power from other sources include:

- Pollution from fossil fuels.
- Dangers of exposure to radioactive materials from nuclear generation.

Caution
Malaria is a killer disease. It can be prevented by keeping mosquitoes away i.e sleeping under a mosquito net.

While planning to build a dam, for hydroelectric power, one has to make sure that there are minimal negative effects in the environment.

Think about this!
How electricity produced through nuclear reaction and fossils fuel impact the environment.

Exercise 8.1

1. **(a)** Briefly explain how electricity transmitted from Mukungwa power station to your school.

   (b) Discuss the risk involved in the high-voltage transmission.

2. The resistances of a length of power transmitting cables is 10 Ω and is used to transmit 11 kV at a current of 1A.If this voltage is stepped-up to 16 kV by a transformer, determine the power loss.

3. A generator produces 660 kW at a voltage of 10 kV. The voltage is stepped up to 132 kV and the power transmitted through cables of resistance 200 Ω to a step-down transformer in a sub-station. Assuming that both transformers are 100% efficient:

   (a) Calculate the

   (i) current produced by the generator

   (ii) current that flows through the transmission cables

   (iii) voltage drop across the transmission cables

   (iv) power lost during transmission

   (v) power that reaches the sub-station

   (b) Repeat (a)(i) to (v), but this time the 10 kV is stepped up only 20 kV instead of 132 kV for transmission.

   (c) Briefly explain three factors that contributes to power loses in a transformer.

4. State the ways through which power loss in transmission cables is minimised.

8.2 Household electrical installation devices and materials

Activity 8.4: **To brainstorm on household electrical installation**

(Work in groups)

Materials:

- Manila paper
- Geometrical set

Steps

1. Think of a newly built house in the school compound or at home. List down the materials and devices you think you would need if you are to install electricity in it.
2. Discuss with your group members the purpose of each of the material/device you have identified in step 1.

Electrical installation in your home is a skill you can acquire. Knowing how circuits work and what can be done with them is useful knowledge. Wiring in a residential house is not that complicated, but it can be dangerous. Proper understanding and caution are required. In this section, we are going to learn how electric installation in houses is done.

8.2.1 Standard symbols for electrical devices

Activity 8.5: **To identify standard symbols for electrical installation**

(Work in groups)

Materials

- Different fuses
- A switch
- A socket
- Bulb
- Chart showing standard symbols for electrical installation.

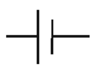
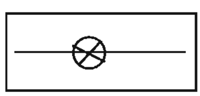
Steps

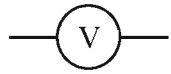
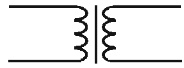
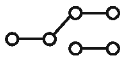
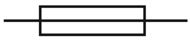
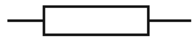
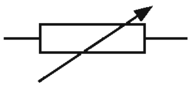
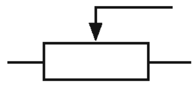
1. Take the electrical devices provided to you. Draw their symbols as used in electrical circuit.
2. Tell your group members the uses of each electrical device provided.
3. Now, take the chart provided to you. Compare your drawings of the symbols with the ones on the chart. How accurate were your drawings?
4. Cover up the symbols in the book and chart and test each other to see if you can draw them from memory.

Most of the electrical devices are made in different styles, appearances and colours according to users' requirements. However, standard electrical symbols are used to represent various electrical and electronic devices in schematic diagrams of electrical or electronic circuits. They are easy to understand.

The following table lists some basic electrical symbols.

Table 8.1

Device	Symbol	Device	Symbol
Cell		Battery	
Lamp		ac supply	

Ammeter		Voltmeter	
Galvanometer		Transformer	
Heating element		Switch	
2-way switch		Bell	
Fuse		Fixed resistor	
Variable resistor (rheostat)		Potentiometer	

8.2.2 Electrical Lamps

Activity 8.6: **To observe and describe different types of electrical lamps used for lighting**

(Work in groups)

Materials

- Different types of electrical lamps
- Reference books
- Internet

Steps

1. Take different electrical lamps provided to you and discuss their appearances and structures. What differentiates them from each other?
2. Identify which electrical lamps are more efficient for use at homes.
3. Conduct a research on types of electrical lamps used for lighting.
4. In your research, find out the structure and the gases used in the lamps (if any).
5. Present a summarized report of your findings to the whole class through your group secretary.

An electrical lamp is a light emitting electrical device used in electric circuits, mainly for lighting and indicator purposes. It has a filament surrounded by a transparent glass. The filament of the lamp is usually made of tungsten since it has high-melting point.

When current flows through lamp, the tungsten filament glows without melting, producing light energy.

Types of lamps

There are three main categories of electrical lamps namely: incandescent lamp, LED lamps and gas-discharge lamps.

(a) Incandescent lamps

These are lamps which produce light from a filament heated white-hot by an electric current. They are also known as tungsten lamps.

Fig. 8.3: An incandescent lamp

These lamps are often considered the least *energy efficient type of electric lighting*. They are commonly found in residential buildings. Although inefficient, incandescent lamps posses a number of advantages: *they are cheap, turn on instantly, are available in a huge array of sizes and shapes and provide a pleasant, warm light with excellent colour rendition.*

An example of incandescent lamps is a vacuum lamp. As the name suggest, the vacuum lamp has the glass enclosing the tungsten filament has no gas in it. It has a vacuum. The tungsten filament is heated to a temperature at which visible light is emitted. The light from the low temperature lamps appear reddish yellow while that from the high temperature lamps has a white appearance. The filament acts as an electrical filament resistor, that dissipates power proportional to the product

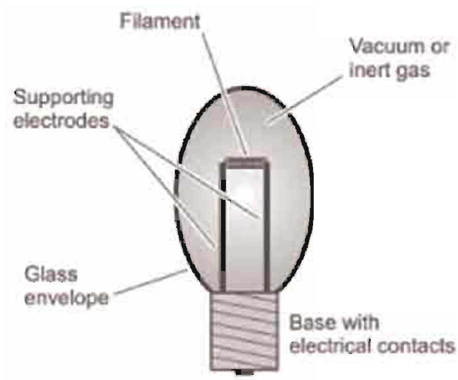


Fig. 8.4: Vacuum lamp

of the voltage applied and the current through the filament. When the power supplied is sufficient to raise the temperature to above 1 000 K, visible light is produced. As the power dissipated is increased, the amount of light produced increases.

(b) LED lamps

A LED lamp is made using light emitting diodes (LED). A LED consists of a junction diode made from a semi conductor material usually gallium arsenide phosphide. When current is passed through the diode, it emits light. LED lamps are *cheap* and *highly efficient* because they emit almost no heat.

Fig. 8.5: LED lamp

(c) Gas-filled lamps

Gas-filled lamps produce light from an incandescent filament operated in an inert gas atmosphere. The inert gas suppresses the evaporation of the tungsten filament, increasing the lifetime of the lamp and allow the lamp to operate at higher temperature. The commonly used gases are neon, argon xenon, sodium, mercury. The cost of gas-filled lamps depends on the gases used. For instance, the one filled with xenon is more expensive due to its low natural abundance.

The advantage of the higher atomic weight gases is that they suppress the evaporation of the tungsten filament more effectively than the lower weight gases. This allows the filament of gas filled lamps to run at temperature up to 3200 K and achieve reasonable life times. The light from these lamps has a high blue content giving the light a pure white appearance.

The *disadvantage* of a gas filled lamps is that *they require more power to achieve* the same *temperature than incandescent lamps*.

Fig. 8.6: Gas filled lamps

Safe energy!
Use energy saver lamps on lighting system in your homes to minimise electricity bills.

8.2.3 Fuses and circuit breakers

(a) Fuses

Activity 8.7: **To find out the function of a fuse and interpret power ratings of fuses**

(Work in pairs)

Materials

- Fuses of different rates

Steps

1. Tell your class partner what a fuse is and its function in an electrical circuit.
2. Keenly observe the fuses provided to you. Check and record their voltage and current ratings.
3. Determine the amount of the current allowed by each fuse to pass through without breaking.

A fuse is a short thin piece of wire of low melting point. The wire melts as soon as the current through it exceeds its rated value. Fig. 8.7 shows pictures of fuses.

Fig. 8.7: A fuse

Fuses are usually fitted in all electrical circuits to prevent dangerously large currents from flowing. They melt or "blow off" and stops the flow of current hence protecting the electrical appliances against the risk of fire caused by the heat. The fuses are therefore fitted on the live wire. Thus, the fuses though very cheap, protect expensive electrical devices from damages caused by electrical faults.

Fuse rating

Fuse rating is the current needed to blow (melt) the fuse. It is usually printed on the side of the fuse. It is usually defined in 'amperes', which are the unit of measuring electrical current (see Fig.8.8).

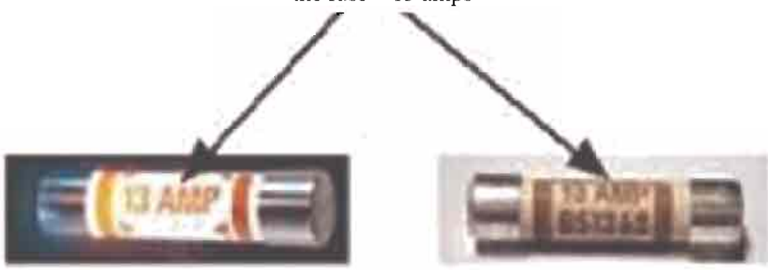


Fig. 8.8: Fuse rating

The fuse used in any electrical appliance should be of a value just slightly higher than the normal current required by the appliance. The common standard values of available fuses are 2 A, 5 A and 13 A, although 1 A, 3 A, 7 A and 10 A fuses are also made. If the power rating of an electrical appliance is '2 000 W, 250 V', the required current through it is 8 A. The correct fuse to protect the appliance is 10 A. Similarly if the required current for an appliance is 4 A, the appropriate fuse to be used is 5 A.

(b) Circuit breakers

Activity 8.8: **To describe the working of circuit breakers**

(Work in groups)

Materials

- School circuit breaker
- Internet
- Reference books

Steps

1. With the permission of your teacher, switch on and off the circuit breaker. What do you notice? Explain.
2. Tell your group members what a circuit breakers is and discuss how it works.
3. Do research from reference sources on how a circuit breaker works.
4. Share your findings to the whole class.

A circuit breaker (Fig. 8.9) is an automatically operated electrical switch designed to protect an electrical circuit from damage caused by either excess current, overload or short circuit.

Fig. 8.9: Circuit breaker

The basic function of a circuit breaker is to put off the circuit to discontinue current flow after a fault has been detected. Unlike a fuse which operates once and then must be replaced, a circuit breaker can be reset (either manually or automatically) to resume normal current flow.

Exercise 8.2

1. Table 10.2 shows standard symbols for electrical installation. Fill in the appropriate name or symbol.

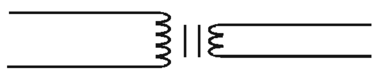
	Name	Standard symbol
(a)	Bulb/lamp	
(b)		
(c)	Fuse	
(d)		
(e)	Capacitor	
(f)	D.C Voltage	
(g)		
(h)	Circuit breaker	

Table 8.2

2. Explain why tungsten is used in lamps and not any other metal.
3. What is a fuse? Explain its function in an electrical circuit.
4. A microwave is rated 1 500 W, 240 V. What is the appropriate fuse used in its circuit?
5. What is a circuit breaker? Explain how it functions.
6. Differentiate between a fuse and a circuit breaker.

8.2.4 Types of electrical cables, plug and their sizes

Activity 8.9: **To find out the types of electrical cables and their standard sizes**

(Work in groups)

Materials

- Electrical cables
- Internet
- Reference books

Steps

1. Remove the outer jacket of the cable provided to you. How many differently coloured cables are there? Write down their colours.
2. Suggest the name of each wire in the cable guided by their colours.
3. Now conduct a research find out how the wires are connected to the electric circuits.

More often than not, the term wire and cable are used to describe the same thing, but they are actually quite different. A wire is a single electrical conductor whereas a cable is a group of wires covered in a sheath.

A cable usually has three wires namely the *live wire* (L), *neutral wire* (N) and *Earth wire*. Fig. 8.10 shows a cable with the live, neutral and earth wires.

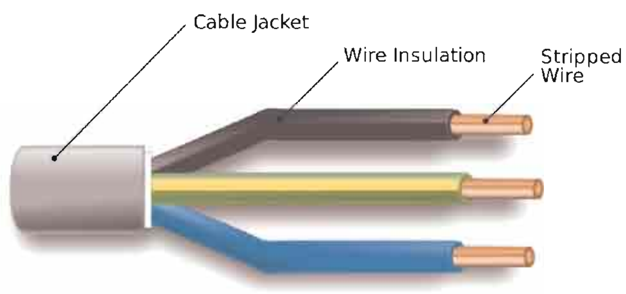


Fig. 8.10: Electrical cable

The domestic supplies in most countries are 240 V AC with a frequency of 50 Hz. This is supplied by two cables from a local sub-station to different homes, industries and offices for consumption. Let us now discuss these cables in details.

Live (L), neutral (N) and earth (E) wires

The live wire may be linked to the positive terminal of a cell or a battery and the neutral wire to the negative terminal (Fig. 8.11 (a) and (b)).

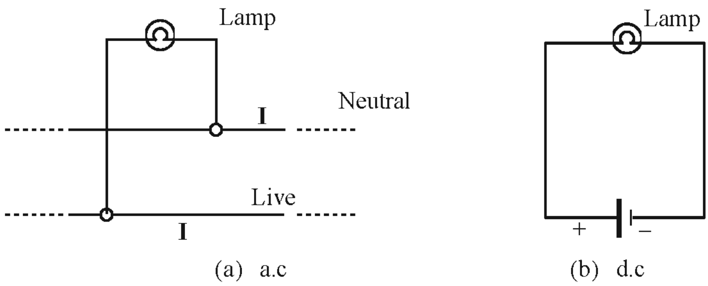


Fig.8.11: Live and neutral wires

All electrical appliances need a live and a neutral wire to form a complete circuit from the power supply through the appliance and back to the power supply. The live wire delivers the current to the appliance. It is dangerous, because it is capable of giving electric shocks, if handled carelessly. *Switches in a circuit should be fitted in the live wire*, so that when the switch is off, the high voltage is disconnected from the appliance. The current returns to the supply through the neutral wire. Some electrical appliances have a third wire known as the *earth wire* (E) for safety (is discussed later in the unit).

Colour codes for the wires used in house circuits

The insulation, usually of plastic, on the three wires of a cable is distinctively coloured to denote the live, neutral and earth wires. The basic idea of using different colours is to easily identify the wires so that correct connections are made with care. The present international convention is *brown f*or live, blue for neutral and green with yellow stripes for earth. Electrical wiring should be checked to ensure that the earth wire lead to (connected to) the outside case of the appliance to protect users from shock.

Fig. 10.12 shows a 3-pin plug. It is usually marked with letters L, N and E to stand for live, neutral and earth respectively.

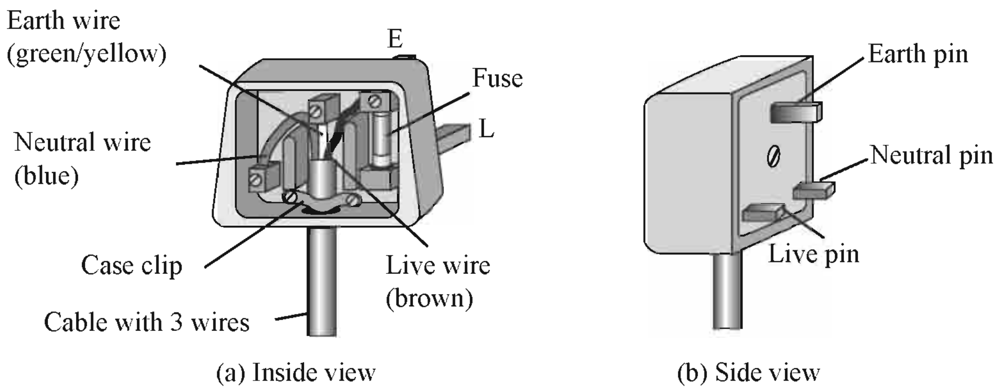


Fig. 8.12: 3-pin plug

Note that the earth pin is slightly longer than the other two pins and that the live pin is on the right hand side of the plug when connected to the socket.

Earth connection

The earth wire connects the metal case of an appliance (e.g. an electric iron) to the ground and prevents it from becoming *live*, if a fault develops. If, for example, the cable insulation wears out due to the heating effect of the current, there are chances that a few fine strands of the bare live wire could touch the metal case. When such a fault occurs, a current flows through the live wire and the earth wire in series. The fuse in the live wire will blow and cut off the power supply. If on the other hand, there was no earth wire connection, a person touching the metal case would get an electric shock.

In appliances like television set, record player, etc. the outer case is not metallic and hence 2-pin plugs are sufficient. It is dangerous to use the 2-pin plug with any appliance which has an outer metal case.

Short circuits

If a few strands of the fine bare live wire touch, by chance, those of neutral wire, a large current can flow between the live and the neutral wires of the supply cables. This is due to the fact that current tends to take the path of least resistance. This is called *short-circuiting* of the appliance.

On such occasions, the fuse usually blows off. Otherwise if no fuse was filted in the circuit, the 'sparking' produced by the large current might burn the cable and there are risks of fire being produced.

In a socket for 3-pin plug, the holes for the live and the neutral pins are usually closed by an insulating material called a *'blind'* (Fig. 10.13). This is a safety measure, especially to children who may like to play with the circuit and might cause short circuiting by putting wires in the socket. The 'blinds' are opened by the longer earth pin of the 3-pin plug. The moment the earth pin touches and opens the socket, any leakage current through the metal case will straight away be earthed hence making the appliance safe.

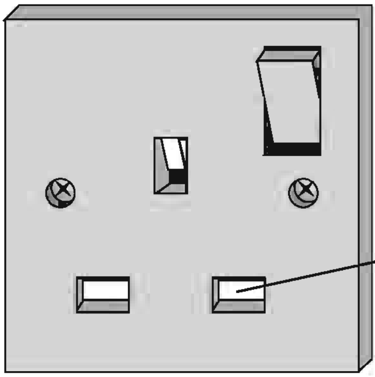


Fig. 10.13: A socket

8.3 Household wiring

Activity 8.10: **To describe domestic wiring system**

(Work in pairs)

Materials:

- Chart showing domestic wiring system

Steps

1. Take a walk around the school premises and identify where the following electrical components are situated:
   (a) Main switch (b) Meter box
   (c) Sockets (d) Circuit beakers
2. Now look at the chart provided to you. Identify the various electrical devices we have already learnt about, using their symbols.
   Identify the lighting and ring circuit, the meter box and the consumer unit. Justify the purpose and the positioning of each of them in the instalation.
3. Make a presentation to the rest of the class.

Fig. 8.14 shows the drawing for the domestic wiring system consisting of the following: the main fuse, electricity meter, consumer unit or the fuse box, lighting circuit and the ring main circuit.

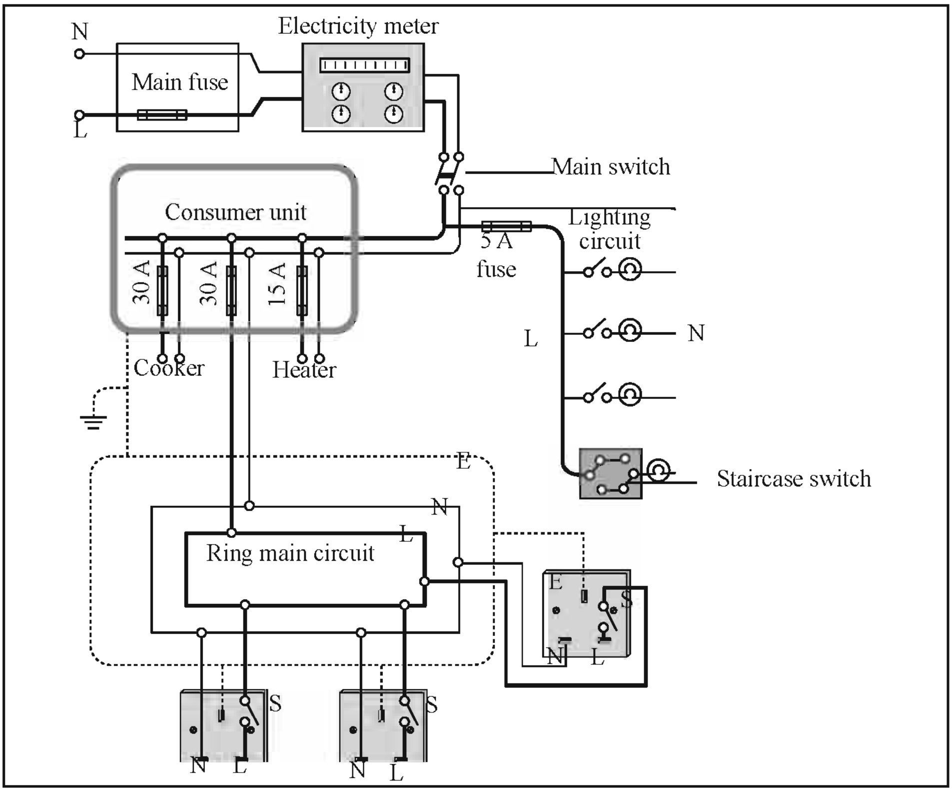


Fig. 8.14: Domestic wiring system

Electricity is supplied from a transformer to the house via two wire (L and N) cables. Earthing for one of the wires is done at the transformer. It then goes through a fuse which usually differ depending on the amount of the current required. It is then wired to the meter box which contains all the fuses and circuit breakers.

