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Form 4

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Form 4

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Distributed throughout Malawi by:

Grey Matter Ltd.,
Lilongwe City Mall, Area 4
Shop GF 28B, Lilongwe
P. O Box 2608, Lilongwe, MALAWI.
Tel: +265 1 755411/ Fax: +265 1755430
Cell: +265 995967011/ 995967001
E-mail: distribution@greymattermw.com
operations@greymattermw.com

Under agreement with the publishers

Longhorn Publishers Ltd,
Funzi Road, Industrial Area,
P.O. Box 18033,
Nairobi, Kenya.

© L. Kaonga, C. Kariuki, J. Ngomo 2017.

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First published 2017
Second Printing - 2018

ISBN 978 9996 038 457

Printed in UAE by
Masar Printing and Publishing
www.masarprint.com

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Properties of matter

Outcome

The students will be able to relate the behaviour of matter from microscopic level to the macroscopic level when subjected to different environments and creatively apply these properties to bring about technological developments at the same time examine the ethical and moral implications of using and applying science

Unit 1: Thermal Expansion

UNIT

1 Thermal Expansion

Success criteria

By the end of this unit, you must be able to:

- Define the term temperature.
- Explain the thermal expansion in solids, liquids and gases.
- Explain expansion in terms of particle behaviour.
- Describe the unusual expansion of water and its effects.
- Explain the effects and application of thermal expansion.

Introduction

In Form 2, we were introduced to thermal expansion. We learnt that most substances increase in size when heated and decrease when cooled. The increase in size on heating of a substance is called *expansion*. The decrease in size on cooling of a substance is called *contraction.* We demonstrated thermal expansion of solids liquids and gases using a number of methods. In this unit we will discuss thermal expansion for the three states of matter in terms of particle behaviour.

1.1 Definition of temperature

A piece of ice is very cold while boiling water is very hot. *The degree of coldness or hotness of a body is called temperature*. According to kinetic theory of matter particles of matter are always moving randomly. The energy due to motion is known as *kinetic energy*. Thus, *temperature* is a measure of the average *kinetic energy* of the molecules of a substance. The temperature of a substance is low if the molecules are moving slowly and high if the molecules are moving fast.

The SI unit of temperature is the *kelvin (K)*, named after the physicist *Lord Kelvin*. However, the commonly used unit of measuring temperature is *degree celcius (°C)* named after Swedish scientist called *Celcius*.

What is the difference between heat and temperature?

We know that molecules in boiling water (100°C) move faster than molecules in ice (0°C). This means that the molecules in boiling water contain more energy than those in ice.

If hot water is poured into a bowl containing ice at 0°C, the temperature of ice and the bowl increases. The fact that the temperature increases suggests that ice and the bowl have gained the energy in form of heat. Thus, *heat is a form of energy which*

passes from a body of high temperature to a body of low temperature. The SI unit of heat energy is joule (J).As already defined, *temperature is the degree of hotness or coldness of a body hence is a measure of the heat energy of the molecules in a body.*

1.2 Thermal expansion in solids, liquids and gases

Thermal expansion in solids

In Form 1 we learnt that when solids are heated they:

(a) increase in length.

(b) increase in volume.

(c) increase in area.

We demonstrated expansion of solids using *the ball and ring apparatus*, and the *bar and gauge apparatus*. The following experiments will help us to further understand thermal expansion and contraction in solids.

Experiment 1.1: To demonstrate thermal expansion and contraction in solids using the cast iron bar breaker

Apparatus

- Cast iron bar breaker
- Two Bunsen burners
- Thin cast iron rod

Procedure

Case 1

1. Fix the steel bar in the frame of the bar breaker (Fig 1.1).
2. Lock the steel bar on the frame by inserting the thin cast iron rod in the hole on the steel bar as shown in Fig.1.1. Clamp the steel bar strongly and observe what happens to the cast iron rod.