The circuit breakers are normally labelled clearly to show to which each circuit breaker belongs. Wiring for each part of the house is done starting at this unit box also referred to as consumer unit.

Every circuit is connected in parallel with the power supply, i.e. across the live and the neutral wires. Every circuit receives 240 V ac. There is no connection between the live and the neutral wires except through an electrical appliance.

The *electricity meter* records the electric energy consumed in the whole house.

The *consumer unit* is a junction box which distributes current to several separate circuits. The consumer unit also houses the main switch which can switch off all the circuits in the house, if required.

The *lighting circuit* contains lights for different places and the 2-way switches for places like the staircases. Each lamp is connected in parallel at a suitable point along the cable. The lighting circuit does not require the earth connection, as the current is normally quite low.

The *ring main circuit* provides parallel circuit connections to each electrical appliance plugged into the sockets. Since the current drawn is high, the ring main circuit incorporates the earth wire connection.

Activity 8.11: **To practise replacing a faulty socket**

(Work in groups)

Materials

- A test light
- Wire strippers
- Wire cutters
- Double cutlet sockets
- Screw drivers
- 3-wire cable

Procedure

1. Take a 3-wire cable and assume it is already fixed in the ring circuit of a house.
2. Using the wire strippers, strip off the wire casing and prepare the wires.
3. After preparing the wires of the junction box, screw the black wire to the socket terminal with a neutral sign, the red wire to the terminal with live sign, the green wire to the terminal with earthing sign.
4. Show your set up to the teacher to confirm it is correctly wired. If well done, this is how one should repair a spoilt socket in the ring circuits.

8.4 Dangers of electricity

Activity 8.12: **To describe the dangers of electricity and safety measures**

(Work in pairs)

Materials

- Reference sources

Steps

1. Discuss the possible electrical hazards in our homes and the safety measures that should be taken.
2. Confirm your faults in step 1 above by conducting a research from reference sources on the dangers of electricity.
3. Organise a classroom debate on the subject "Electricity is a necessary threat in our homes." Let there be proposers and opposers.

Working with electricity can be dangerous. Engineers, electricians and other workers deal with electricity directly including on overhead lines, electrical installation and circuit assembling. Users like office workers, farmers and construction workers deal with electricity indirectly.

Some of us may have experienced some form of shock where electricity causes our body to experience pain or trauma.

Those of us who were fortunate, the extend of that experience was limited to tingles or jolts of pain. But electrical shocks from electrical circuits are capable of delivering high power to loads, which cause much more serious damage.

It is therefore important to be aware of hazards brought about by electricity and how to avoid them in order to be safe.

Electrical hazards

A hazard is a situation that poses a threat to life, health, property or environment.

The following are some common electrical hazards in our homes, offices and factories.

- Poor wiring and defective electric wires can lead to electric shock and fires.
- Water outlets being close to electric outlets.
- Pouring water on electrical fire. This can lead to electric shock.
- Covering electrical cords and wires with heavy cover can lead to overheating.
- Overloading the outlets leading to overheating and electrical fire.
- Use of long extension cords which can cause tripping or accident.
- Touching electrical appliances with wet hands leading to shocks.
- Broken sockets and electrical appliances leading to electric shock.

8.5 Electrical safety

Every electricity user should observe safety measures when using electricity and electrical appliances. The following are some of the electrical safety measures.

- Do not touch naked electric cables with bare hands to avoid electric shock.
- Always pay attention to the warning signals given out by your appliances e.g. if a circuit breaker repeatedly trips, you should confirm the problem.

Be safe

Whenever you see this electricity sign, it warns you to keep off. You may be electrocuted.

- Use the right size circuit breakers and fuses to avoid overloading.

- Ensure that potentially dangerous electrical devices or naked wires are out of reach of children.
- You should avoid cube taps, also known as splilters or adapters and other outlet-stretching devices.
- Always replace broken plugs and naked wires.
- Use the correct appliances in a socket to avoid overload.

Exercise 8.3

1. State the international standard colours for the live (line), neutral and earth leads of a 3-core flex.
2. Define 'fuse' and state its function in an electrical circuit.
3. Sketch and label a three pin plug.
4. Explain why the earth connection is important.
5. (a) Explain how to install lightning arrestor in a house.
   (b) Highlight the general design rule that must be followed to ensure highest level of electrical safety of modern houses.
6. A laboratory building in a Voluntary Counselling and Testing Centre (VCT) is to be supplied with electricity. Briefly explain how wiring would be done in the laboratory building for effective supply of electricity.

Topic summary

- An electronic symbol is a pictogram used to represents various electrical and electronic devices in a schematic diagram of an electrical or electronic circuit.
- A fuse is a short thin wire of low melting point. It melts when a large current flows through it hence breaking the circuit.
- The earth wire is connected to the ground and prevent an appliance or house from becoming live. This is important incase there is an electrical fault.
- Electric Lamps are of many types. They are categorised into three major groups namely: Incandescent, LED and gas-discharge lamps.
- A circuit breaker cuts off the flow of current when there is an electric fault within the circuit thus keeping the premises and appliances safe from electric fire.
- When wiring a house, there are many types of wire to choose from, some copper, others aluminium, some rated for outdoors, others indoors.
- Every electricity user should be aware of electrical hazards and practice safety measures.

Topic Test 8

1. (a) Name five electrical components used in house wiring.

   (b) Draw the standard electrical symbols used for each of the component named in (a)

   (c) Briefly explain the functions of each of the component you named in (a) above.

2. Explain why the earth connection is so important to appliance at home.

3. Fig.8.15 shows an electrical cable. Name the earth, live and neutral wire.

Fig.8.15: Electrical cable

4. (a) Name three types of electric lamps.

   (b) List any two gases used in lamps.

   (c) What is the purpose of the presence of the gases inside the bulb?

5. Brief explain the function of the following electrical component in an electric circuit

   (a) a circuit breaker

   (b) a fuse

6. Describe briefly how you can do electrical wiring in a house.

7. Mukantagara a student in Senior 3 saw an electric post with cables collapse and block the path way. Describe some of the safety measures she and the people near the cable should observe for them to be safe from any harm.

8. Explain why a fuse is always fitted to the live wire.

9. State three necessary precautions to be taken when connecting a metal-framed electrical appliance to the mains power supply?

10. An electric iron rated 240 V, 750 W is to be connected to a 240 V mains supply through a 3 A fuse. Determine whether the fuse is suitable or not.

11. Find the maximum number of 75 W bulbs that can be connected to a 3A fuse on a mains power supply of 240 V.

12. In the circuit shown in Figure 8.16, each bulb is rated 6 V, 3 W.

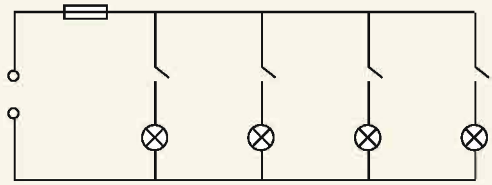


Fig. 8.16

(a) Calculate the current through each bulb when the bulbs are working normally.

(b) Is a 3 A fuse suitable for the circuit when all the switches are closed?

(c) Calculate the power delivered by the power supply

(d) What is the advantage of connecting all the bulbs in parallel rather than in series?

14. Figure 8.17 shows a staircase double switch.

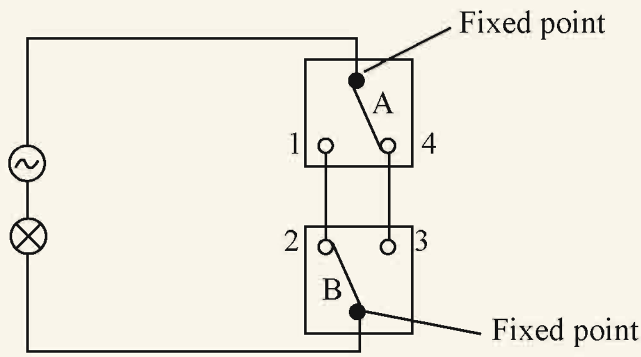


Fig. 8.17

In Table 8.4, write down whether the lamp will be ON or OFF for the various combinations of switch positions.

Table 8.4

Position of switch A	Position of switch B	Lamp ON/OFF
1	3	
1	2	
4	3	
4	2	

UNIT 6 Cathode Ray Tube

Topic in the unit

Topic 9: Cathode Ray Tube

Key inquiry question

- Why cathode ray tube is evacuated?
- Why use florescence screen in cathode ray tube?
- Why cathode rays are deflected by magnet?

Learning outcomes

Knowledge and understanding

- Understand the structure and function of cathode ray tube.

Skills

- Investigate the characteristic and behaviour of an electron beam and how it can be deflected by varying magnetic field or electric field.

Attitude and value

- Appreciate use of CRO.

TOPIC 9 Cathode Ray Tube

Topic outline

- Production of cathode rays
- Properties of cathode rays
- Cathode ray oscilloscope (C.R.O)
- Uses of cathode ray oscilloscope
- Television tube

Introduction

Up to a few years ago, when flat screens were developed, the standard in most display devices like televisions and desktop computers, cathode ray oscilloscope has been used as cathode ray tubes to display images on the screen. But what exactly happens in the cathode ray tube? This will be the focus of our study in this topic.

9.1 Production of cathode rays

Activity 9.1: To determine how cathode rays are produced

(Work in groups)

Materials

- Reference sources

Steps

1. Do research from reference sources on cathode rays.
2. Use your research to explain:
   (a) how cathode rays are produced.
   (b) the purpose of extra high tension (voltage) in a cathode ray tube.
   (c) why the glass tube of a cathode ray tube is evacuated.
3. Present your findings to the rest of the class.

9.1.1 Electric discharge tube

Michael Faraday demonstrated the passage of electricity through a gas — called *a discharge*. In order to study the electric 'discharge' in air at low pressures, a glass tube of about 0.5 m long, connected to a vacuum pump and a pressure gauge is used (Fig. 9.1). The tube contains a cathode, C, and an anode, A, connected to the negative and positive terminals respectively of a very high voltage supply, usually called the *extra high tension* (E.H.T.)

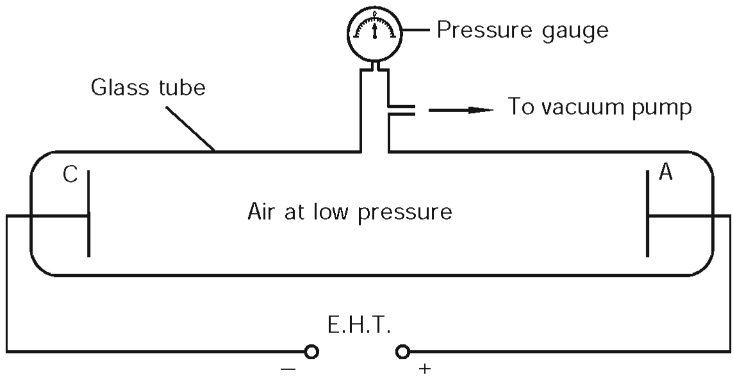
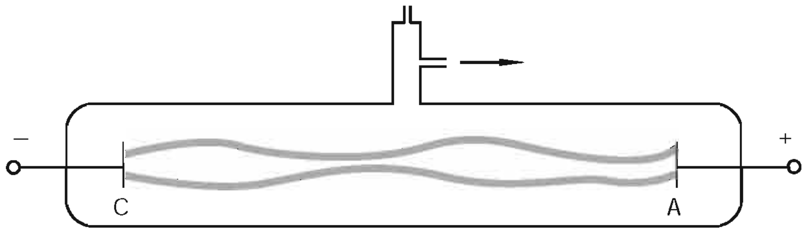


Fig. 9.1: Electric discharge tube

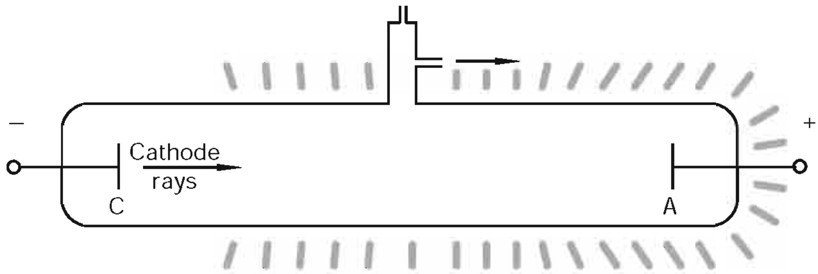
As the air inside the discharge tube is pumped out, initially there is no effect. When the pressure inside is a few millimetres of mercury pressure, thin streams of luminous gas appear between the electrodes C and A

(Fig. 9.2 (a)). When the pressure inside the tube is reduced further to about 0.01 millimetres of mercury pressure, the walls of the tube fluoresce (gives out a 'green glow') (Fig. 9.2 (b)).

A number of physicists have given explanations of the "discharge" phenomenon. They all suggest that some kind of *radiation* is proceeding in straight lines from the cathode towards the anode and that the *radiation* consists of a stream of particles shot out from the cathode with high velocity. Sir William Crookes described these particles as *radiant matter* while J. J. Thomson referred to them as *corpuscles of negative charge*. A German physicist, Eugen Goldstein, suggested the term, *cathode rays*, which is commonly being used nowadays. Further experiments have proved beyond doubt that cathode rays consist of streams of particles of negative electricity known as *electrons*.



(a) Streams of luminous gas



(b) Glass walls show fluorescence

Fig. 9.2: Electric discharge through air at low pressures

The electric discharge method to produce cathode rays in a tube containing the gas is not a convenient one because

1. a gas is needed at the appropriate low pressure,
2. a very high potential difference is needed across the electrodes.

These drawbacks are overcome in a modern cathode ray tube.

9.1.2 Cathode ray tube

A modern cathode ray tube consists of a long evacuated tube with a metal filament, *F*, at one end and a small metal plate called the anode, *A*, at the other end (Fig. 9.3). Close to the filament is another metal plate called cathode, *C*, which is in the form of a cylinder covering the filament. The filament is connected to a 6 V ac or dc supply called the *low tension* (*L.T*) supply. A potential difference of about 4 000 V is set up between the cathode and the anode.

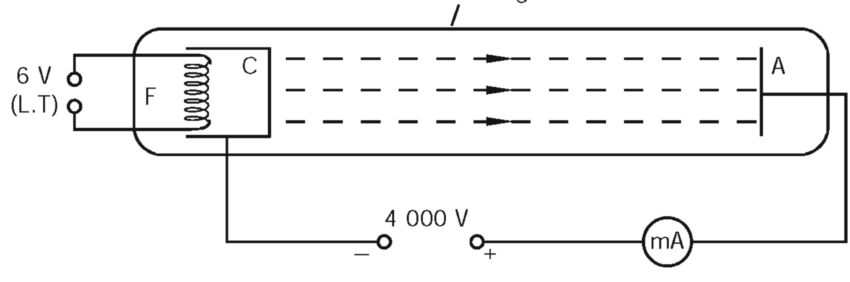


Fig. 9.3: Cathode ray tube

The filament is heated by the current from the low tension supply. The filament in turn heats the cathode C. As the temperature of the cathode is raised, the thermal speed of the free electrons in the cathode is increased and the electrons escape from the atoms of the metal plate. Thus by heating a metal to a high temperature, electrons can be '*boiled off*'. This process is known as *the thermionic emission* and the emitted electrons are called *the thermions*. These emitted electrons are accelerated by the negative potential of the cathode and are attracted by the anode at a positive potential. The milliammeter in the circuit shows a current, proving that negatively charged electrons are moving from the cathode towards the anode inside the evacuated tube. The streams of negatively charged fast moving electrons are called *the cathode rays*.

The cathode is usually coated with barium and strontium oxides to give a copious supply of electrons. The emitted electrons can reach the anode without any hindrance, as is evacuated.

9.2 Properties of cathode rays

Activity 9.2: **To find out the properties of cathode rays.**

(Work in groups)

Materials

- Reference sources
- Cathode ray tube

Steps

1. Conduct a research on the properties of cathode rays.
2. Use your research to find out and explain:
   - What happens to cathode rays as they pass through magnetic and electric fields.
   - the effect of cathode rays on the gases they pass through and photographic paper.
3. Present a summarised report of your findings to the whole class through your group secretary.

Cathode rays cause fluorescence on certain materials

Cathode rays are produced by an *electron gun* (Fig. 9.4). An electron gun in a cathode ray tube consists of the filament, cathode and the accelerating anode.

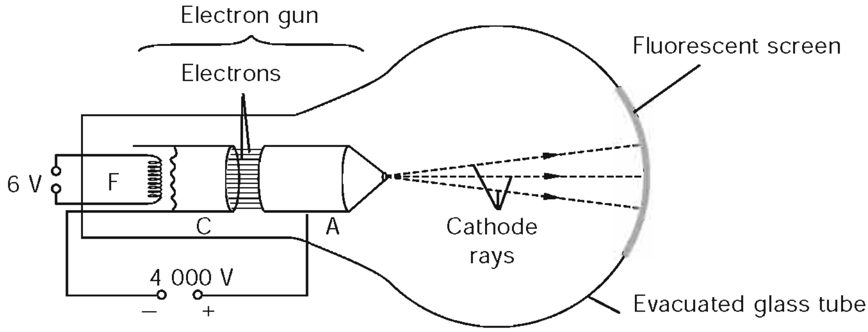


Fig. 9.4: Fluorescence effect of the cathode rays

The cathode rays travel freely across the tube. They produce a '*glow*' when they collide with the screen which is coated with a fluorescent materials like phosphor on the inside and lose their energy. The 'glow' produced shows the existence of cathode rays. The kinetic energy of the electrons is converted into light energy by a process called *fluorescence*.

9.2.2 Cathode rays travel in straight lines

If an aluminium maltese cross is introduced between the anode and a fluorenscent screen as shown in Fig. 9.5, the light beam from the cathode casts a shadow of the aluminium cross on the fluorescent screen. The fact that cathode rays cast a shadow shows that they travel in straight lines.

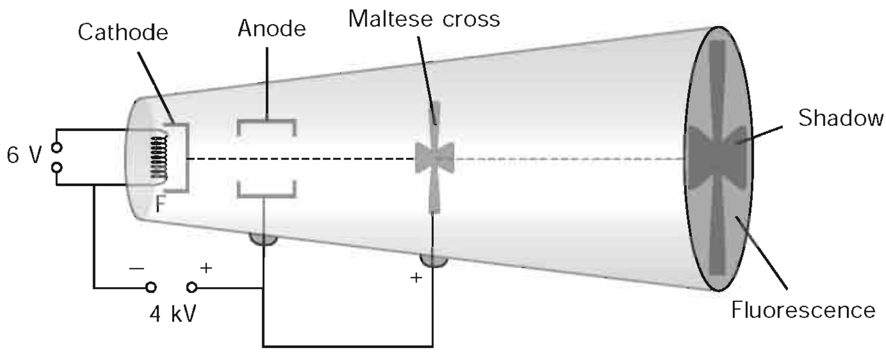


Fig. 9.5: Cathode rays travel in straight lines

9.2.3 Cathode rays travel with a high speed and possess a lot of kinetic energy

Fig. 9.6 shows one type of cathode ray tube which houses a small paddle wheel with mica vanes capable of rotating on the horizontal rails inside the tube. The cathode and the anode are so arranged that when cathode rays are produced, they collide with the vanes of the paddle wheel which are above the horizontal axis, as shown in Fig. 9.6.

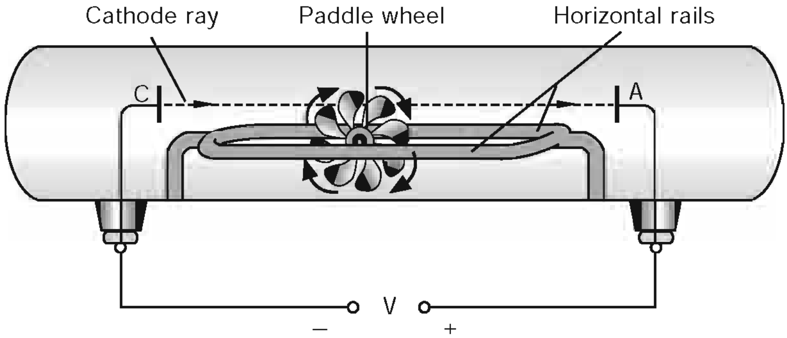


Fig. 9.6: Cathode rays possess a lot of energy

When the electric field is set up between the cathode and the anode, the wheel starts rotating on the rails. When the field is switched off, the wheel tends to stop, showing that the wheel rotates due to the energy provided by the cathode rays. The speed of the electrons can be found as follows:

The average kinetic energy of an electron = $\frac{1}{2} mv^2$............(1), where m is the mass of electron and v is its speed. By definition, the potential difference V between the two electrodes is given by:

$$V = \frac{\text{work done or energy spent}}{\text{charge}} = \frac{W}{Q}$$

Work done by the electric field on an electron is given by:

$W = QV = eV$ ....(2), where e is the charge of an electron.

From equations 1 and 2 we get;

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

Hence, the speed of electron can be found. As seen from the above equation, the speed can be increased by increasing the potential difference V between the electrodes.

Cathode ray can ionise the gas through which they travel

When cathode rays are incident on gas molecules, ionisation takes place—electrons are knocked off from the orbits of the atoms.

Cathode rays affect photographic papers

When cathode rays are incident on a photographic paper in a dark room, the paper gets 'fogged'.

Cathode rays are deflected in an electric field

Fig. 9.7 shows a cathode ray deflection tube. The path of the cathode rays is made visible on a phosphor-coated mica screen mounted inside the tube.

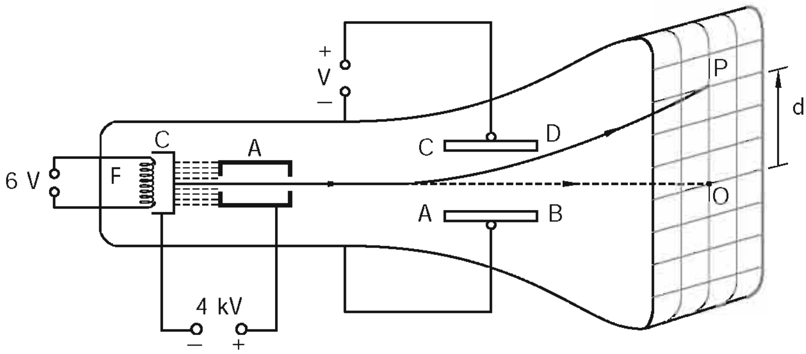


Fig. 9.7: Deflection of cathode rays in an electric field

Two parallel metal-plates AB and CD, which are close together, are housed inside the tube. A deflecting voltage, *V*, is applied between them. In the absence of an electric field between AB and CD, the cathode rays travel in a straight line and hit the screen at O. When an electric field is applied as shown in Fig. 9.7, the cathode rays get deflected upwards, away from the negative plate AB. This proves that cathode rays are negatively charged since they are repelled by the negative plate AB. If the polarities of the plates are reversed, the deflection, *d*, is in the opposite direction.

Cathode rays are deflected in a magnetic field

If a magnetic field is suitably applied to the path of the cathode rays in the evacuated tube so that the field is perpendicular to the motion of the cathode rays, the rays get deflected downwards as shown in Fig. 9.8.

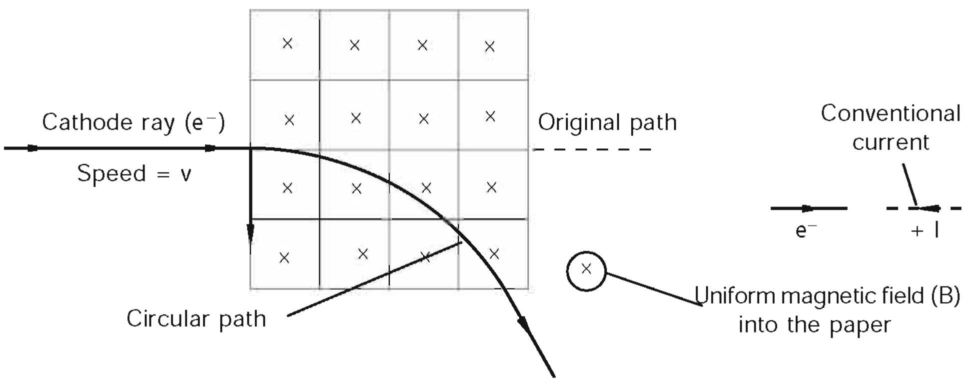


Fig. 9.8: Deflection of cathode rays in a magnetic field.

The path of the cathode rays inside the magnetic field is circular. The direction of the conventional current is opposite to the direction of flow of electrons (e^-). The magnetic field B is at 90° to the plane of the paper and also into the paper. The field is also perpendicular to the direction of the flow of cathode rays.

By applying Fleming's left-hand rule, the magnetic force, F, on the moving charge is downwards, at 90° to the path of the cathode rays and is along the plane of the paper.

9.3 Cathode ray oscilloscope (C.R.O.)

A cathode ray oscilloscope (C.R.O.) uses cathode rays to display waveforms on a fluorescent screen. The main features of cathode ray oscilloscope are the electron gun, deflection system and the fluorescent screen housed in an evacuated tube. A cathode ray oscilloscope is basically a cathode ray tube with the addition of the deflection system. Fig. 9.9 shows the main features of a cathode ray oscilloscope.

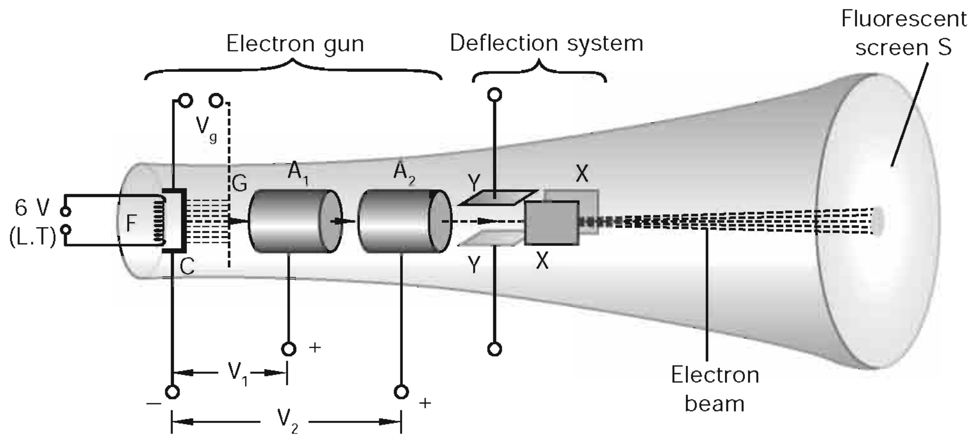


Fig. 9.9: Features of a cathode ray oscilloscope

The *electron gun* consists of a *filament F*, which is surrounded by a *cathode C*, *two anodes* A_1 and A_2 and a third electrode called the *control grid G*. The *deflecting system* consists of two pairs of plates: a horizontal pair called *the Y-plates* and a vertical pair called *the X-plates*. At the end of the evacuated glass tube is the *fluorescent screen S* coated with a fluorescent material like phosphor and zinc sulphide.

When the cathode is heated by the current from a low tension (L.T) supply, free electrons are thermionically emitted from its surface. The emitted electrons are *accelerated* and *focused* by anodes A_1 and A_2 maintained at a positive voltage with respect to the cathode. The shapes and potential of the anodes are so chosen that the electric fields between them converge the beam into a fine spot on the fluorescent screen S.

The brightness of the spot on the screen is controlled by the control grid. If the grid is made more negative in potential with respect to the cathode, the number of electrons per second passing through the grid decreases and the spot becomes less bright. The reverse is the effect if the grid is made less negative in potential with respect to the cathode.

The Y-plates of the deflection system are connected internally to the input terminals (one of which is earthed) of the cathode ray oscilloscope (Fig. 9.10).

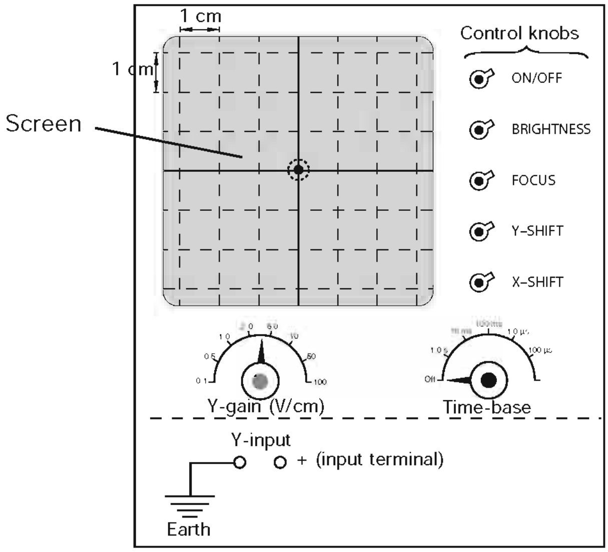


Fig. 9.10: Basic controls on a laboratory cathode ray oscilloscope

The X-plates are connected to a system inside the cathode ray oscilloscope known as *the time-base circuit*. *X* and *Y-shift* controls are used to move the spot 'manually' in the X and Y direction respectively. They apply a positive or a negative voltage to one of the deflecting plates according to the shift required. The *Y-gain* control is an amplifier control. The input voltages go through an amplifier before reaching the Y-plates. The amplification is altered by the Y-gain control which is calibrated in volts per division. These divisions are usually marked in centimetres on the plastic filter fitted in front of the screen.

The procedure for operating a cathode ray oscilloscope is as follows:

1. Switch on the oscilloscope and make sure that the time base knob is in the ' off' position.
2. Adjust the X-shift and Y-shift till the spot appears.
3. Set the spot to the centre of the screen by adjusting the X and Y-shift controls.
4. Adjust the focus and brightness control to obtain a sharply focused bright spot.

9.3.1 The Y-deflection plates

When the time base is switched 'off' and a potential difference is applied to the Y-plates, the electron spot is deflected up or down along the y-axis. Sometimes the deflection produced on the y-axis of the screen may be too small. This deflection can be adjusted with the help of Y-gain knob calibrated in volts per centimetre. The Y-gain is merely a scale used on the y-axis.

Activity 9.3: To demonstrate the deflecting action of the Y-plates using a dc source

Materials

- Cathode ray oscilloscope (CRO)
- d.c supply

Steps

1. Switch on the cathode ray oscilloscope and make sure that the time-base knob is in the 'off' position.
2. Adjust the control knobs until a sharply focused bright spot is obtained at the centre of the cathode ray oscilloscope screen. The potential difference between the Y-plates is zero and the deflection of the spot is zero Fig. 9.11 (a).
3. Connect a dc voltage to the Y-plates as shown in Fig. 9.11 (b) and observe the effect on the screen. Explain your observation.
4. Reverse the polarities of the Y-plates and observe the effect. What happens in each case?

In Fig. 9.11 (b), the input dc voltage applied to the lower plate is negative and repels the negatively charged beam of electrons upwards and the spot on the screen is deflected upwards (Fig. 7.11 (c)). In Fig. 9.11 (d), the reverse effect is seen.

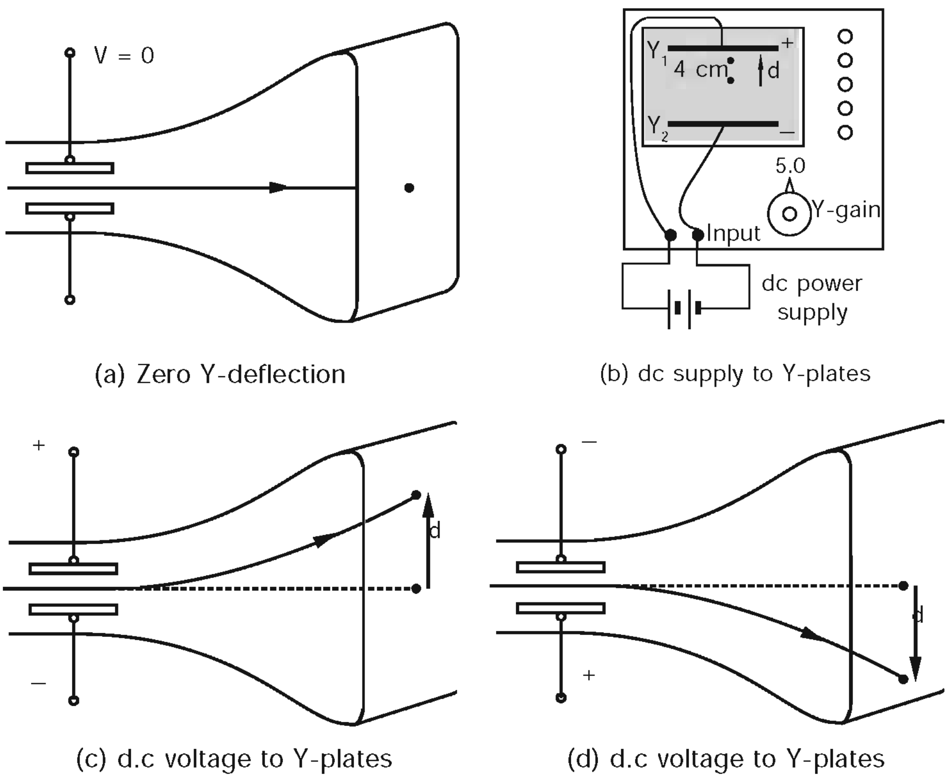


Fig. 9.11: Deflecting action of the Y-plate

In each of the cases (b) and (c), note the Y-gain setting (V/cm) and observe the deflection, *d*, produced on the cathode ray oscilloscope screen. What is the value of the input dc voltage applied to the Y-plates? — If the Y-gain control is at 5.0 V/cm and the deflection, *d*, is 4 cm.

Then, the input dc voltage is 5.0 (V/cm) × 4 (cm) = 20 V.

Activity 9.4: **To demonstrate the deflecting action of the Y-plates using an ac source**

(Work in groups)

Materials

Cathode ray oscilloscope

a.c source

Steps

Repeat Activity 9.12 by replacing the dc source with an ac source, Fig. 9.12 (a). Observe the effect on the cathode ray oscilloscope screen. Explain the deflection on the screen.

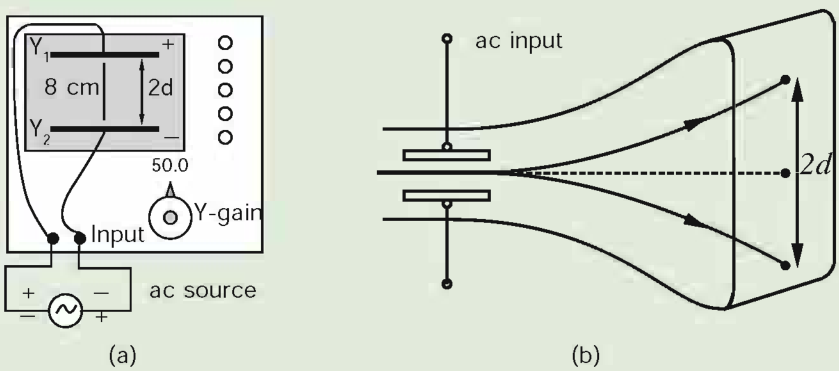


Fig. 9.12: ac voltage to Y-plates

Note the Y-gain setting (V/cm) and observe the total length, 2*d*, of the vertical line. What is the peak value of the input ac voltage? — The ac voltage applied to the Y-plates makes the beam move up and down at a particular frequency and the electron spot appears as a continuous vertical line on the screen (Fig. 9.12 (b)).

If the Y-gain control is at 50.0 V/cm and the deflection, *d*, is (±) 4 cm, then the peak value of the input ac voltage is 50.0 V/cm × 4 cm = 200 V.

9.3.2 The X-deflection plates

The X-plates are internally connected to the time-base circuit, which applies a saw-tooth voltage to the X-plates as shown in Fig. 9.13.

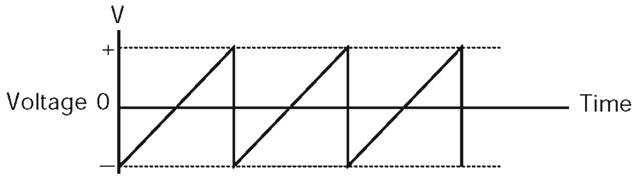


Fig. 9.13: Saw-tooth voltage waveform

The electron beam is moved from the left hand side of the screen to the right during the time that the voltage rises to maximum and then is returned rapidly to the left as the voltage returns to zero. This mechanism is called *the fly back mechanism*. The fly back mechanism 'sweeps' the spot along the X-axis from *left to the right hand side* of the screen. The frequency of motion of the electron along the X axis can be adjusted with the help of the time-base knob and can be varied from 1 s to 1μs per division. For example, if the time-base is set at 1 s/cm (1 second per division), then the electron spot takes 1 s to move through 1 cm along the X-axis. If the time-base is set at 1 ms/cm, then the time taken is 0.001 s for the spot to move 1 cm etc.

Activity 9.5: **To demonstrate the variations of time-base with no input voltage to the Y-plates**

Materials

- Cathode ray oscilloscope
- Time-base

Steps

1. Switch on the cathode ray oscilloscope and make sure that the time-base is in the 'off' position.
2. Adjust the control knobs until you obtain a sharply focused bright spot at the centre of the cathode ray oscilloscope screen. The potential difference between the Y-plates is zero and the Y-deflection is zero.
3. Set the time-base at 1 s/cm and observe what happens to the spot.
4. Repeat the activity by setting the base at 1 ms/cm. What is the effect?

When the time-base is set at 1 s/cm, the potential difference between the X-plates changes at such a rate that the spot starts moving along the X-axis and it takes 1.0 s for the spot to travel 1.0 cm on the screen (Fig. 9.14 (a)). When the time-base is set at 1 ms/cm, the potential difference between the X-plates changes so rapidly that the spot starts moving faster along the X-axis and a horizontal line is seen on the cathode ray oscilloscope screen (Fig. 7.14 (b)).

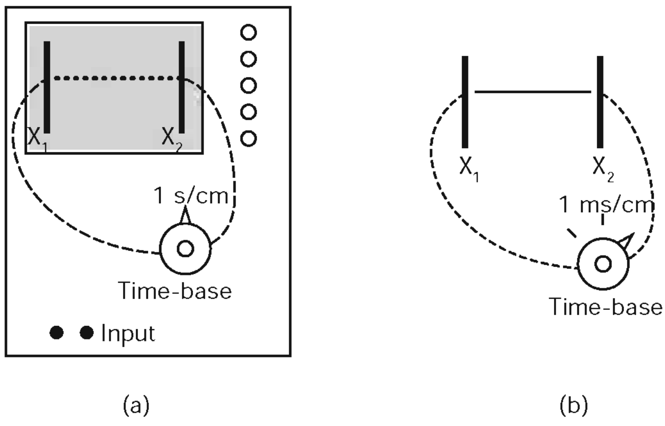


Fig. 9.14: Time-base 'on' with no input voltage to the Y-plates

Activity 9.6: **To demonstrate the variations of the time-base with a d.c voltage on the Y-plates**

(Work in groups)

Materials

- Cathode ray oscilloscope
- DC voltage

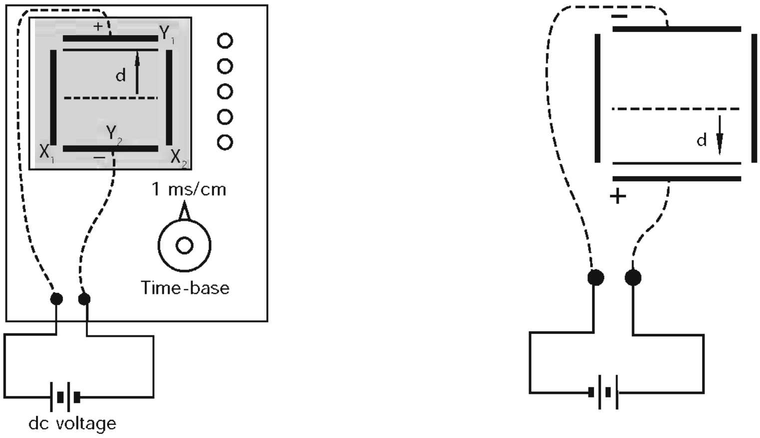
Steps

1. Repeat Activity 9.3 with the time-base set at 1 ms/cm and a d.c voltage applied to the input of the cathode ray oscilloscope. What is the effect? Explain.
2. Reverse the polarities of the Y-plates by interchanging the terminals of the d.c voltage supply. What happens? Explain the observation.