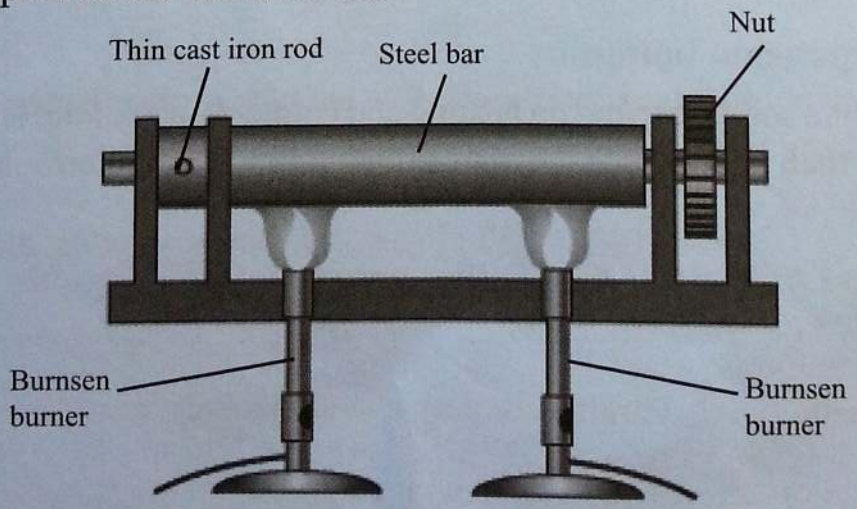


Fig.1.1 Thermal expansion in solids

3. Heat the steel bar strongly using two burnsen burners and observe what happens to the cast iron rod.

Case 2

4. Repeat this experiment but in this case, first heat the steel bar strongly and insert the cast iron rod through the hole then clamp the rod firmly. Observe what happens as the steel bar cools.

Observation

- When the steel bar is heated strongly in case 1, the cast iron rod breaks with a loud sound.
- When the steel bar is cooled in case 2 the cast iron rod breaks.

Discussion

On heating, the steel bar *expands* pushing the cast iron rod against the outer frame of the bar breaker. Hence the rod breaks.

On cooling, the steel bar *contracts* and pulls the cast iron rod against the inner frame of the bar breaker. Hence the rod breaks.

Conclusion

Solids expand on heating and contract on cooling.

Particle behaviour during thermal expansion in solids

We learnt that molecules in solids are closely packed and are continuously *vibrating* about their fixed positions. When a solid is heated, the molecules vibrate with larger amplitude about their fixed positions. This makes them to *collide* with each other with larger forces which push them far apart. The distance between the molecules increases and so the solid expands.

Thermal expansion in liquids

Liquids, just like solids, expand on heating and contract on cooling. However, liquids expand more than solids since they have relatively weaker intermolecular forces.

Experiment 1.2: To demonstrate thermal expansion in liquids

Apparatus

- Water bath
- Paraffin
- Alcohol
- Heater
- Water
- Similar test tubes with fitted similar capillary tubes through the corks

Procedure

1. Label the three test tubes as A, B and C; and fill them with alcohol, paraffin and water respectively. Cork them and place/put them in water bath as shown in fig. 1.2 (a).