   Repeat the Activity by replacing the dc voltage source by an ac voltage source. Observe the effect on the cathode ray oscilloscope screen. What is happening now? Change the input voltage or the time-base setting. What is the effect?

When a d.c voltage is applied to the Y-plates, the horizontal line is seen to move up i.e. deflected upwards due to the lower plate (Y_2) being at a negative potential (Fig. 9.15 (a)).

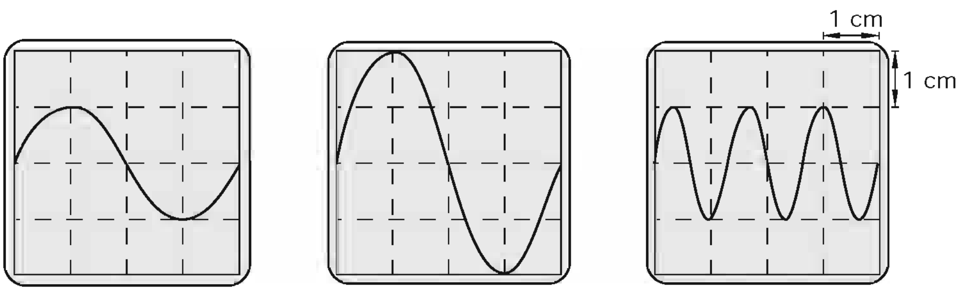
When the polarities of the Y-plates are reversed, the horizontal line seen in Fig. 9.15 (b) moves down i.e. deflected downwards.



(a) (b)

Fig. 9.15: Time-base 'on' with dc voltage to the Y-plates

In Fig. 9.16 (a), we see a 'sine curve' on the screen. When the input alternating voltage to the Y-plates is increased, the peak value of the sine curve increases (Fig. 9.16 (b)). When the time-base setting is changed, we get more crests of the sine curve on the screen (Fig. 9.16 (c)).



(a) Time-base at 1 ms/cm

(b) Time-base at 1 ms/cm but a large input to y-plates

(c) Alternating current input to the y-plates, same as (a), but different time-base

Fig. 9.16: Time-base 'on' with alternating current voltage to the Y-plates

9.4 Uses of cathode ray oscilloscope

Activity 9.7: **To find out the uses of cathode rays**

(Work in groups)

Materials

- Reference sources

Steps

1. Discuss in groups, the uses of cathode rays oscilloscope.
2. Present a summarised report of your discussion to the whole class through your group secretary.

The cathode ray oscilloscope can be used to display any electrical signal whose variations can be put in form of a voltage. An oscilloscope can also be used as a measuring instrument. The cathode ray oscilloscope can be used to:

1. Measure amplitudes of both dc and ac voltages.
2. Measure frequency of waves.
3. Measure small time intervals.

9.4.1 Measurement of voltages

The voltage to be measured is applied to the input of the cathode ray oscilloscope. If the time base is 'off', dc or ac signals appear as a deflected 'spot' or as a vertical line respectively. (See Fig. 9.11 (b), (c), (d) and Fig. 9.12 (a) and (b)).

If the time-base is 'on', dc voltages appear as shown in Fig. 9.15 (a) and (b), whereas a sinusoidally alternating voltage produce a display of the forms shown in Fig. 9.16 (a), (b) and (c). In each of the above cases, it may be necessary to adjust the Y-gain or V/cm control to give a display within the screen.

The cathode ray oscilloscope is particularly useful for measuring voltage, because no current is taken by it, i.e. there is no resistance wire or coil across the input terminals. Hence the cathode ray oscilloscope tends to have an infinite resistance, which is the condition required for an ideal voltmeter. The cathode ray oscilloscope can be used to measure direct current, alternating current or voltage accurately (Experiments 9.1 and 9.2). *The deflection (d) produced on the screen along the y-axis is directly proportional to the input voltage.*

Unlike a moving coil voltmeter, there is no coil in an oscilloscope which can burn out due to excess current. Also the electrons behave like a virtually weightless pointer enabling instantaneous response to direct current or alternating current voltages. However, compared to a moving coil voltmeter, the cathode ray oscilloscope is rather expensive, cumbersome and not very sensitive.

9.4.2 Measurement of frequencies

The signal of an unknown frequency e.g. the frequency of the heart beat of a person or that of a musical sound, is fed to the input terminals of the oscilloscope. Using the calibrated time-base, adjust the time-base so that the waveform seems to be stationary on the screen. Now the frequency of the input signal is equal to the frequency with which the electron beam is forced to 'fly' (oscillate) between the X-plates. The time base is read off from the scale division and the mean wavelength determined by counting the number of full waves in a certain distance measured on the X-axis on the screen.

$$\text{Mean wavelength } (\lambda) = \frac{\textit{distance measured}}{\textit{number of full waves}}$$

Knowing the wavelength and the time base, the mean time period, T, for one full wave is found. The frequency, f, of the signal is calculated using the formula $f = \frac{1}{T}$.

9.4.3 Measurement of small time interval

If two events occur within a short interval of time, say a student strikes the skin of a drum twice consecutively, one after another, the sound waves produced by the drum can be picked by a microphone. The microphone converts the sound energy into electrical pulses. These signals from the microphone are fed to the input terminals of the cathode ray oscilloscope whose time-base is on. The two 'pulses' produced are seen on the cathode ray oscilloscope's screen as shown in Fig. 9.17.

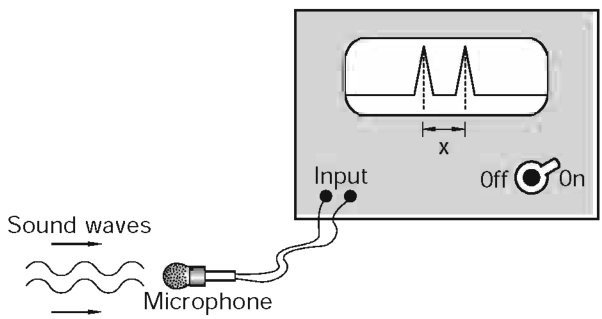


Fig. 9.17: Measurement of small time intervals

Knowing the time base of the cathode ray oscilloscope and the distance x between the two pulses, the time intervals between the two signals can be calculated.

Example 9.1

In a cathode ray tube, an electron is accelerated by a potential difference of 2 000 V. Calculate the speed of the electron. (Take the mass of an electron $m = 9.1 \times 10^{-31}$ kg, the charge of an electron $e = 1.6 \times 10^{-19}$ C).

Solution

By definition, the potential difference $V = \frac{\text{work done}}{\text{charge}} = \frac{W}{Q}$

Work done by the electric field on an electron $W = QV = eV$, where e is the charge of an electron ....(1)

The kinetic energy of an electron = $\frac{1}{2}mv^2$ ....(2)

where m is the mass of an electron and v its speed.

From 1 and 2, $\frac{1}{2}mv^2 = eV$

$$v^2 = \frac{2eV}{m}$$

$$= \frac{2 \times 1.6 \times 10^{-19} \times 2 \times 10^3}{9.1 \times 10^{-31}}$$

$$= \frac{6.4}{9.1} \times 10^{15}$$

$$= 7.03 \times 10^{14}$$

$$v = \sqrt{7.03 \times 10^{14}}$$

$$= 2.65 \times 10^7 \text{ m/s}$$

The speed of the electron is 2.65×10^7 m/s

Example 9.2

Fig. 9.18 shows the waveform displayed on the cathode ray oscilloscope screen when an alternating voltage is applied to the Y-input. The time-base is set at 1 ms/cm and the Y-gain at 10 V/cm. Calculate

(a) the amplitude of the ac input voltage,

(b) the frequency of the ac input voltage signal.

Solution

(a) Since the peak value is 2 cm on the screen and the Y-gain is 10V/cm, then the amplitude of the ac input voltage
= 10 × 2 = 20 V.

(b) There are 2 complete waves in 5.0cm. Since the time base is 1 ms/cm, the time taken by the spot to travel 5.0 cm is 5 ms. Hence the time period, *T*, of a wave is 2.5 ms.

Frequency $f = \frac{1}{T} = \frac{1}{2.5 \times 10^{-3} s} = 400$ Hz.

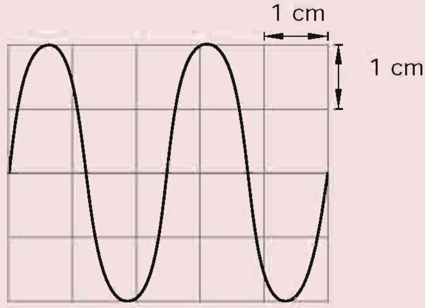


Fig. 9.18

Example 9.3

In Fig. 9.19, the length of the vertical line on the screen of a cathode ray oscilloscope is 7.2 cm and the Y-gain is set at 80.0 V/cm. Calculate the amplitude of the ac input voltage.

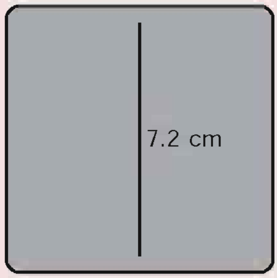


Fig. 9.19

Solution

Since the length of the vertical line is 7.2 cm, the deflection, *d*, is 3.6 cm. The Y-gain is 80 V/cm. Hence the amplitude of the ac voltage input = 80 × 3.6 = 288 V.

Example 9.4

Draw the trace on a graph paper to show the waveform of an ac voltage of frequency 100 Hz and amplitude 10 V. The following are the settings of the cathode ray oscilloscope:

1. The time-base is 10 ms/cm.
2. The Y-gain is 5 V/cm.

Solution

The frequency *f* of ac voltage = 100 Hz.

$\therefore$ The time period, $T = \frac{1}{f} = \frac{1}{100} = 0.01$ s

The time-base is set at 10 ms/cm = 10×10^{-3} s/cm = 0.01 s/cm.

Since the time period is 0.01 s and the time-base is 0.01 s/cm, then the wave length λ is 1 cm.

Since the Y-gain is set at 5 V/cm and the amplitude of the ac voltage is 10 V, the amplitude on the Y-axis should be 2 cm. Hence we draw a sine wave of amplitude 2 cm and wavelength 1 cm, as shown in Fig. 9.20.

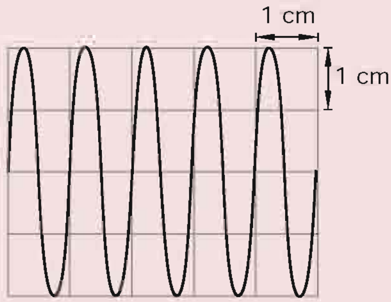


Fig. 9.20

Example 9.5

Two Kenyan athletes completed a race very close to each other in the 2004 Olympic games held in Athens, Greece. A cathode ray oscilloscope, with a time-base set at 50 ms/cm had been deployed to see the time interval between the athletes. Two 'pulses' produced on the screen are shown in Fig. 9.21. Calculate the time interval separating the two athletes.

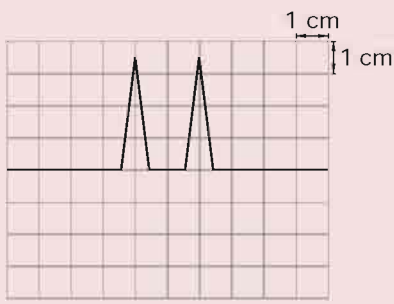


Fig. 9.21

Solution

From the cathode ray oscilloscope screen, the distance between the pulses = 2 cm

The time-base = 50 ms/cm

= 0.05 s/cm

Since the distance between the pulses is 2 cm, the time interval between them

$= 2 \times 0.05$ s

$= 0.10$ s

$\therefore$ the time interval between the two athletes is 0.10 s.

Topic Summary

- The process of removing an electron completely from an atom is called ionisation.
- Thermionic emission is a process where electrons are emitted from the surface of a hot metal plate or a hot filament.
- Cathode rays are the streams of negatively charged fast moving electrons, moving from the cathode towards the anode.
- Cathode rays travel in a straight line and cause fluorescence on certain materials.
- Cathode rays travel with a high speed and possess a lot of kinetic energy. In an electric field created due to a potential difference V, the kinetic energy of an electron is equal to work done by the electric field i.e

  $mv^2 = eV$ for an electron.
- Fast moving electrons can ionise the gas through which they travel and can affect photographic papers.
- Cathode rays can be deflected in both electric and magnetic fields.
- A cathode ray oscilloscope is an important electrical instrument which uses cathode rays to display waveforms on a fluorescent screen.
- The Y-plates of a cathode ray oscilloscope are horizontal plates connected to the input terminals of a cathode ray oscilloscope. These plates are used to deflect the electron beam up and down along the Y-axis.
- The X-plates of a cathode ray oscilloscope are vertical plates connected internally to a circuit called the time-base circuit. These plates are used to 'sweep' the electron beam along the X-axis at a particular frequency which can be varied.
- The brightness of the electron spot on the cathode ray oscilloscope screen can be controlled by giving either positive or negative potential to the control grid, with respect to the cathode.
- In addition to displaying waveforms, the cathode ray oscilloscope can be used to measure both direct and alternating voltages, frequencies of signals and also small time intervals.

- A television set makes use of a cathode ray tube. The electron beam is deflected by two pairs of magnetic coils placed at 90° to each other.
- The magnetic field produced by the coil can deflect the electron beam by a wider angle and hence we can have a television set with a wider screen but a relatively short cathode ray tube.

Topic Test 9

(Where necessary, take the charge of an electron $= 1.6 \times 10^{-19}$ C, the mass of an electron $= 9.1 \times 10^{-31}$ kg)

1. Explain the meaning of the terms (a) ionisation (b) thermionic emission.
2. (a) What are cathode rays? (b) Explain how cathode rays are produced?
   (c) Explain why a cathode ray tube is evacuated?
3. State four properties of cathode rays.
4. Copy and complete the diagram to show the path of cathode rays in an electric field (Fig. 9.24 (a)) and in a magnetic field (Fig. 9.24 (b)).

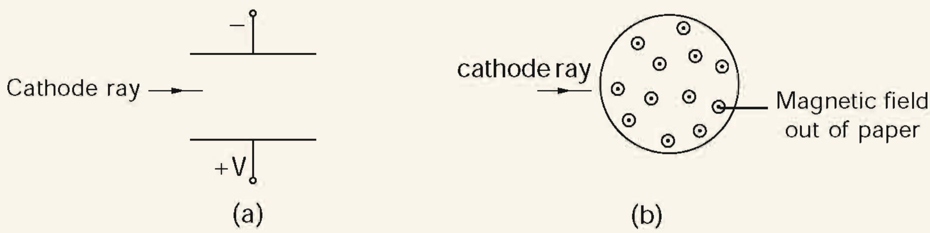


Fig. 9.24

5. A television tube uses a potential difference of 4 000 V to accelerate the electrons emitted by thermionic emission. Calculate
   (a) the energy of an electron as it strikes the screen,
   (b) the speed of the electron as it hits the screen.
6. State the functions of the anodes and the control grid of a cathode ray oscilloscope.
7. State the function of the following components in a cathode ray oscilloscope.
   (a) Time-base
   (b) Y-gain or volt per centimetre gain
   (c) Control grid
8. Explain why a cathode ray oscilloscope is considered to be an ideal voltmeter.

9. Fig. 9.25 shows the deflection of an electron spot from zero position in a cathode ray oscilloscope when a potential difference of 2 V is applied to the Y-plates.

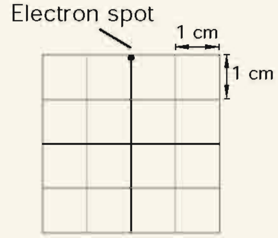


Fig. 9.25

Copy the diagram and show the spot or trace when

(a) dc voltage of 1 V is applied to the plates,

(b) ac voltage of 1 V is applied to the plates.

10. Explain how a cathode ray oscilloscope can be used to find the short interval between the firing of a pistol and detecting an echo produced from a cliff, a short distance away from the pistol.

11. The trace of a waveform on the screen of a cathode ray oscilloscope is shown in Fig. 9.26 (a). When the teacher made some alterations to the cathode ray oscilloscope settings, the following traces were formed as shown in Fig. 9.26 (b) and (c). How did the teacher obtain the traces in Figure (b) and (c)?

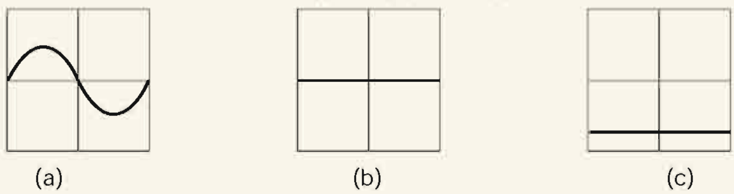


Fig. 9.26

12. The heartbeat of a person is recorded on a cathode ray oscilloscope as shown in Fig. 9.27. Calculate the average heartbeat per minute, if the time-base setting is 500 ms/cm. (Hint: $2\lambda = 3.6$ cm)

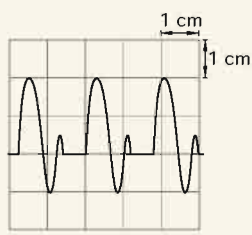


Fig. 9.27

13. The waveform in Fig. 9.28 (a) is displayed on a cathode ray oscilloscope screen. A Form 4 student then alters two controls to get the waveform shown in Fig. 9.28 (b).

Explain how the student obtained the waveforms shown in (b).

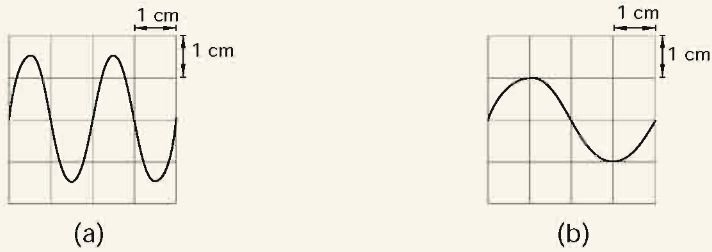


Fig. 9.28

14. Explain why magnetic fields are preferred in a television set to electric fields.

UNIT 7

Radioactivity and Nuclear Energy

Topic in the unit

Topic 10: Radioactivity and Nuclear Energy

Key inquiry question

- Why are radioactive wastes hazardous?
- Why is nuclear energy not common in South Sudan?

Learning outcomes

Knowledge and understanding

- Understand radioactivity and its use in providing nuclear energy.
- Explain the detection of radioactive emission.
- Describe the types of radiations emitted in natural radioactivity.
- Know the uses of radioactivity.

Skills

- Write balanced nuclear equations.

Attitude and value

- Consider the moral issues of nuclear energy.

TOPIC 10

Radioactivity and Nuclear Energy

Topic outline

- Introduction to radioactivity
- Radioactivity decay
- Types of radiations emitted and their properties
- Detectors of radiation
- Equations to describe radioactive decay
- Natural and artificial radioactivity

Introduction to Radioactivity

We are already familiar with sources of energy such as sunlight, wind, hydroelectric power and geothermal power which have been in use for many years.

In 1896, Henry Becquerel discovered another source of energy that takes place due to changes that takes place inside the nucleus of an atom. This process is known as *radioactivity*. In this unit, we will learn about the sources of radioactivity, its applications and dangers.

10.1 Definition of radioactivity

Experiments have shown that as the atomic number of elements increases, the number of neutrons also increase. Usually, the increase in the number of neutrons (N) is more than the increase in the number of protons (P).

Atoms whose ratio of N:P = 1:1 are said to be stable. Most of these are atoms of elements with atomic numbers between 1 and 20.

When the ratio N:P is much greater or much smaller than a certain range, then the atoms become unstable. The atoms disintegrate and emit some particles and/or radiations to become stable. This distergration is known as *radioactive decay*.

It is not yet understood what causes a particular atom to disintegrate at a particular moment. The disintegration is random and haphazard, and it is not possible to predict which atoms are going to decay and when they are likely to decay. Hence *radioactivity is a spontaneous and random process*.

Therefore, radioactivity is the process by which an unstable nucleaus spontaneously disintegrate to release energy by emitting radiations or particles.

As we will learn later in this topic, radioactivity can take place naturally (natural radioactivity) or can be artifically induced (artificial radioactivity).

10.2 A model of radioactive decay

Activity 10.1: **To illustrate the randomness and the experimental nature of radioactive decay**

Materials

- 256 bottle tops
- Carton

Steps

1. Collect about 256 bottle tops and put them in a large empty carton.
2. Shake the carton and suddenly empty it onto a table top or a clear floor.
3. Collect all the bottle tops facing upwards and record them as decayed.
4. Take the remainder (undecayed atoms) and replace them into the carton.
5. Repeat the experiment about 12 times.
6. Record the results as shown in Table 10.1.
7. Plot a graph of the number of tops remaining against the number of tops throws. Use the graph to describe radioactive decay.

You will obtain values similar to the ones in Table 10.1 below.

Table 10.1

Throws	0	1	2	3	4	5	6	7	8	9	10	11	12
No. of tops	240	240	202	170	143	120	100	85	71	60	50	42	36
No. of tops removed	0	38	32	27	23	20	15	14	11	10	8	6	6
No. of tops remaining	240	202	170	143	120	100	85	71	60	50	42	36	30

On plotting, a graph similar to the one in Fig. 10.1 is obtained.

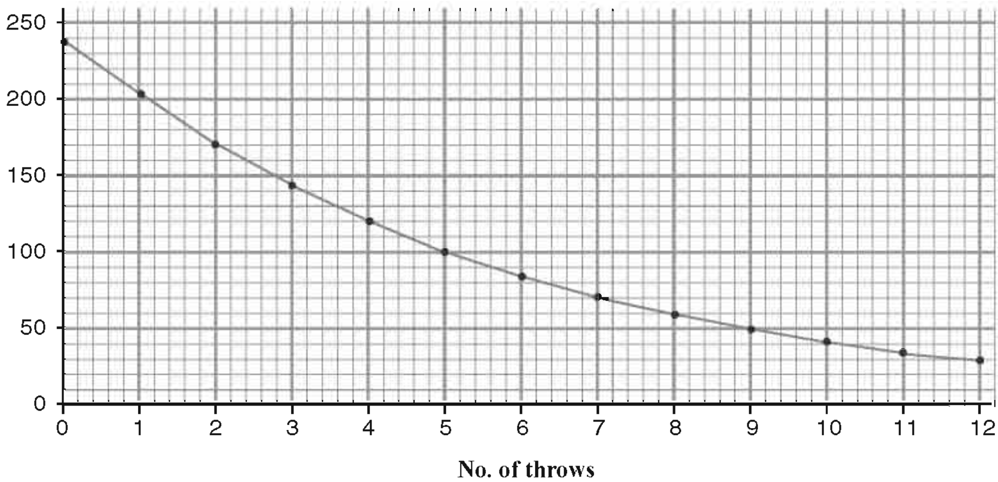


Fig. 10.1: Graph a model of radioactive decay model.

The graph gradually gets less steep and eventually gets close to zero but never reaches zero. After every 4 throws, the number of tops remaining (undecayed atoms) reduces to half of the original value. The graph is an *exponential curve*.

The number of tops removed (the number of atoms decayed) is not uniform and there is uncertainty in the decay rate. We cannot predict how many tops will fall facing upwards.

Experimental and statistical analysis reveal that any radioactive element has a definite rate of decay, known as the *activity* of the element. *Activity* is defined as *the rate of disintegration or the number of disintegrations per second of the radioactive substance*. It is measured in a unit called *becquerel* the symbol being Bq. *1 Bq is equal to 1 decay* or one disintegration per second.

10.3 Half-life

For a radioactive substance, the number of undecayed nuclei present decreases continuously with time. If at time $t = 0$, the number of nuclei present in a sample is N_0, then there will be a time when the number of undecayed nuclei N present in the sample will be exactly, half of the original number N_0, i.e. $N = N_0/2$. During this time, the activity of the sample will have reduced to half the original rate. This particular time is referred to as the *half-life* of the radioactive substance.

The *half-life* of a substance is defined as *the average time taken for the activity to decrease to half of the initial value or* the time taken for half *of the number of radioactive nuclei present to decay*.

In general, if the original activity is A_0, it reduces to $A_0/2$ in one half life period; $A_0/2$ reduces to $A_0/4$ in another half-life period, etc. as shown below:

$$A_0 \xrightarrow[T_{\frac{1}{2}}]{} \frac{A_0}{2} \xrightarrow[T_{\frac{1}{2}}]{} \frac{A_0}{4} \xrightarrow[T_{\frac{1}{2}}]{} \frac{A_0}{8} \xrightarrow[T_{\frac{1}{2}}]{} \frac{A_0}{16} \xrightarrow[T_{\frac{1}{2}}]{} \frac{A_0}{32}$$

Hence, the activity reduces to 1/32 of the original value after 5 half-lives.

Alternatively, if the original number of nuclei present in a sample is N_0, it reduces to $N_0/2$ in one half-life; $N_0/2$ reduces to $N_0/4$ in another half life, etc. as shown below:

$$N_0 \xrightarrow[t_{\frac{1}{2}}]{} \frac{N_0}{2} \xrightarrow[t_{\frac{1}{2}}]{} \frac{N_0}{4} \xrightarrow[t_{\frac{1}{2}}]{} \frac{N_0}{8} \xrightarrow[t_{\frac{1}{2}}]{} \frac{N_0}{16}$$

Hence, N_0 reduces to $N_0/16$ in 4 half-lives.

The idea of half-life period is represented graphically in Fig. 10.2, where $t_{\frac{1}{2}}$ is the half-life of a radioactive sample. The activity decreases exponentially with time.

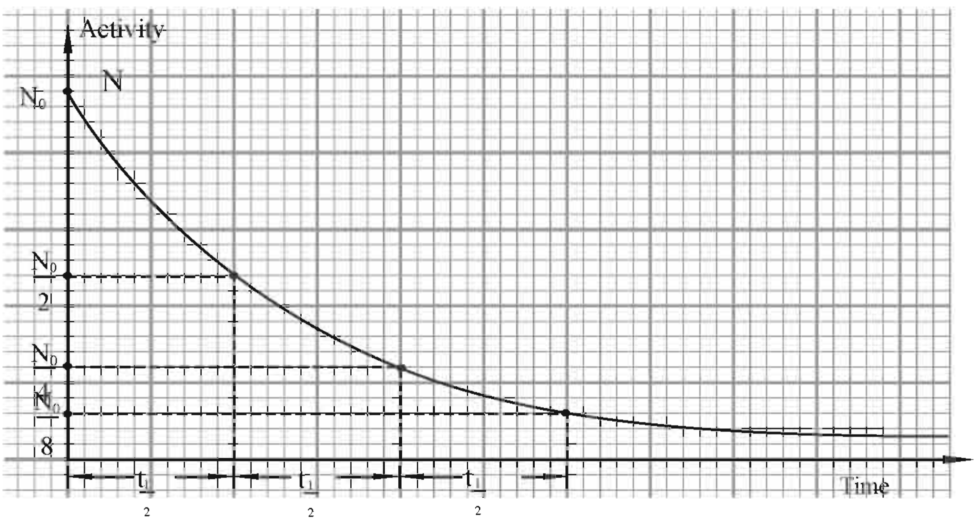


Fig. 10.2: Decay curve for a radioactive material

Half-life periods of the radioactive substances range from milliseconds to millions of years. The half-life is unique to each radioactive element.

Measurement of half-life is important in identifying specific radioactive element. For example, carbon-14, has a half-life of 5 600 years, iodine-131 is 8 days, whereas for uranium-238, the half-life is 4.5×10^9 years, i.e. 4 500 million years. Table 10.2 shows the half-life of some elements.

Table 10.2

Element	*Mass number*	*Half-life*
Uranium	238	$4\,500 \times 10^6$ years
Plutonium	239	24 000 years
Carbon	14	5 600 years
Radium	226	1 600 years
Caesium	137	30 years
Iodine	131	8 days
Bismuth	210	5 days
Sodium	24	15 hours
Bismuth	212	1 hour
Polonium	218	3 minutes
Radon	220	54 seconds
Polonium	214	1.6×10^{-4} seconds

Note:

If N_0 is the quantity of the radioactivity material present at the beginning, the quantity N remaining after a given time T is given by:

$N = N_0(\frac{1}{2})^{\frac{T}{t}}$ where *t* is the half life of the substance

Example 10.1

The half-life of iodine-131 is 8 days. If at time t = 0, the mass of iodine is 1 g, how much of iodine-131 will be left after 48 days?

Solution

48 days correspond to 6 half-lives 48 ÷ 8. A mass of 1 g will reduce to half a gram in one half-life; to quarter gram in another half-life, etc. as shown below.

$$1 \rightarrow \frac{1}{2} \rightarrow \frac{1}{4} \rightarrow \frac{1}{8} \rightarrow \frac{1}{16} \rightarrow \frac{1}{32} \rightarrow \frac{1}{64}$$

Alternatively by using the formula

$N_0 = 1$g, t = 8 days, T = 48 days, N = ?

$$N = N_0(\frac{1}{2})^{\frac{T}{t}} = 1 \times (\frac{1}{2})^{\frac{48}{8}} = 1 \times (\frac{1}{2})^6 = \frac{1}{64}\text{g}$$

Hence the mass of iodine left behind after 48 days = $\frac{1}{64}$ g.

Example 10.2

A radioactive substance has decayed to $\frac{1}{128}^{\text{th}}$ of its original activity after 49 days. What is its half-life?

Solution

As discussed in Example 8.1

$$1 \xrightarrow{1} \frac{1}{2} \xrightarrow{2} \frac{1}{4} \xrightarrow{3} \frac{1}{8} \xrightarrow{4} \frac{1}{16} \xrightarrow{5} \frac{1}{32} \xrightarrow{6} \frac{1}{64} \xrightarrow{7} \frac{1}{128}$$

Alternatively by using the formula

Let $N_0 = x$, $N = \frac{1}{128}x$, T = 49 days, t = ?

$$N = N_0\left(\frac{1}{2}\right)^{\frac{T}{t}} \Rightarrow \frac{x}{128} = x\left(\frac{1}{2}\right)^{\frac{49}{t}}$$

$$\text{Cancelling x} \Rightarrow \frac{1}{128} = \left(\frac{1}{2}\right)^{\frac{49}{t}} = \left(\frac{1}{2}\right)^{7} = \left(\frac{1}{2}\right)^{\frac{49}{t}}$$

$$7 = \frac{49}{t} \Rightarrow t = \frac{49}{7} = 7 \text{ days}$$

The time taken is 7 half-lives = 49 days

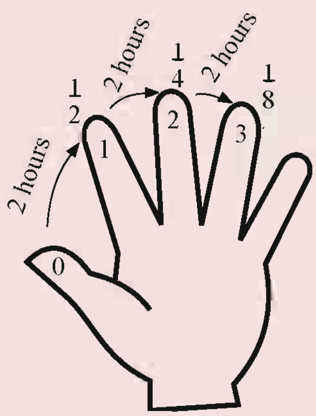
$\therefore$ Half-life of the substance = $\frac{49}{7}$ = 7 days

Example 10.3

A radioactive substance has a half-life of 2 hours. What fraction of the substance will remain after 6 hours have passed?

Solution

Here is a suggestion of how to do this. Simply count on your fingers as follows (Fig 10.3)



- **Thumb:** It represents the original substance.
- **First finger:** After one half-life (2hrs) $\frac{1}{2}$ of the original substance is left.
- **Second finger**: After two half-lives (4hrs), half of the $\frac{1}{2}$ that was left decay so $\frac{1}{4}$ that is left.
- **Third finger:** After three half-lives (6hrs) $\frac{1}{2}$ of the $\frac{1}{4}$ was left decay so that $\frac{1}{8}$ is left.

Fig.10.3: Using fingers of the hand to calculate the remaining fraction of radioactive atom

In this example, for a substance with a half-life of 2 hours, $\frac{1}{8}$ of the original atoms will remain after 6 hours have passed.

Example 10.4

A radioactive element is giving count rate of 15 counts per second. What was its count rate 8 hours ago if its half life is 2 hrs?

Solution

N = 15, t = 2 h, T = 8 h, N = ?

$N = N_0(\frac{1}{2})^{\frac{T}{t}} \Rightarrow 15 = N_0(\frac{1}{2})^{\frac{8}{2}}$

$$15 = N_0(\frac{1}{16}) = No = 15 \times 16 = 240$$

Its count rate 8 hours ago is 240 counts per second

Example 10.5

A nucleid of radium has half life of 1622 year. How long will it take 98.4375% of its original amount to decay?

Solution

N_0 = 100%, N = 100% – 98.4375% = 1.5625, T = ?, t = ?

$N = N_0(\frac{1}{2})^{\frac{T}{t}} \Rightarrow 1.5625\% = 100\% \times (\frac{1}{2})^{\frac{T}{t}}$

Letting n = number of half lives that elapse during the decay period,

$1.5625\% = (\frac{1}{2})^n \times 100\%$

Dividing both sides by 100, we get

$$0.015625 = (\frac{1}{2})^n \Rightarrow 0.015625 = (0.5)^n$$

Taking logs both sides we get Log 0.015625 = Log $(0.5)^n$

log 0.015625 = n log (0.5)

$$n = \frac{\log 0.0156\ 25}{\log (0.5)}$$

$$= \frac{\log (0.5)6}{\log (0.5)}$$

$$= \frac{\log (0.5)}{\log (0.5)} = 6 \text{ half lives}$$

Total time taken = 1 622 yrs × 6 = 9732

Exercise 10.1

1. What is meant by the following terms in relation to radioactivity:
   (a) Randomness. (b) Activity.
   (c) Radioactive decay. (d) Half-life.
2. (a) Define the terms radioactivity and background radiation.
   (b) State two possible sources of background radiation.
3. The half-life of a radioactive substance is 30 minutes. What fraction of the substance will have decayed after 120 minutes.
4. A sample of uranium-238 has a half-life of 4 500 million years. How long will it take for 15/16 of the original amount of uranium-238 in the sample to decay?
5. Explain the following statements:
   (a) Alpha particles have more ionising power than beta particles.
   (b) Beta particles are deflected more than alpha particles in a magnetic field.
   (c) During gamma ray emission, there is no change in either atomic number or the mass number of the radioactive substance.
   (d) A spark counter is not suitable to detect beta or gamma radiation.
6. What are gamma rays? State three properties of gamma rays which differ from that of alpha and beta rays.
7. At time $t = 0$, the activity of iodine -131 is 512 counts/minute and after 40 days it has decreased to 16 counts/minute. Calculate the half-life of Iodine-131
8. A radioactive substance is set up in front of a Geiger-Müller tube connected to a scaler counter and at the same time a stopwatch is started. The counter reading are recorded at 1 hour interval as shown in the Table 10.3.

Table 10.3

Time (hour	0	1	2	3	4	5	6
Corrected count rate per minuted	1000	781	609	476	371	290	226

Plot a graph of the corrected count rate against time. Determine the half-life of the radioactive substances.

9. Radon decays to 12.5% of its original activity in 12 days. What is its half life?

10. M grams of radiopactive element of half life of 28 days was left to decay. If only 8 g of the original mass was remaining after 140 days, find;

(i) value of (M)

(ii) mass that decayed.

11. In an experiment to determine the half-life of a radioactive element, a student uses an ionisation chamber and a very sensitive ammeter and obtains the results shown in Table 10.4.

Table 10.4

Time (s)	0	30	60	90	120	150	180
Current (mA)	3.00	1.95	1.26	0.82	0.53	0.35	0.22

Plot a graph of current against time. Determine the half-life of the substance.

12. Table 10.5 shows the results obtained in an experiment to study the absorption of beta particles by thin sheets of aluminium.

Table 10.5

Thickness of aluminium (mm)	0	2	4	6	8	10	12
Count rate (counts per minute)	800	629	495	389	306	241	190

(a) Plot a graph of the count rate against thickness. Determine the thickness of aluminium that could result in a count rate of 400 counts per minute.

10.4 Types of radiations emitted and their properties

A number of experiments were carried out by a physicist called Ernest Rutherford, to determine the exact nature of radiations emitted by a radioactive substance during the process of disintegration. On the basis of such experiments, it has been established that the radiation emitted by a radioactive substance are of three different types. The radiations are called the *alpha* (α), *beta* (β) and *gamma* (γ) rays. Every radioactive element does not necessarily emit all the three types of radiations.

Alpha particles (α)

Detection of alpha particles in a magnetic and uniform electric fields

Activity 10.2: **To detect alpha particles**

Do as a class demonstration.

Materials

- Element americium – 241
- A thick block drilled with a small hole.
- Evacuated chamber
- Electric and magnetic

Steps

1. Place a small amount of element americium-241 at the bottom of a small hole drilled in a thick lead block as shown in Fig. 10.4. Note: Radiations that strike against the walls of the block are usually absorbed.
2. Leave the whole arrangement in an evacuated chamber so that the radiations emitted from the source do not collide with the air molecules which would ionise them and hence lose energy.
3. Apply a strong uniform magnetic field to the chamber acting at right angles to the plane of the paper and directed into the paper, away from the reader. Record your observation. The radiation from the source S move in the plane of the paper and at 90° to the direction of the magnetic field (Fig. 10.4(a)).
4. Repeat step 3 with uniform electric field applied instead of magnetic field (Fig. 10.4 (b)). Record and explain your observations.

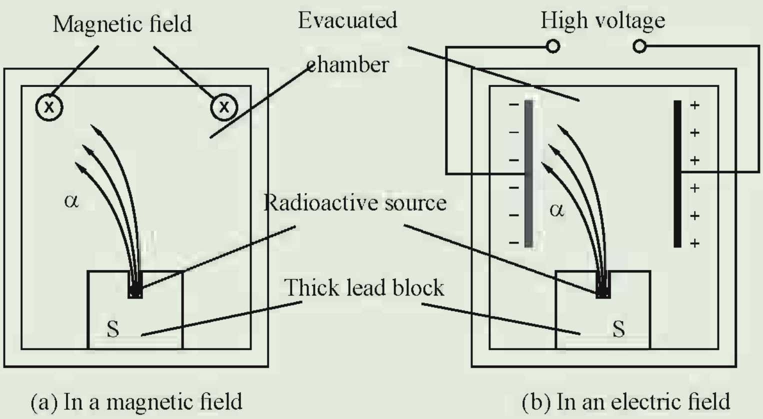


Fig. 10.4: Detection of α - rays

It is observed that the radiations emerging out of the hole of the lead block are deflected to the left. The deflection implies that the radiation is made up of charged particles. By applying Fleming's left hand rule (motor effect), we see that these particles carry positive charge.

It is found that these radiations get deflected towards the negative plate, showing that they are positively charged. These radiations emitted by the source were originally referred to as *alpha rays*. Because the rays are deflected in both magnetic and electric field, they have been proved to be *charged particles*.

In 1909, Rutherford and Royds showed experimentally that an alpha particle is a helium nucleus, i.e, a helium atom which has lost two electrons.

They sealed a large quantity of radon gas which emits alpha particles above mercury in the thin walled glass tube A (Fig. 10.5). Alpha particles emitted by radon gas escapes through the thin walls of the tube into the evacuated chamber enclosed by the thick walled tube B. After a week, the mercury level in the tube B was raised so that the gas collected in the tube B was forced into the capillary tube C, with 2 electrodes E_1, E_2 sealed into it. Each alpha particle passing through the tube A collects 2 electrons and becomes a neutral helium atom.

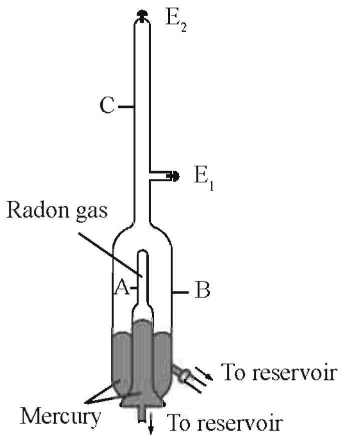


Fig. 10.5: Rutherford and Royd's experiment on alpha particles

A discharge was set up between the electrodes. The light coming from the discharge was analysed i.e the wavelength calculated and was found to be of helium. Ordinarily, helium sealed in tube A could not pass through the walls of tube A. Hence the above experiment proved that alpha particles may be identified with helium atoms.

Properties of alpha particles

1. An *alpha particle* is a helium nucleus, i.e, a helium atom without the two orbital electrons. An alpha particle is about 8 000 times heavier than an electron. The charge of an alpha particle is + 2e, where e is the charge of a proton which is equal

to the charge of an electron in magnitude. It thus has a mass number 4 and atomic number 2.

2. Alpha particles, travel in a straight line in free space
3. Alpha particles travel almost with the same speed, which is about 1×10^6 m/s.
4. Due to their heavy mass, alpha particles possess a lot of kinetic energy and also are mono-energetic, since they all have approximately the same energy.
5. They affect photographic papers, — the 'fogging' effect is prominent.
6. They ionise the gas through which they travel.
7. They cause fluorescence on certain substances like zinc sulphide, barium, platinocyanide, etc.
8. Their range in air is about 5-7 cm. During this distance, they ionise the air molecules and lose their energy almost completely.
9. Since they lose their energy in the ionisation process, their penetration power is limited.
10. Alpha particles are deflected in both magnetic and electric fields.
11. Alpha particles get scattered while passing through thin metal foils.