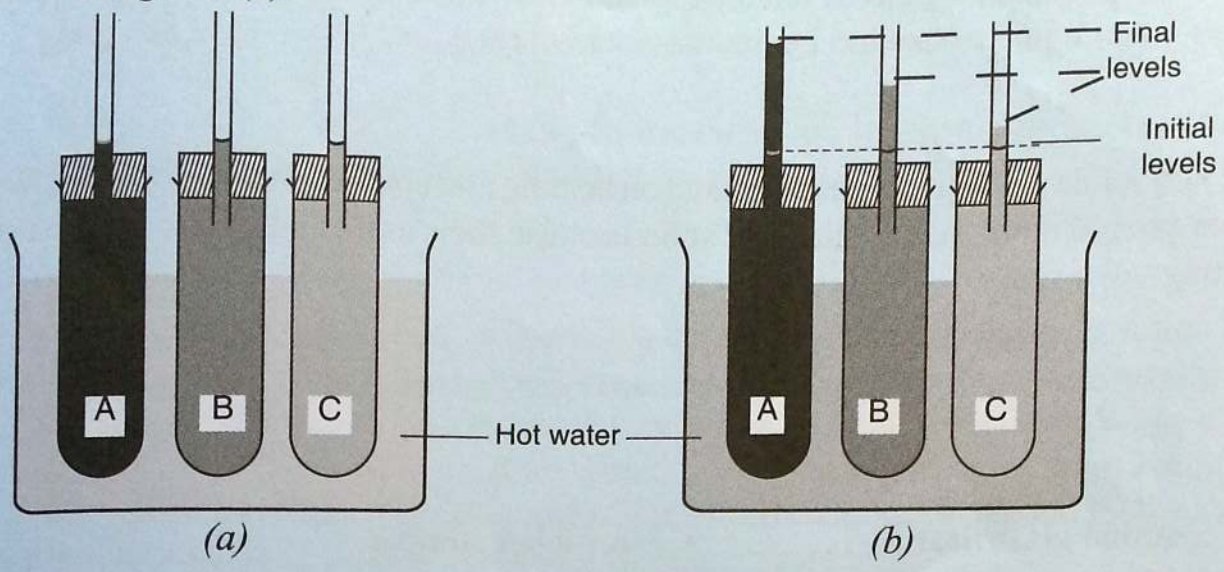


Fig. 1.2: Expansion of liquids

2. Heat some water to boiling point using the heater and place it in a water bath.
3. Tie the three test tubes A, B and C together and place them inside the water bath while stirring the hot water to ensure even distribution of heat in contact with tube A, B and C (Fig. 1.2 (a)).
4. Observe the level of the liquids in the test tubes after 3 minutes (Fig. 1.2 (b)).

Observations

The level of the liquids in the three test tubes falls slightly at first then start rising again up the capillary tubes after sometimes. Alcohol rises to the highest level in the capillary tube followed by paraffin then water.

Discussion

Heat from the water bath reaches the test tubes first making them to expand and increase in volume hence the liquid levels fall. After sometime, the heat reaches the liquids and they start expanding. Alcohol expands more than paraffin, while paraffin expands more than water as seen in Fig. 1.2(b) above.

Conclusion

Liquids expand on heating and contract on cooling.

Explanation of thermal expansion in liquids in terms of particle behaviour

Liquid molecules are loosely packed and move freely. The force of attraction between their molecules is weaker than in solids. On heating, the speed of the molecules increases. The collisions between the molecules increase the distance between them causing the liquid to expand i.e. increase its volume.

Thermal expansion and contraction of gases

Just like solids and liquids, gases expand on heating and contact on cooling. However, gases expand more than liquids and solid because their molecules move furthest on heating.

Experiment 1.3: To demonstrate expansion in gases

Apparatus

- A thin glass flask
- A long narrow glass tube
- A rubber stopper
- A balloon

Procedure

1. Take a thin glass flask and the balloon tied on it as shown in Fig. 1.3 (a). Immerse them in the water bath as shown in in Fig 1.3(a)