Beta particles (β)

Detection of beta particles (β)

Activity 10.3: **To detect beta particles**

Do as a class demonstration.

Materials

- Strontium-90
- A thick block drilled with a small hole.
- Evacuated chamber
- Electric and magnetic

Steps

- Replace the source used in the detection of alpha particles with element strontium-90, and repeat steps 1, 2 and 3 of activity 10.2.
- Record and explain your observations

The radiations emerging out of the hole of the lead block are deflected as shown in Fig. 10.6 (a) and (b).

By applying Fleming's left hand rule (motor effect), we see that the radiation carry negative charge. In the electric field, the radiation is deflected away from the negative plate, showing that the radiation is negatively charged. These radiations originally called the beta rays are actually the particles referred to as *beta particles*.

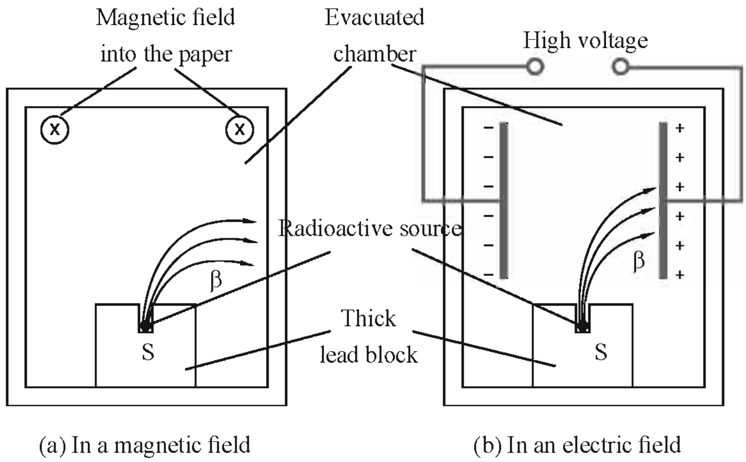


Fig. 10.6: Detection of beta rays

Properties of beta (β) particles

1. A beta particle is a negatively charged fast moving electron emitted from the nucleus. During a beta emission, a neutron which is slightly heavier than a proton, emits an electron and becomes a proton.

   neutron $\rightarrow$ proton + electron.

2. Beta particles do not have a well defined path like alpha particles.
3. Speed of beta particles is about 10-15 times the speed of alpha particles. The most energetic beta particles are emitted with almost the speed of light.
4. Beta particles are emitted with different energies.
5. Beta particles affect photographic paper but the effect is slightly less than that of alpha particles.
6. Beta particles ionise the gas through which they travel, but their ionising power is less than that of alpha particles.
7. Beta particles cause fluorescence on certain substances like zinc sulphide and other fluorescent materials.
8. The 'range' in air of beta particles is a few metres, the maximum range being about 5 m.
9. The penetrating power of beta particles is more than that of the alpha particles.
10. Beta particles are deflected by both magnetic and electric fields.

Gamma (γ) rays

Detection of gamma (γ) rays

Activity 10.4: **To detect gamma rays**

Do as a class demonstration.

Materials

- Cobalt – 60

Steps

- Replace the source used in the detection of beta rays in activity 10.3 with element cobalt-60 and repeat the activity.
- Record and explain your observations.

The radiations emerging out of the hole of the lead block are observed to go straight through the fields without any deflection.This shows that the radiations are not charged. Further experiments have proved that these radiations are pure electromagnetic radiations. These radiations are called *gamma* (γ) *rays*.

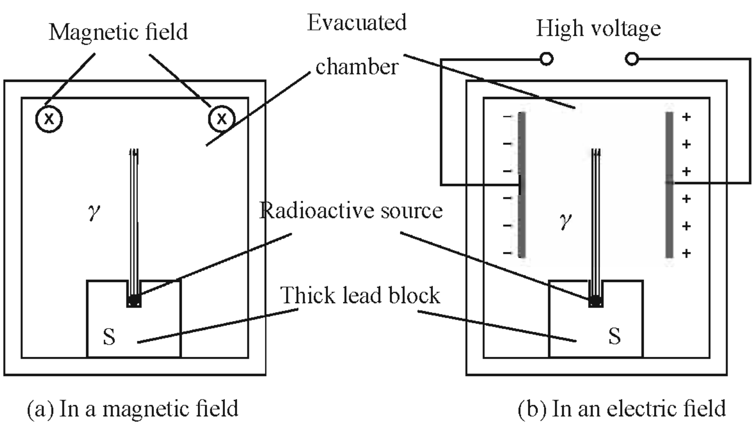


Fig. 10.7: Detection of γ - rays

Properties of gamma (γ) rays

Gamma rays:

1. Are uncharged electromagnetic radiation having no mass and no charge. They are like visible light or X-rays, but of very short wavelength ($10^{-11} – 10^{-13}$ m) and high frequencies. They originate from the energy changes in the nucleus of an atom. There is no change in the composition of the nucleus during gamma ray emission.
2. Travel in a straight line, but have no well defined path.

3. Travel with a speed of light (3×10^8 m/s) in air.
4. Possess energy called *photon energy*. Each gamma ray photon has an energy = *hf*, where *h* is the Planck's constant and *f* is the frequency of the gamma rays emitted.
5. Affect photographic papers, but the effect is the least as compared to alpha and beta particles.
6. Ionise the gas through which they travel.
7. Cause fluorescence on certain materials.
8. Have an almost infinite range in air.
9. Have the highest penetrating power when compared to alpha and beta particles.
10. Are not deflected in either electric or magnetic field.
11. Show diffraction effect in crystals and they are transverse in nature.

Summary of types of radiation

Table 10.6

Properties of α, β, γ			
Nature	α -particles	β -particles	γ -rays
	Are positively charged helium nucleus. 2 protons and 2 neutrons are emitted from the nucleus of an atom.	Are negatively charged electrons are emitted from the nucleus. A neutron which is heavier than a proton emits an electron.	Uncharged electro-magnetic radiation.
Charge	+2e	–e	0
Mass	8 000m_e	m_e (neglible)	0
Path in air	Travel in a straight line	No defined path like α particles	Travel in a straight line, but have no well defined path
Speed in air	About 1×10^6m/s	$1 \times 10^7 – 1 \times 10^8$m/s	3×10^8m/s
Energy	Possess maximum K.E and are mono-energetic as all the particle have approximately the same energy.	Energy is less than that of a α particle and are limited with different energies.	Possess energy called photon energy. Each gamma ray photon has an energy = *hf*, where *h* is the Planck's constant.

Effect on photographic paper	Affect photographic papers since the 'fogging' effect is maximum.	Effect is less than α–particles	Effect is the least
Ionising power	Ionising power is the most due to their heavy mass, high charge and low speed.	Less than that of α–particle.	Least compared to α– and β–particle
Range in air	About 5–7 cm	About 3 cm	Almost infinite
Fluorescence effect	Cause fluorescene on certain materials like zinc sulphide.		
Penetrating power	The penetrating power is the least. *About 5 cm of air, 4mm thick paper or 1 mm aluminium can 'stop' α–rays*	More than that of α–particles. Paper cannot 'stop' them, 4mm thick aluminium or a thin lead sheet can 'stop' them	Highest penetrating power. Paper or aluninium cannot 'stop' them. 4cm thick lead block reduces the intensity of γ-rays by about 90%. It is difficult to 'stop' γ-rays completely.
Effect of electric and magentic fields.	Deflected in both electric and magnetic fields		Not deflected in either field.
Source used in physics laboratories	Americium - 214 (Am)	Strontium - 90 (Sr)	Cobalt - 60 (Co)

10.5 Detectors of radiation

Many methods have been developed to detect radioactive radiations. We shall now discuss some of the detectors developed and the detection methods of radioactive emissions.

(a) The leaf electroscope

Activity 10.5: **To detect alpha particles using a leaf electroscope**

Do as a class demonstration.

Materials

- Leaf electroscope
- Source of alpha particle

Steps

- Bring a radioactive source that emits only alpha particles near the cap of positively charged leaf electroscope as shown in figure 10.8.
- Explain the observation through a group discussion.

If a radioactive source which emits only alpha particles (e.g. Americium-241) is brought near the cap of a positively charged leaf electroscope, as shown in Fig. 10.8 the leaf falls, i.e. the electroscope gets discharged. A suggestion on how to construct a simple electroscope is shown at the end of this unit.

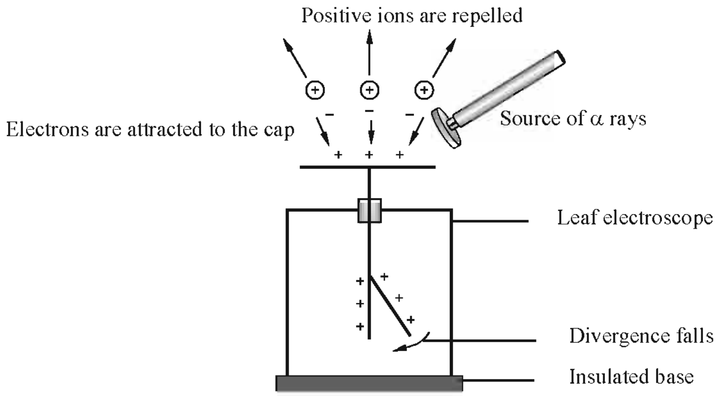


Fig. 10.8: Detection of a radiation with a leaf electroscope

Alpha particles, having the maximum ionising effect, knock off electrons from the surrounding air molecules leaving them as positively charged air ions.

The electrons are attracted by the positively charged electroscope and the charge on the electroscope is neutralised, i.e. it losses its charge.

If the electroscope is negatively charged, the positive ions from the air are attracted to the cap and the electroscope is neutralised.

This method is not suitable for beta and gamma radiations because their ionising effects in air are not sufficiently high.

(b) The spark counter

Fig. 10.9 below shows a spark counter.

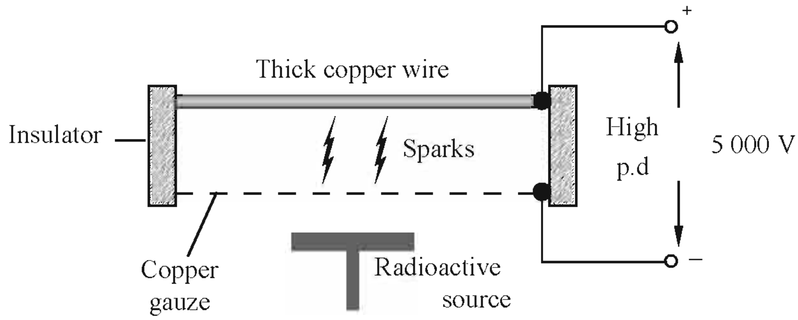
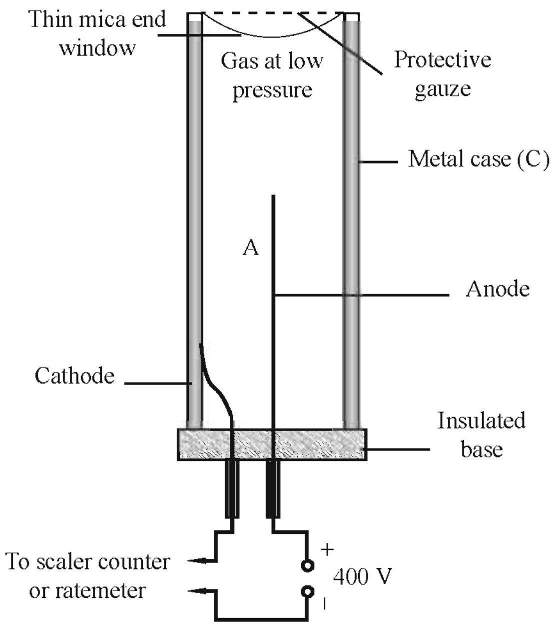


Fig. 10.9: A spark counter

The high potential difference applied makes air to conduct electricity. When the air between the gauze and the metal wire is ionised by the radiations from the source, a spark occurs. This detector provides a useful means of detecting alpha rays. If the source is weak, the individual sparks produced can be counted and used as a measure of the radioactivity of the source. Once again, this method is not quite appropriate for detection of beta and gamma radiation, due to their weak ionising effect.

(c) The Geiger-Müller tube (G.M tube)

This instrument is probably the most versatile and useful of the devices available for detecting radiations from radioactive substances. The typical design is shown in Fig. 10.10 (a) and (b).



(a)

(b)

Fig. 10.10: The Geiger-Müller tube

A Geiger-Müller tube consists of a partially evacuated metal tube (pressure = 1×10^4 N/m^2) containing an inert gas such as argon with traces of bromine. At the centre, there is a thin metal wire A which acts as anode. The metal case, C, acts as cathode. The anode and the cathode are separated by an insulated base. The anode should be a thin wire, so that a strong electric field is created near it, when a power supply is connected between the anode and the cathode. The tube has a very thin mica end window through which radiation can pass with very little absorption.

When any ionising radiation enters the tube, the air molecules are ionised. The ions produced are then accelerated by the electric field between the anode and the cathode. Collision with other gas molecules causes further ions. These ions in turn, are accelerated and produce even more ions. This 'avalanche' effect causes a pulse of current between the anode and the cathode.

The pulse of currents produced are amplified and fed either to a digital scaler counter which counts the actual number of pulses or to a ratemeter, which measures the average number of pulses over an interval of time.

It is important that only one pulse should be registered for each ionising particle entering the Geiger-Müller tube. But the positive ions formed in the gas, having more energy, may reach the cathode and liberate secondary electrons from it. These electrons can cause a further avalanche of electrons and number of pulses may be produced by a single original particle entering the tube. A suitable method of preventing this to happen is to include a small quantity of a halogen vapour as 'a quenching' agent e.g. bromine. Bromine will absorb the energy of the positive ions before they cause secondary electron emission. During a time interval, called the *dead time* (about 10^{-4} s), the tube becomes insensitive to the arrival of further particles. With the presence of bromine inside the tube, *only one pulse is produced by one radioactive particle entering the tube*. Therefore, a Geiger-Müller tube with a scaler counter can be used to find the activity, i.e. the rate of disintegration of a source accurately.

(d) Diffusion cloud chamber

We cannot see the radiation emitted by a radioactive substance directly. The radiation emitted by a radioactive source ionise the medium through which they travel. The path along which ionisation takes place is visible, when the path is illuminated suitably by light. A diffusion cloud chamber makes use of this property. When an ionising particle passes through a gas it leaves a trail of positive ions along its track.

The cloud chamber enables photographs to be obtained on the paths of the ionising particles. Fig. 10.11 illustrates the basic design of a diffusion cloud chamber.

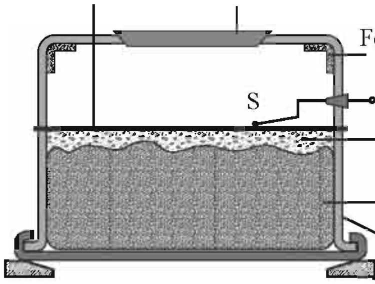


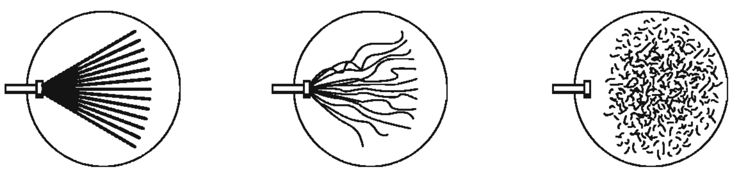
Fig. 10.11: A diffusion cloud chamber

A diffusion cloud chamber consists of a perspex cylindrical container with a perspex top and a strip of felt at the top containing excess of a mixture of alcohol and water. The bottom compartment which houses a sponge has a removable plastic base with levelling wedges to keep the chamber horizontal. The dark metal base is kept at a low temperature of about $^{-}50°$ C by dry ice (solid carbon dioxide) packed below it. The sponge keeps the dry ice in contact with the metal plate. Alcohol vapour diffuses continuously from the top to the metal base of the chamber and the vapour becomes supercooled.

By rubbing the perspex top with a dry cloth or duster, the dust particles suspended in the top compartment are attracted to the charged perspex top by electrostatic induction. Now the air molecules are dust free and the supercooled alcohol vapour cannot condense on the heavier dust free air molecules.

A radioactive source S is now introduced into the top compartment from the side. The radiations emitted by the source ionise the air molecules. The supercooled alcohol vapour immediately condenses on these tiny ionised molecules. The tracks along which the positive ions pass remain behind and can be clearly seen from the top.

Fig. 10.12 (a), (b), (c) show the tracks produced by alpha, beta and gamma radiations in different chambers.



(a) α - tracks (b) β - tracks (c) γ - tracks

Fig 10.12: Appearance of α, β and γ ray tracks

Alpha particles having maximum ionising power produce straight thick tracks of short length (Fig. 10.12 (a)). Beta particles give rise to thin broken erratic tortuous tracks. The length of the tracks are greater than those of alpha particles (Fig. 10.12 (b)). Gamma rays cause tracks which do not appear to have come directly from the source. Gamma rays do not produce ionisation directly but release electrons from the gas atoms which they strike. These electrons behave like beta particles and produce their own tracks (Fig. 10.12 (c)).

Nowadays detectors like *bubble chamber, solid state detectors, scintillation counter*, etc. are being employed to study the properties of radiations emitted by radioactive sources.

(e) Photographic plates

These are used in a sealed badges worn by scientists working with radiations. The plates are replaced when their exposure to radiations exceed a certain level as seen by the blackening of the plates.

(f) Ionisation detectors

This detects and measures the ionisation properties of radiations such as alpha, beta and gamma rays.

(g) Scintillation counter

This involves the use of a flourescent screen together with a microscope of a flouresecent crystal placed in contact with a photomultiplier. As the radioactive rays strike the crystal, light rays (scintillations) are produced.

This light rays (scintillations) are detected by the photomultiplier.

Background radiation

Activity 10.6: **To detect background radiation at a place**

Do as a class demonstration.

Materials

A geiger – muller tube

Scaler – counter

Steps

- With no radioactive material nearby, switch on a Geiger-Müller tube connected to a scaler-counter.
- Observe the counter readings at 1 minute interval for a few minutes and record these values. What information can be deduced from these readings?

The Geiger-Müller counter registers some radiations, though there are no radioactive sources nearby. The readings are almost a constant but shows considerable random fluctuations (see Table 10.7).

Table 10.7: The background radiation detected by a Geiger-Müller tube with no radioactive source

Time (minute)	1	2	3	4	5	6	7	8
count rate (counts per minute)	20	21	20	19	18	22	19	21

The average background count = 20 counts / minute.

The detector is recording the *background radiation*, which is present in the atmosphere. Background radiation is the 'stray' radiation present in the atmosphere and it is not due to a particular radioactive material. The possible causes of these background radiations include the cosmic radiation which originate outside the earth (from the sun), the presence of natural radioactive materials in the rocks around us, granite rocks, fossil fuels (very old tree trunks), etc.

The average background radiation count rate should be calculated and the average value subtracted from all the count rate reading during any experiment to give the corrected count rate.

If Experiment 10.9 is repeated with a radioactive source near the mica window of a Geiger-Müller tube, the readings shown in Table 10.4 is obtained.

Table 10.8: The reading of a Geiger-Müller tube with a radioactive source

Time (min)	0	1	2	3	4	5	6	7	8
count rate (counts per minute)	861	680	535	426	339	269	213	172	160
corrected count rate (counts per minute)	841	660	515	406	319	249	193	152	140

Corrected count rate = counter reading – background reading.

Experiments using detectors of radiation

Activity 10.7: **To determine the half-life of a radioactive substance**

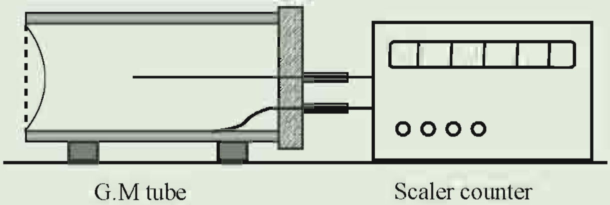
Do as a class demonstration.

Materials

- G.M tube
- Scaler counter
- Radioactive sources

Steps

(a) With no radioactive source nearby, switch the Geiger-Müller counter on and note the counter reading every minute, say for 8–10 minutes (Fig. 10.13 (a) and (b)).



(a)

(b)

Fig. 10.13: Background radiation

Calculate the average background count per minute.

(b) Place the radioactive source S inside a thick lead block, in front of a Geiger-Müller tube, at a fixed distance x from the window of the tube as shown in Fig. 10.14.