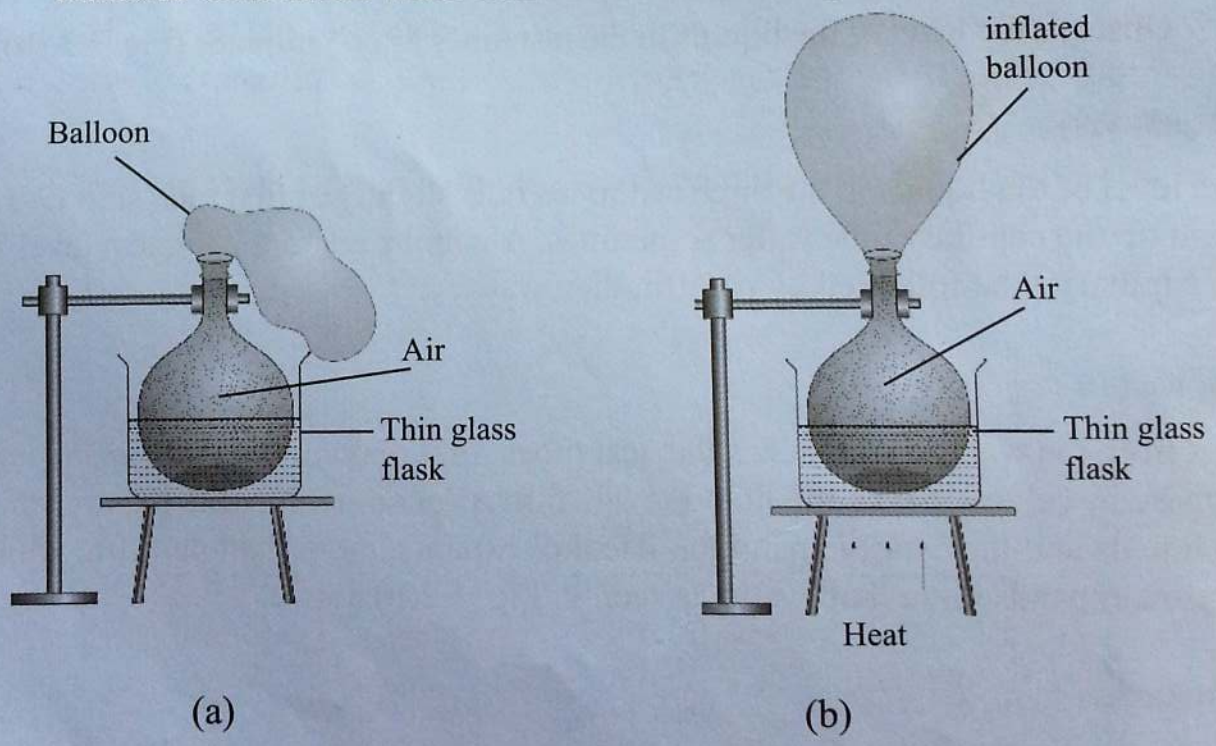


Fig. 1.3: Expansion of air

2. Heat the apparatus placed on the tripod stand as shown in Fig 1.3(b).
3. Observe what happens.

Observation

On heating, the balloon is inflated hence bulges (Fig. 1.3 (b).

Discussion

On heating, the air in the thin glass flask expands, increasing volume in flask and in the balloon hence inflating the balloon.

Conclusion

Gases expand on heating and contract on cooling.

Explanation of thermal expansion in gases in terms of particle behaviour

The intermolecular distances in gases are large compared to those in solids and liquids. The forces of attraction between the molecules of a gas are very weak (almost negligible) hence, the molecules move freely in all directions. When a gas is warmed, the molecules gain more kinetic energy and move far apart hence its volume increases. Note that same quantities of different gases expand by the same amount when heated equally and under the same pressure.

1.3 Anomalous expansion of water

Most liquids expand steadily on heating. Water behaves in an unusual/abnormal manner in the sense that when heated at 0°C, its volume decreases (contracts) as temperature rises from 0°C to 4°C. Beyond 4°C, water expands like other liquids. This unusual (abnormal) behavior of water when it is heated from 0°C to 4°C is referred to as *anomalous (abnormal) expansion of water*. Thus, a fixed mass of water has a minimum volume at 4°C.

Fig. 1.4 shows the graph of volume against the temperature of water.