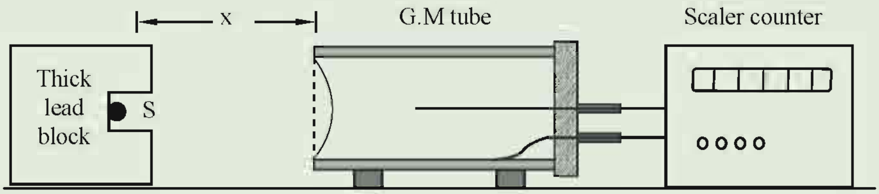


Fig. 10.14: Count rate of a radioactive substance

Switch the counter on and note the counter readings, say, for one minute. Continue the procedure for a few hours and tabulate the readings similar to Table 10.8.

(c) Calculate the corrected count rate per minute by subtracting the average background count per minute.

(d) Plot a graph of the corrected count rate per minute against time.

(e) Determine the half-life of the source from the graph as shown in Fig. 10.15.

The above method is effective if the half-life of the source is of the order of few hours or a few days. If the half-life is too short, of the order of a few minutes, an ionisation chamber with a sensitive ammeter should be used. On the other hand, if the half-life is too long, in the order of million of years, the activity (A) of the source is constant for a long period of time as shown in Fig. 10.15. Knowing the activity and the number of atoms present in the source, it is possible to calculate the half-life of the source.

Fig. 10.15: Activity of a source of long half-life

Example 10.6

During a physics lesson, a teacher took 8 readings by switching on the scaler counter at one minute intervals and observing the background count in that time. The following are the teacher's results: 27, 28, 24, 27 28, 26,28, 28. What is the average background count in the laboratory?

Solution

$$\text{The average background count} = \frac{27 + 28 + 24 + 27 + 28 + 26 + 28 + 28}{8}$$

$$= \frac{216}{8} = 27 \text{ counts/min.}$$

Activity 10.8: To demonstrate the penetrating power of alpha particles

Do as a class demonstration.

Materials

- G.M tube
- Scaler counter
- Radioactive sources

Steps

(a) Determine the background radiation at a place using G.M tube.

(b) Set up the arrangement as shown in Fig. 10.16 with a source of alpha particles (Americium-241) facing the mica windows of a Geiger-Müller tube at a fixed distance r away.

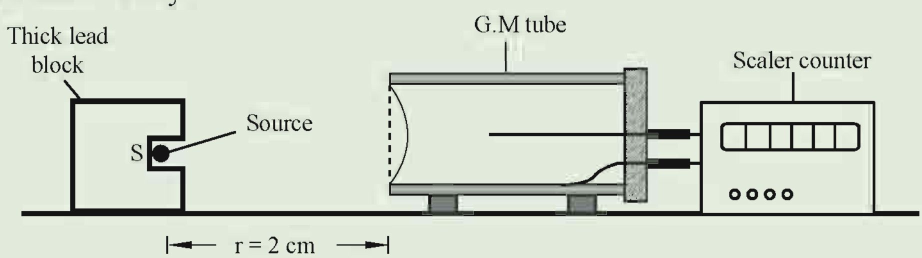


Fig. 10.16: Range of α rays in air.

Note the counter reading. Calculate the corrected counter-rate. Repeat the experiment by increasing the distance r. What happens to the counter reading?

(c) In the setup of Fig. 10.15, introduce a thin sheet of paper between the source and the Geiger-Müller tube and observe the counter reading. Increase the number of sheets, i.e. the thickness of paper and note the counter reading. What happens to the counter reading?

(d) Repeat the step (c) by introducing a thin aluminium foil of thickness 1 mm. What happens to the counter reading? Explain your observation.

As the distance r increases, it is found that the counter reading decreases. When the distance is more than 7 cm, it is found that the counter registers only the background radiation. This is the maximum range of alpha particles in air. While travelling this distance in air, alpha particles ionise the air molecules and lose all their energy.

Also as the thickness of the paper is increased, the counter reading decreases. When the thickness of the paper is about 4 mm, the counter registers only the background radiation. This means that about 4 mm of paper can completely "stop" the alpha particles.

The counter reading drops to background radiation. This means that a thin aluminium foil "absorbs" all alpha particles.

Hence when alpha particles travel through either 4 mm of paper or 1 mm of aluminium foil, they ionise the molecules of paper or aluminium and lose their energy. When they emerge out, the energy is almost zero.

Activity 10.9: **To demonstrate the penetrating power of beta particles**

Do as a class demonstration.

Materials

- G.M tube
- Scaler counter

Steps

- Repeat Activity 10.8 by replacing the source of alpha particles with a source of beta particles (strontium-90). What happens to the counter readings in each case? Explain your observation.

It is found that:

(i) The maximum range of beta particles in air is a few metres.

(ii) Beta particles penetrate through paper of several millimetres thick. Paper cannot "stop" beta particles.

(iii) Aluminium foil of several millimetres thickness can “stop” beta particles. If a graph of the corrected count rate against thickness of aluminium foil is drawn, the graph is an exponential curve as shown in Fig. 10.17.

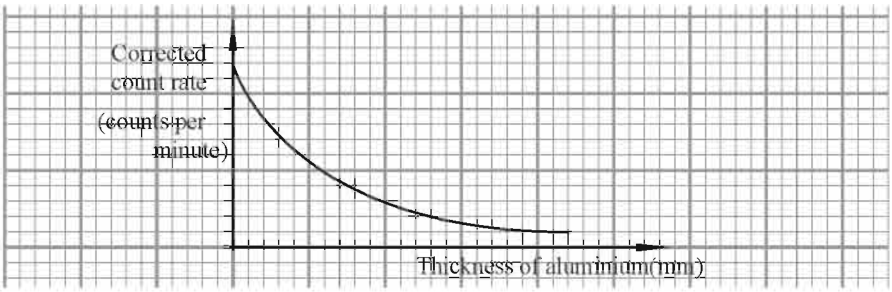


Fig. 10.17: Graph of beta particles count rate against thickness of aluminium

If activity 10.9 is repeated by introducing a thin lead sheet between the beta particles source and the Geiger-Müller tube. What happens to the counter reading? — The counter reading drops to almost the background radiation. This shows that a thin lead sheet can completely “stop” the beta particles.

Activity 10.10: To demonstrate the penetrating power of gamma rays

Materials

- G.M tube
- Scaler counter
- Radioactive source

Steps

- Repeat Activity 10.9 by replacing the source by a source of gamma rays (cobalt-60). What happens to the counter reading? Explain your observation.

It is found that the range of gamma rays in air is *almost* infinite. Paper or aluminium cannot “stop” gamma rays. About 4 cm thick lead block reduces the intensity of radiation by about 90%. It is difficult to “stop” gamma rays completely.

Example 10.7

A radioactive source is set up in front of a Geiger-Müller tube connected to a counter and at the same time a stopwatch is started. The counter readings are recorded at 1 minute interval as shown in the table below. (The counter is not switched off during the experiment)

Table 10.9

Time (minute)	0	1	2	3	4	5	6	7
Reading on the scaler counter (counts per minute)	0	330	557	719	838	926	994	1049
Count rate (counts per minute)	–	–	–	–	–	–	–	–
Corrected count rate (counts per minute)	–	–	–	–	–	–	–	–

The average background radiation is 30 counts/minute.

(a) Complete Table 10.9.

(b) Plot a graph of the corrected count rate against time. Determine the half-life of the radioactive substance.

Solution

(a) Subtract each reading from the next reading to get the count rate in each successive minute. The average background count is subtracted from these readings to get the corrected count rate (Table 10.10).

Table 10.10

Count rate (counts per minute)	–	330	227	162	119	88	68	55
Corrected count rate (counts per minute)	–	300	197	132	89	58	38	25

(b)

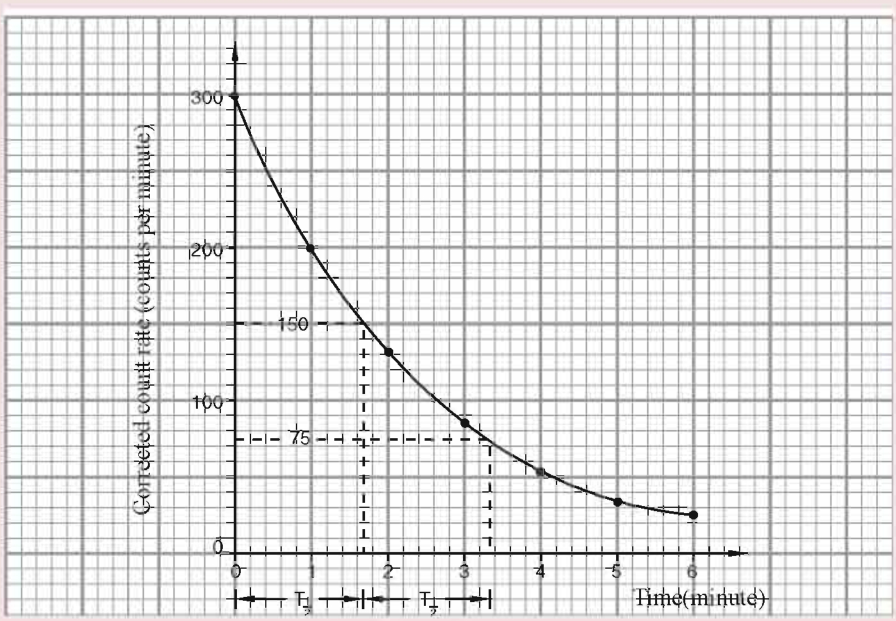


Fig. 10.17

From the graph, half-life of the substance is 1.7 minutes i.e. time for 300 counts to reduce to 150 or 150 to reduce to 75 counts.

Exercise 10.2

1. What is meant by the following terms in relation to radioactivity:
   (a) Randomness. (b) Activity.
   (c) Radioactive decay. (d) Half-life.
2. (a) Define the terms: radioactivity, background radiation.
   (b) State 2 possible sources of background radiation.
3. Describe a simple experiment to demonstrate that a radioactive substance emits 3 types of radiation.
4. The half-life of a radioactive substance is 30 minutes. What fraction of the substance will have decayed after 120 minutes?
5. A sample of uranium-238 has a half-life of 4 500 million years. How long will it take for 15/16 of the original amount of uranium-238 in the sample to decay?
6. Explain the following statements:
   (a) Alpha particles are more ionising than beta particles.
   (b) Beta particles are deflected more than alpha particles in a magnetic field.
   (c) During gamma ray emission, there is no change in either atomic number or the mass number of the radioactive substance.
   (d) A spark counter is not suitable to detect beta or gamma radiation.
7. What are gamma rays? State three properties of gamma rays which differ from that of alpha and beta rays.
8. At time $t = 0$, the activity of iodine -131 is 512 counts/minute and after 40 days it has decreased to 16 counts/minute. Calculate the half-life of Iodine-131
9. A radioactive substance is set up in front of a Geiger-Müller tube connected to a scaler counter and at the same time a stopwatch is started. The counter reading are recorded at 1 hour interval as shown in the Table 10.11.

Table 10.11

Time (hour)	0	1	2	3	4	5	6
Corrected count rate per minute	1 000	781	609	476	371	290	226

Plot a graph of the corrected count rate against time. Determine the half-life of the radioactive substance.

10. In an experiment to determine the half-life of a radioactive element, a student uses an ionisation chamber and a very sensitive ammeter and obtains the results shown in Table 10.12.

Table 10.12

Time(s)	0	30	60	90	120	150	180
Current(mA)	3.00	1.95	1.26	0.82	0.53	0.35	0.22

Plot a graph of current against time. Determine the half-life of the substance.

11. Fig. 10.19 shows an experimental set-up in vacuum for investigating the effect of a magnetic field on the radiation emitted by a radioactive source.

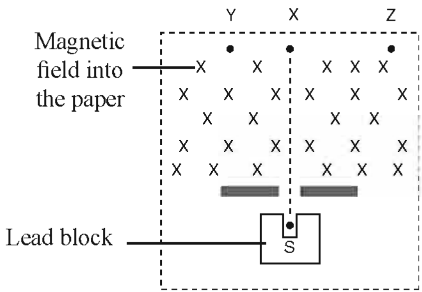


Fig. 10.19

The background radiation at the place is 20 counts/minute. A detector is placed at points X, Y and Z and the results obtained are shown in Table 10.13.

Table 10.13

Position	X	Y	Z
Count/min	240	20	220

Use the table to explain which of the 3 types of radiations alpha particles, beta particles or gamma rays are emitted from the source.

12. Table 10.14 shows the results obtained in an experiment to study the absorption of beta particles by thin sheets of aluminium.

Table 10.14

Thickness of aluminium(mm)	0	2	4	6	8	10	12
Count rate (counts per minute)	800	629	495	389	306	241	190

(a) Plot a graph of the count rate against thickness. Determine the thickness of aluminium that could result in a count rate of 400 counts per minute.

(b) Use the graph to determine the count rate if the thickness of aluminium is 3 mm.

10.6 Equations to describe radioactive decay

(a) Alpha emission

We have learnt that an alpha particle is actually a helium nucleus. Helium nucleus is represented as $^{4}_{2}He$. During an alpha emission, 2 protons and 2 neutrons are emitted spontaneously from the nucleus of an atom of the radioactive element. Hence during the alpha emission, the atomic number (Z) of the atom decreases by 2 and the mass number (A) decreases by 4. For example, if polonium $^{210}_{84}Po$ emits an alpha particle, the resulting products could be an alpha particle and a lead nucleus. The reaction could be represented by:

$$^{210}_{84}Po \longrightarrow \alpha - \text{particle} + \text{Lead}$$

Polonium is called the *parent nuclide* and lead is the *daughter nuclide*. This is called a *nuclear equation*. Since an alpha particle is a helium nucleus, it is represented by the symbol: ^{4}He or $^{4}\alpha$. Hence,

$$\therefore \quad ^{210}_{84}Po \longrightarrow {}^{4}_{2}He + Pb$$

To balance the equation on both sides, the atomic number of lead should be 84 – 2 = 82 and the mass number should be 210 – 4 = 206.

$$\therefore \quad ^{210}_{84}Po \longrightarrow {}^{4}_{2}He + {}^{206}_{82}Pb$$

Similarly, when americium ($^{241}_{95}Am$) decays into neptunium -237 by emitting an alpha particle, the nuclear decay equation can be written as:

$$^{241}_{95}Am \longrightarrow {}^{4}_{2}He + {}^{237}_{93}Np$$

It should be noted that A and Z are *balanced* across the equation (both atomic and mass number are conserved).

The general evaluation for alpha particle emission is

$$^{A}_{Z}X \longrightarrow {}^{A-4}_{Z-2}Y + {}^{4}_{2}He$$

(b) Beta emission

A beta particle is a fast moving electron emitted from the nucleus. It is represented as $_{-1}e$ or $_{-1}\beta$. During beta emission, a neutron inside the nucleus becomes a proton, i.e. the neutron number decreases by 1 whereas the proton number increases by 1. Hence the atomic number increases by 1 whereas the mass number (A) remains the same. For example, if an isotope of carbon, ^{14}C, emits a beta particle, the reaction produces a beta particle and a nitrogen nucleus. The reaction can be written as:

$$^{14}_{6}C \longrightarrow \beta - \text{particle} + \text{Nitrogen}$$

$$^{14}_{6}C \longrightarrow {}^{0}_{-1}e + N$$

To balance the equation on both sides, the atomic number of N should be
6 – (–1) = 7 and the mass number should be 14 – 0 = 14.

$$\therefore \quad C \longrightarrow {}^{0}_{-1}e + {}^{14}_{7}N$$

Similarly, when an isotope of Strontium, $^{88}_{38}Sr$ decays into an isotope of yttrium by emitting a beta particle, the nuclear decay equation can be written as:

$$^{88}_{38}Sr \longrightarrow {}^{0}_{-1}e + {}^{88}_{39}Y$$

The general equation for beta particle emission is

$$^{A}_{Z}X \longrightarrow {}^{A}_{Z+1}Y + {}^{0}_{-1}e$$

(c) Gamma ray emission

Gamma rays are represented by $^{0}_{0}\gamma$. They have no mass and no charge. If an element decays by emitting gamma rays only, then its mass number and atomic numbers do not change. The nuclear equation for gamma emission of cobalt – 60 is

$$^{60}_{27}Co \longrightarrow {}^{60}_{27}Co + {}^{0}_{0}\gamma$$

The general equation for γ – emission is

$$^{A}_{Z}X \longrightarrow {}^{A}_{Z}X + {}^{0}_{0}\gamma$$

Example 10.8

A Radon nucleus $^{222}_{86}Rn$ emits an α-particle followed by a β-particle. What is the atomic number and mass number of the nuclear formed after the emission?

Solution

Nuclear reaction.

$$^{222}_{86}Rn \xrightarrow{\alpha} {}^{218}_{84}X + {}^{4}_{2}He$$

$$^{218}_{84}X \xrightarrow{\beta} {}^{218}_{85}Y + {}^{0}_{-1}e$$

Therefore the atomic number is 85 and the mass number is 218.

Example 10.9

A radioactive nucleus is denoted by the symbol $^{218}_{92}Y$. Write down the composition of the nucleus at the end of the following stages of disintegration:

(a) The emission of an alpha particle.

(b) The further emission of beta particle.

(c) The emission of some gamma rays.

Solution

(a) α- decay;

$$^{288}_{92}Y \xrightarrow{\alpha} {}^{284}_{90}X + {}^{4}_{2}He + \text{Energy}$$

The composition will be; mass number 284 and atomic number 90, ($^{284}_{90}X$).

(b) β-decay;

$$^{284}_{90}X \xrightarrow{\beta} {}^{284}_{91}Z + {}^{0}_{-1}e + \text{Energy}$$

The composition will be; mass number 284,atomic number is 91.

(c) γ-decay

$$^{284}_{91}Z \longrightarrow {}^{284}_{91}Z + \gamma + \text{Energy}$$

i.e. the composition remains the same as (b) above.

Example 10.10

Find the values of a,b,c and d in the following decay equation.

(a) $^{213}_{84}Po \longrightarrow {}^{209}_{82}Pb + {}^{a}_{b}A$

(b) $^{209}_{82}Pb \longrightarrow {}^{c}_{d}Bi + {}^{0}_{-1}e$

(c) Identify element A in equation (i) above?

Solution

Sum of atomic numbers and mass numbers on both sides must be equal.

(a) $a + 209 = 213$

$a = 213 - 209$

$a = 4$

$b + 82 = 84$

$b = 84 - 82 = 2$

$b = 2$

(b) $c + 0 = 209$

$c = 209 - 0$

$= 209$

$d + -1 = 82$

$d = 82 + 1$

$a = 83$

(c) since a = 4, b = 2 then, $^{4}_{2}A$ is helium nucleus.

Exercise 10.3

1. Balance the nuclear reaction equation below.

$$^{24}_{11}Na \longrightarrow Y + {}^{0}_{-1}e + \text{Energy}$$

2. Radioactive Carbon -14 decays to Nitrogen by releasing a beta emissions as shown. Determine the values of **x** and **y** in the equation.

$$^{14}_{6}C \longrightarrow {}^{x}_{7}N + {}^{u}_{y}\beta + \text{Energy}$$

3. Alpha particles have a higher ionising power than Beta particles. Give one reason for this.

4. State two factors that determine the extent of the damage to the body cell caused by the radiation from radioactive substances.

5. A radioactive substance $^{238}_{92}X$ decays by emission of two alpha particles and one beta particle. Write a balanced equation of this emission.

6. Uranium –238 disintegrates by emitting an alpha particle to form nuclide Y. Nuclide Y emits a beta particle to form substance Z. Write down nuclear equations to show how substance Y and Z are formed (Atomic number of Uranium is 92).

7. The following is a part of Uranium decay series

$$^{238}_{92}U \xrightarrow{\text{Step I}} {}^{234}_{90}Th \xrightarrow{\text{Step II}} {}^{234}_{91}Pa \xrightarrow{\text{Step III}} {}^{Z}_{A}X$$

   (a) Which particles are emitted in steps I and II

   (b) If a beta particle is emitted in step III, find Z and A.

10.7 Natural and artificial radioactivity

Natural radioactivity is the type of radioactivity by which atoms disintegrate on their own in order to be stable. Elements that undergo natural radioactivity have extremely long half-life. They are not useful in research, treatment and technology because of their long half-lives.

Table 10.15 shows some of the naturally radioactive elements.

Table 10.15

Natural nuclide	Half life
Uranium – 283 $^{238}_{92}U$	4.5 x 10^9 years
Carbon – 14 $^{238}_{92}$	C 5.7 x 10^3 years
Radium – 226	$^{238}_{92}Ra$ 1.6 x 10^3 years

Scientist induce radioactivity in materials that are naturally stable. To induce radioactivity, atoms of stable elements are bombarded with neutrons.