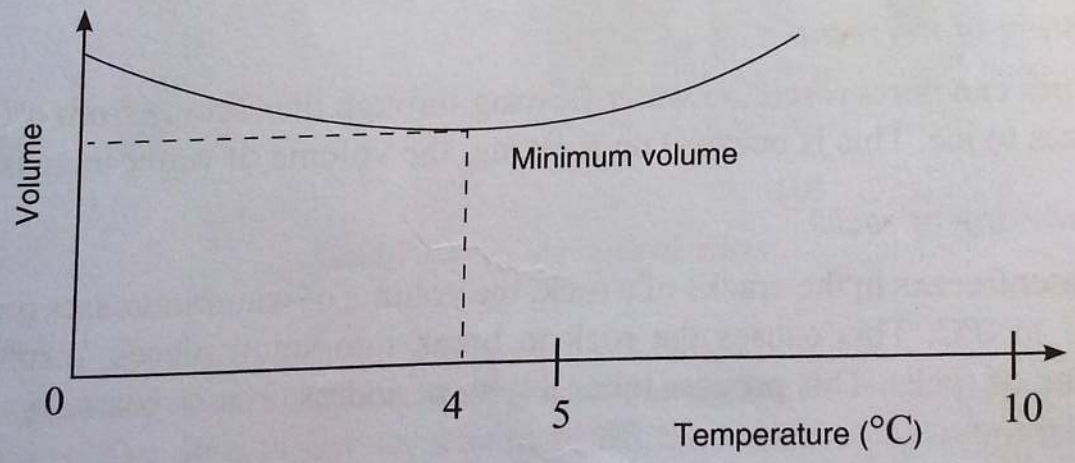


Figure 1.4: A graph of volume against temperature of water

From the graph, we see that the volume of a fixed mass of water is minimum at 4°C. At this temperature, the density of water is maximum. Fig. 1.5 shows the graph of density against temperature.

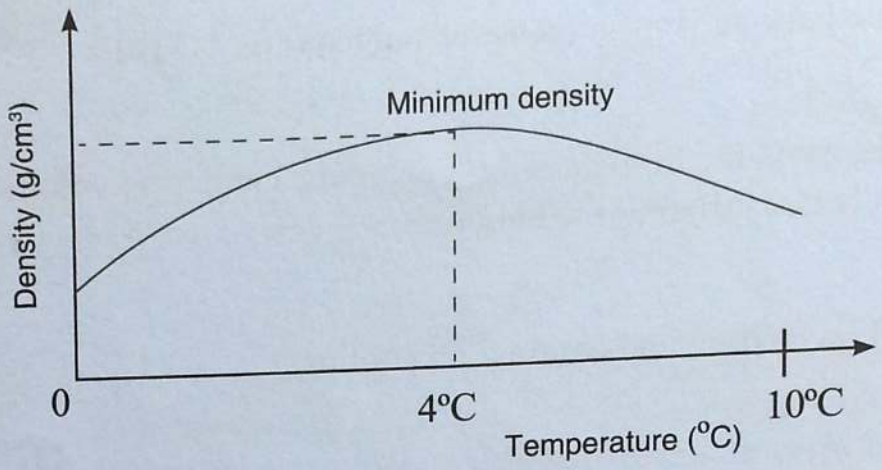


Fig. 1.5: A graph of density against temperature for water

Effects of anomalous expansion of water

(a) Survival of aquatic organisms in freezer of lakes and ponds

In cold weather, when the temperature of the atmosphere falls below 0°C, water in a lake or pond freezes and ice is formed. *How do fish and other living things survive in frozen water?* The question can be answered by looking at the graph of density of water against temperature in the range 0°C to 10°C as shown in Fig. 1.5 above.

The volume of a fixed mass of water is minimum at 4°C hence density of water is maximum at this temperature. As the temperature of air above the lake falls from 10°C to 4°C, the density of water increases. This denser water at the top sinks to the bottom of the lake and remains there in liquid form. The water on the top freezes to ice at 0°C and floats. The fish and other aquatic animals and plants survives in the liquid water at 4°C below the ice during the cold weather.

(b) Bursting of water pipes

Water pipes can burst when the water flowing through them cools from 4°C to 0°C and freezes to ice. This is because on freezing, the volume of water increases.

(c) Weathering of rocks

When water freezes in the cracks of a rock, the volume of water increases on cooling from 4°C to 0°C. This causes the rock to break into small pieces, resulting into weathering of rocks. This process takes a long period of time in years.

1.4 Applications of thermal expansion

Thermal expansion and contraction, though on one hand is a nuisance and on the other hand is quite useful. The following are some of the applications of thermal expansion and contraction.

(a) Loose fittings of electrical cables

The electric wires transmitting electricity on the national grid are loosely held (Fig 1.6(b)). This gives room for expansion and contraction as the weather changes (Fig. 1.6(a)).

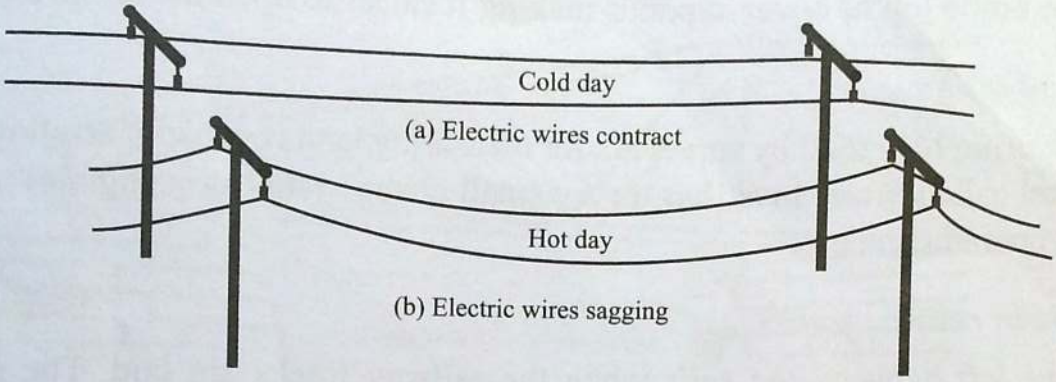
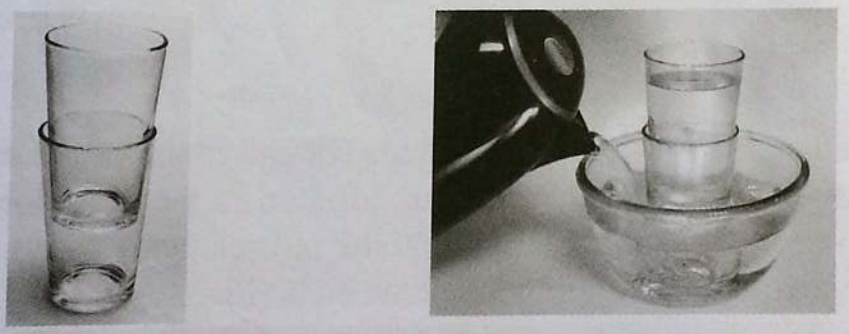


Fig. 1.6 Electric wires on electric pylons

This explains why the wires are seen to be sagging (expand) during hot days and are seen taut and straight (contract) on cold days. If they were tightly held, they would break during cold days causing a lot of destruction.

(b) Separating stuck tumblers/glasses

Fig. 1.7(a) shows two tumblers that are stuck together. They can be easily separated by placing them upright in warm water and pouring very cold water in the inner tumbler Fig. 1.7(b). The outer tumbler will expand more than the inner one hence can be separated. This shows one use of the thermal expansion and contraction of solids.



(a) (b)

Fig. 1.7 Seperating stuck tumblers

(c) Tooth filling

Some people have dental cavities or structural damage in their teeth. i.e. teeth have holes. Dentist can do a minor surgery to re-fill these holes. The material used to refill these holes must have the same coeffiecient of thermal expansion as the tooth itself. This will make both the material and the tooth expand and contract uniformly.

> ⚠ Dental cavities and other dental diseases are preventable. Brush your teeth regularly after meals and avoid eating too much sugary foods.