Radioactive $^{32}_{15}P$ is obtained by radioactivity is known as *artificial radioactivity*. For example bombarding the stable $^{32}_{15}P$ with a neutron.

$$^{1}_{0}n + ^{31}_{15}P \longrightarrow ^{32}_{15}P$$

(stable) (Unstable)

$^{32}_{15}P$ being heavier than the stable isotope, undergoes beta decay to become sulphur $^{32}_{16}S$

Another artificial radioactive isotope obtained on being bombard with a neutron is $^{14}_{6}C$.

$$^{1}_{0}n + ^{14}_{7}N \longrightarrow ^{14}_{6}C + ^{1}_{1}H$$

(stable) (Unstable)

Most artificial radioactive isotopes have very short half-lives. Their short half-life make them useful in scientific work. The shorter the half-life, the faster the isotope decays and the more unstable it is. The intensity of its radiations soon flash below the lethal level.

Table 10.16 show some artificial radioactive isotopes and their half-lives.

Table 10.16

Artificial isotope	Half life
Iodine –131, $^{131}_{53}C$	8.1 days
Phosphorous–32, $^{32}_{15}P$	14 days
Bismath–214, $^{214}_{83}Bi$	19.7 minutes

It is important to note that:

- Phosphorous – 32, has been used to study the uptake and metabolism of phosphorous by plants from phosphate fertilisers.
- Carbon – 14 has been extensively used in the study of carbon pathways including photosynthesis and protein synthesis.

10.8 Nuclear fission and nuclear fusion

(a) Nuclear fission

In 1939 Hahn and Strassman proved that uranium-235 can be split into 2 roughly equal parts by the action of neutrons. Neutrons, having no charge, are able to penetrate deep into the positively charged nucleus of uranium-235. When uranium-235 of a definite mass absorbs a slow neutron, the nucleus becomes unstable and almost immediately splits into 2 lighter nuclei releasing a lot of energy. The splitting of a heavy nucleus into lighter nuclei with the release of energy is called *nuclear fission*. The energy released comes out in the form of heat energy.

For example, when $^{235}_{92}U$ absorbs a thermal neutron, it splits into two particles of uneven mass i.e Barium $^{139}_{56}B$ and Krypton $^{94}_{36}Kr$ releases an average of 3 neutrons and 210 Mev of energy as shown in the Fig. 10.20. The absorption of the neutron induces oscillations in the nucleus that deforms it until it splits into fragments the way a drop of liquid might break into smaller droplets

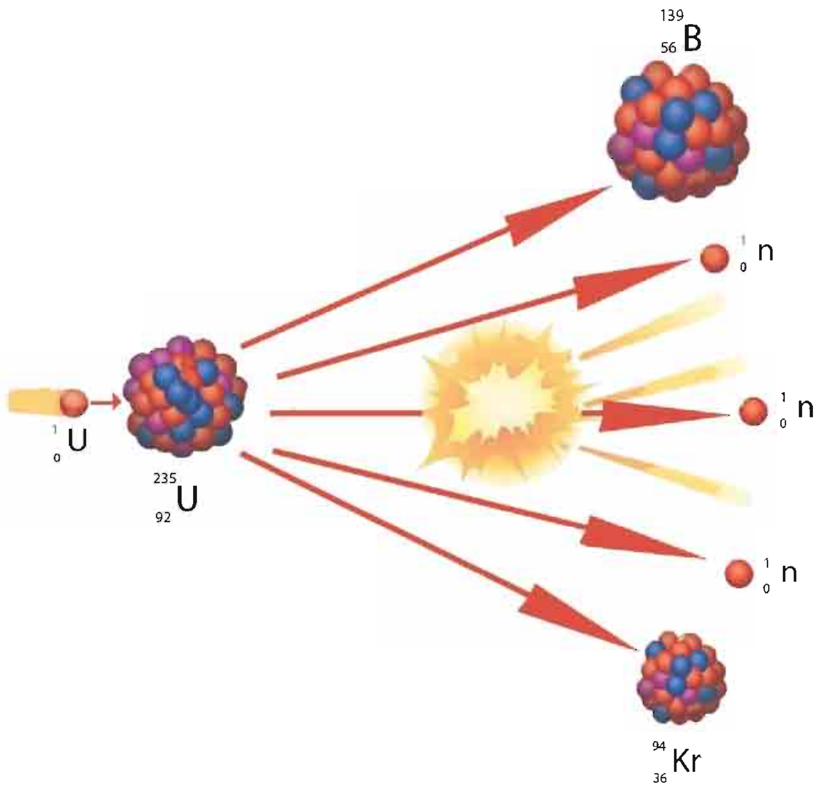


Fig. 10.20: Fission of Uranium atoms

The fission equation is as shown below.

$$^{235}_{92}U + {}^{1}_{0}n \longrightarrow {}^{139}_{56}B + {}^{94}_{36}Kr + 3\ {}^{1}_{0}n$$

Each of the three emitted neutrons bombards another uranium atom releasing energy the process continues leading to a *chain reaction* with a massive release of energy.

This is used to run electric power generation through heating water to steam.

(b) Nuclear fusion

Unlike nuclear fission, *nuclear fusion* is a process where energy is released when two lighter nuclei are fused together to form a heavier nucleus. Once again, the energy released comes out in the form of heat energy.

The fusion of four protons to form a helium nucleus, two positrons (and two neutrinos), for example, generates 24.7 MeV of energy.

$$4\,{}^{1}_{1}H \longrightarrow {}^{4}_{2}He + 2\,{}^{0}_{+1}e$$

Most of the energy radiated from the surface of the sun is produced by the fusion of protons to form helium atoms within its core.

The sun produces its light and heat through hydrogen fussion to form helium. This process has not yet been exploited and is under research.

10.9 Applications of radioactivity

(a) Uses in medicine

Radioactive materials can be used as tracers in medicine. For example, a radioactive nuclide like iodine-131, which has a short half-life, is used as a tracer to monitor the function of thyroid gland which controls the metabolism rate (rate at which the body 'burns' its food). Also blood clots can be traced by injecting radioactive sodium to the body and using detectors to find where the blood flows stops.

Strong sources of radiation, such as gamma rays emitted by cobalt-60, are used to kill the harmful tissues such as cancerous cells inside the human body.

The plastic disposable syringes used for inoculations are sealed inside airtight plastic bags and irradiated with the gamma rays from cobalt-60. This kills all the bacteria in the plastic bag and remains sterile until ready for use.

(b) Uses in biology and agriculture

Tracer techniques are being used to monitor how plants take up fertilisers. Radiation can be used to sterilise insects and to eliminate pests which destroy crops. Wheat, maize etc.. when irradiated with mild gamma rays can be stored for a long time without damage.

(c) Uses in archaeology (Carbo-dating)

High speed neutrons from the outer space collide with nitrogen in the atmosphere and produce ${}^{14}C$ as shown in the equation below.

$${}^{1}_{0}n + {}^{14}_{7}N \longrightarrow {}^{14}_{6}C + {}^{1}_{1}H$$

Living plants and trees absorb carbon-14 (${}^{14}_{6}C$) by photosynthesis.

The amount of C in the tree goes on increasing as long as the tree is alive. When the tree is cut down, it no longer absorbs $^{14}_{6}C$ and the radioactive atoms already absorbed by it start to decay by emitting beta particles and nitrogen atoms as shown below.

$$^{14}_{6}C \longrightarrow {}^{14}_{7}N + {}^{0}_{-1}e$$

The half-life of ^{14}C is about 5 600 years.

If a freshly cut piece of wood gives out, say 64 counts/minute and a 'sample wood' dug by an archaeologist gives 8 counts/minute, the 'age' of the sample wood is 3 half- lives, i.e. about 16 800 years. This process of finding the age of fossils is called *carbon dating*.

Similar technique is used to find the 'age' of bones, human skull, etc. Using this technique, it has been shown that human life existed in East Africa many millenia ago.

(d) Uses in industries

Leakages in underground water pipes can be located using a gamma ray source of short half-life (Fig. 10.21).

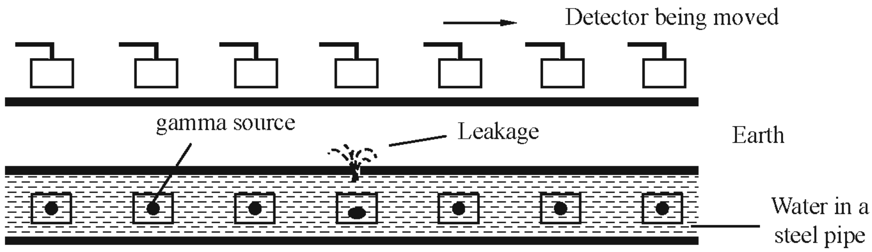


Fig. 10.21: Leakage in underground pipe

The radiations from the gamma rays source emerge out through the leak in the steel pipe and give a much higher count rate than the rest of the pipes. Leakages can be detected without having to dig long distances of the earth.

Also thickness of paper manufactured can be monitored with a beta particle source having a long half-life. Similarly a gamma ray source could be used to gauge the thickness of manufactured metal sheets.

Tea leaves packing industries use beta particles sources to monitor the volume of tea leaves in the packing processes.

(e) Source of electrical energy

Nuclear energy is created through reactions that involve the splitting or merging of the atoms of nuclei together. The process of splitting of large atoms such as those of uranium into smaller atoms is called *fission*. *Fusion* on the other hand, is the combining of two smaller atoms such as hydrogen or helium to produce a heavier atom. All these reactions release heat which is turned into electricity in nuclear power plants (Fig 10.22). An atomic bomb derives its energy from these kinds of reactions.

The energy released in the fission or fusion process could be used to drive a turbine of a generator to generate hydro-electric energy.

Since the fuel required for fusion process (heavy water, ${}^{2}_{1}H$) is available in plenty in the sea, electrical energy from the fusion process may be the solution to man's electrical energy crisis.

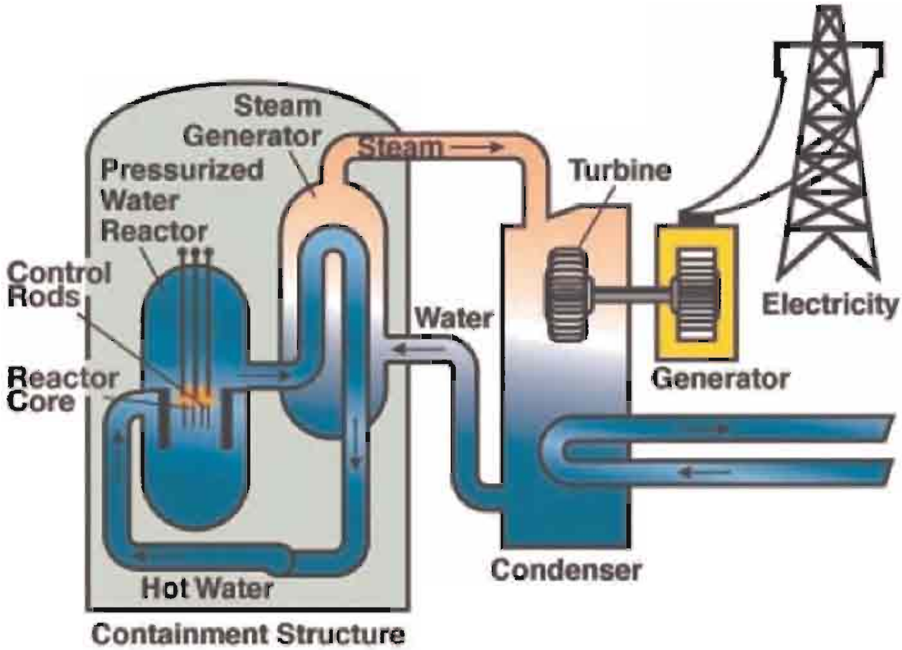


Fig 10.22: Nuclear plant

Advantages of nuclear energy

- Nuclear energy does not produce the air pollution that comes from fossil fuels.
- Produce cheap and reliable electricity if used in full capacity.
- Nuclear energy maintenance and running costs are low.
- Produce sustainable and stable energy.

Disadvantages of nuclear energy

(a) Nuclear energy radiation accidents

Radioactive wastes coming from nuclear power plant have a negative effect on the environment.

Many people died when a nuclear reactor exploded on Chernobyl (Russia) in 1986.

A part from immediate effects like skin burns, vomiting there are also possible delayed effect of radiation like loss of hair, cancer, leukemia and genetic damage.

Necessary care must be taken to avoid radioactive materials being eaten or radiation inhaled from air. No eating, drinking or smoking is allowed where radioactive materials are handled. Disposable gloves, protective clothing (lead lined aprons) and masks are to be worn. The warning symbol alongside should be displayed clearly at the prominent places where radioactive material are kept (Fig. 10.23).

Fig. 10.23: Warning symbol

Gamma rays can penetrate deep into the body. People exposed to external source of gamma rays must be protected by limiting the dosage of radiation using shielding metal (aluminium, lead), keeping the exposure time as short as possible and keeping large distance between the source and the person.

People should use remote controlled tools like tongs to handle the radioactive materials and sit behind a shielding wall made of concrete and lead. People should use radiation "badges".

In medicine, the radioactive materials used should have a short half-life so that the materials reaching the body quickly decays away.

Though the radioactive materials used in the school laboratories have low activity, they should be kept in lead boxes and handled with tongs, forceps, tweezers, etc. for safety. The source should not be pointed at people.

Radioactive waste must be buried in deep trenches inside the earth far away from place of human habitation and their activity monitored till they become harmless.

Critical capital costs

Setting up a nuclear power station requires a lot of capital and well trained personale. This will lead to a lot of investment.

(c) Harm human and animals

Some bad people use nuclear energy to make explosives to harm human and animals. This also caused destructions of infrastructure and natural environment.

The atomic bombs if dropped may kill thousands of people, with the survivors suffering serious mental depression and genetic damage.

Exercise 10.4

1. Which property of the radiation from a radioactive source makes it harmful? Explain.
2. Alpha particles are more dangerous when inside a human body than outside. Explain.
3. In monitoring the thickness of aluminium foil manufactured in industries, explain why
   (a) either alpha or gamma radiation would be unsuitable,
   (b) a beta source of long half-life is advisable.
4. State how radioactivity is used in
   (a) industries (b) archaeology (c) medicine.

Project work

Construction of a simple leaf electroscope

Suggested materials

A transparent conical flask or a tall glass jar having a narrow mouth, thin pieces of aluminium foil, a waxed cork, a brass or copper rod bent into an L shape.

Assembly

- Stick a thin piece of aluminium foil to the lower end of the rod.
- Place the L-shaped rod over the jar and then fit the waxed cork to insulate the rod from the glass jar. Fig.10.24 shows the construction of a leaf electroscope and Fig. 10.25 shows an assembled leaf electroscope.

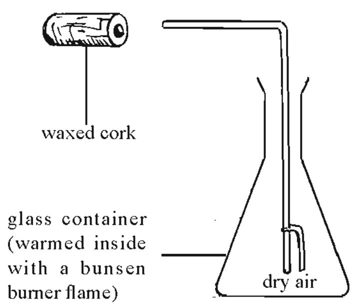


Fig.10.24: Construction of leaf electroscope

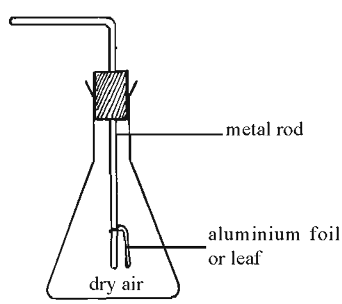


Fig. 10.25: Assembled leaf electroscope

Topic Summary

- Radioactivity is the spontaneous disintegration of the nucleus of certain substances.
- Radioactive decay is a process by which an element changes into another element by emitting a particle(s) or radiations from the nucleus.
- Radiations from a radioactive source are random in nature.
- Activity is the rate of disintegration.
- Half-life $T_{\frac{1}{2}}$ of a substance is the average time taken for the activity to decrease to half of the initial value.
- There are 3 possible types of radiations that are emitted from a radioactive source; alpha particles, beta particles and gamma rays.
- Alpha particles and beta particles are charged particles and are deflected in electric and magnetic fields; gamma rays are uncharged electromagnetic radiations.
- An alpha particle is a positively charged helium nucleus, made of 2 protons and 2 neutrons.
- A beta particle is a negatively charged electron emitted from the nucleus. A heavier neutron emits an electron and becomes a proton.
- Table 10.18 below compares the charge, mass, range in air, ionising power, penetrating power and source of alpha, beta particles or gamma rays.

Table 10.18

	Charge	**mass air**	**range in power**	**ionising power**	**penetrating**	**source**
α	+2e	about 8 000 m_e	about 5–7 cm	most	least	Am–214
β	–e	m_e negligible	about 3–5m	slightly less	slightly more	Sr – 90
γ	0	0	infinite	least	most	Co–60

- Leaf electroscope, spark counter, Geiger-Müller tube, diffusion cloud chamber are a few detectors of radioactivity
- Background radiation is the stray radiation present in the atmosphere. The possible causes of these stray radiations are cosmic radiations from the sun, granite rocks, fossil fuels, etc.
- Atomic number (Z) of an atom is the number of protons in the nucleus of the atom.

- Mass number (A) of an atom is the sum of protons and neutrons in the nucleus of the atom.
- Nucleon number is the common name given to protons and neutrons inside the nucleus.
- Isotopes of an element are atoms which have the same number of protons but different number of neutrons.
- Nuclear fission is the splitting of a heavy nucleus into lighter nuclei, with the release of energy.
- Nuclear fusion is the combination of two lighter nuclei to form a heavier nucleus, with a release of energy.
- The energy released during fission or fusion comes out as heat energy which can be utilised to drive the turbines of a generator to produce electrical energy.
- All radioactive substances are dangerous as they emit radiations which can ionise living cells.
- Necessary precautions should be taken in handling all the radioactive materials.
- Radioactivity is widely used in medicine, agriculture, archaeology, industry, etc.

Topic Test 10

1. Complete the following nuclear equations by filling the go values represented by dashes:
   (a) $^{235}_{7}u + ^{1}_{0}n \longrightarrow ^{138}_{-}Ba + ^{-}Kr + 3(^{1}_{0}n)$
   (b) $H + ^{2}_{1}H \longrightarrow ^{-}He + ^{1}_{0}n$
   (c) $^{14}_{6}C \longrightarrow — + ^{14}_{7}N$
   (d) $^{2}_{1}H + ^{0}_{1}H \longrightarrow ^{4}_{2}He + ^{1}_{0}n$
2. A 'fresh' sample of a tree gives 120 counts/minute and a 'sample' under test gives 15 counts/minutes. What is the 'age' of the sample, if half-life of ^{14}C is 5 540 years? Show your working clearly.
3. Define the terms
   (a) Radioactivity
   (b) Half life
   (c) Radioisotope
   (d) background radiation.
4. Complete the following decay equations
   (a) $^{220}Rn \longrightarrow _{-}Po + ^{4}He$

(b) $^{38}Ar \longrightarrow {}^{38}K +$ ____

(c) $^{210}Po \quad {}^{4}He + {}_{82}Pb$

5. The half-life of the nuclide zinc-71 is 150 s. Initially, its activity is 240 counts/second. What would be the count rate after 600 s?

6. A radioactive substance has decayed to 1/256 of its original activity after 64 days. What is its half-life?

7. A radioactive substance is set up in front of a Geiger counter and at the same time a stopwatch is started. The counter readings are recorded at 1 hour interval as shown in Table 10.19.

Table 10.19

Time (h)	0	1	2	3	4	5
count rate/minute	142	98	70	52	41	34

(Background radiation at the place is 22 counts/minute).

Plot a graph of the corrected count rate against time. Determine the half-life of the radioactive substance.

8. An experiment in radioactivity was carried out as shown in the arrangement in Fig. 10.26 and the results obtained given as shown in Table 10.20.

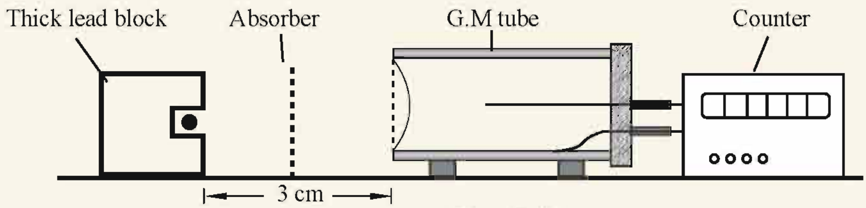


Fig. 10.26

Table 10.20

Absorber used	at 10 a.m (counts/min)	at 12 noon (counts min)
None	2 000	500
Thin paper	1 300	325
5 mm aluminium	22	22

From the results in the table, deduce;

(a) the half-life of the source used.

(b) the type (s) of radiations emitted.

(c) the background radiation. Give reasons for your answer.