(d) Removing tightly screwed covers

Bottle tops and container lids are sometimes hard to open. To open them, place the bottle in cold water and heat or pour hot water on the cover or lid. The bottle contracts while the bottle top or cover expands making it easier to open the bottle top/lid.

(e) Use of alloys

The measuring tape used by surveyors for measuring land is made of an alloy of iron and nickel called *invar*. Invar has a very small change (almost negligible) in length when temperature changes.

(f) Gaps in railway tracks

Gaps are left between the rails when the railway tracks are laid. The rails are joined together by *fish-plates* bolted to rails. The oval shaped bolt holes allow the expansion and contraction of the rails when the temperature changes (Fig. 1.8).

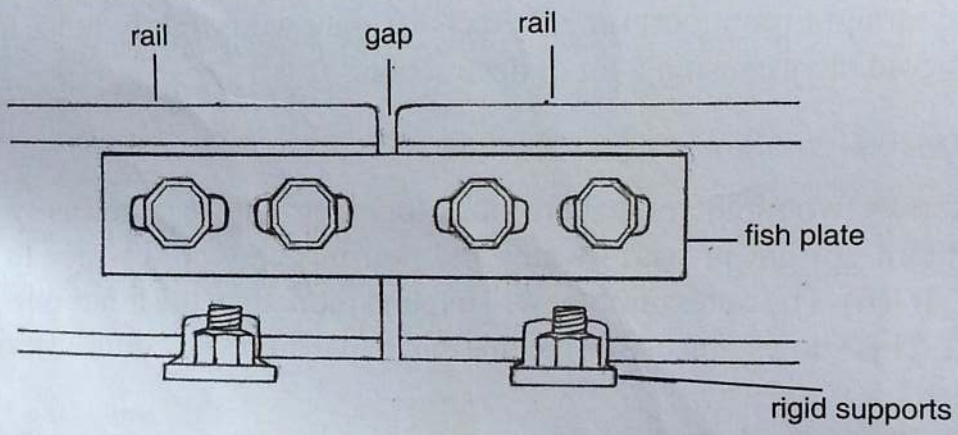


Fig. 1.8: Gaps left between rails

In very hot weather, the gaps may not provide enough room for the expansion if the expansion is large. The rails may *buckle* out. Modern methods use long welded lines rigidly fixed to the beds of the track so that the rails cannot expand. Expansion for the rails is provided by overlapping the plane ends (Fig. 1.9).

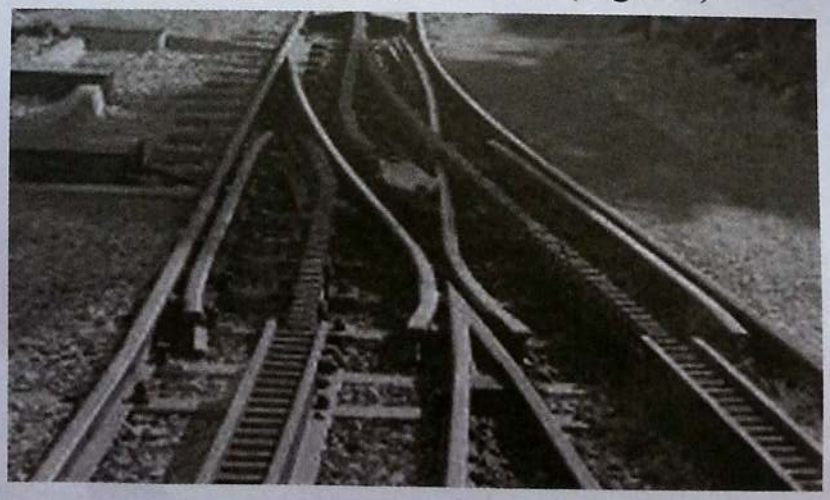


Fig. 1.9: Overlapping joints on rails

(g) Rollers on bridges

The ends of steel and concrete bridges are supported on rollers. During hot or cold weather, the change in length of the steel bridge may take place freely without damaging the structure (see Fig. 1.10).

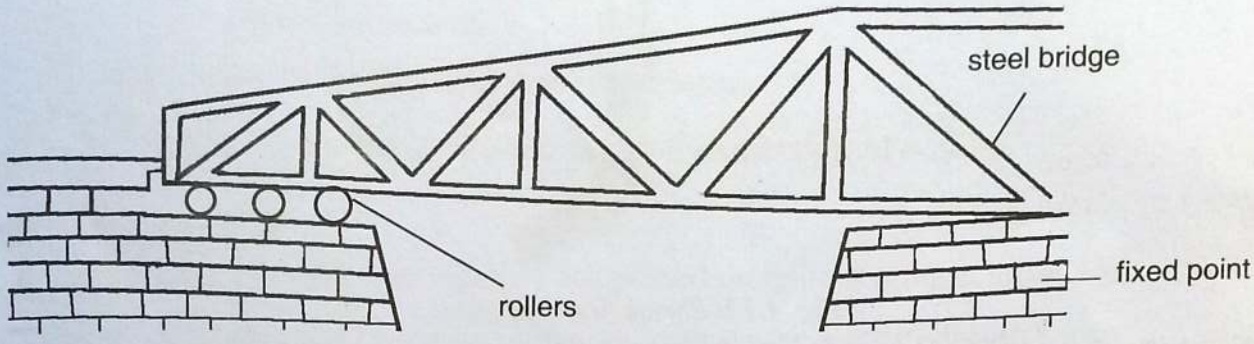


Fig. 1.10: Steel and concrete bridges are supported on rollers

(h) Expansion gaps in fences

Expansion joint/gaps are usually created in walls to allow room for expansion of the bricks or blocks. They break the wall into segments to prevent the cracking caused by changes in temperature, moisture expansion, elastic deformation, settlement and creep. The joints may be horizontal or vertical. They are formed by leaving a continuous opening between the bricks. The opening maybe filled with a highly compressible material that allows the joint to partially close as the brick layers expand. Fig. 1.11 shows a vertical expansion joint in a fence.

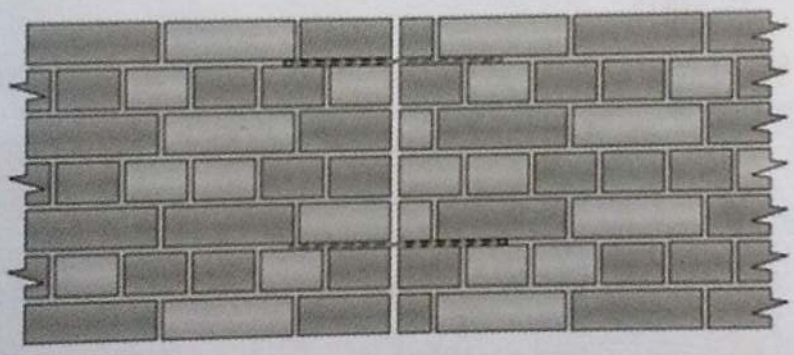


Fig. 1.11: Expansion joint in a fence

(i) Shrink fitting

Shrink fitting is a method used to make mechanical joints when tubes or axles are to be fitted inside other hollow tubes or parts. The hole or the hollow space is made slightly narrower than the tube or axle to be fitted in it. The hollow tube or part is heated to expand; and while still hot, the axle or the other tube is fitted. The joint is then left to cool. On cooling, the initially hollow part contracts (shrinks) and makes a very tight grip of the tube or axle fitted in it. It is almost impossible to separate the two parts without heating. Fig. 1.12 shows parts of pipes that are joined together through shrink fitting.

Fig. 1.12: Shrink fitting in pipes

Shrink fitting is also applied to enhance the joining of metal plates using rivets. Hot rivets are placed in the rivet hole and their ends hammered when still hot. On cooling, the force of contraction pulls the plates firmly together (Fig. 1.13)

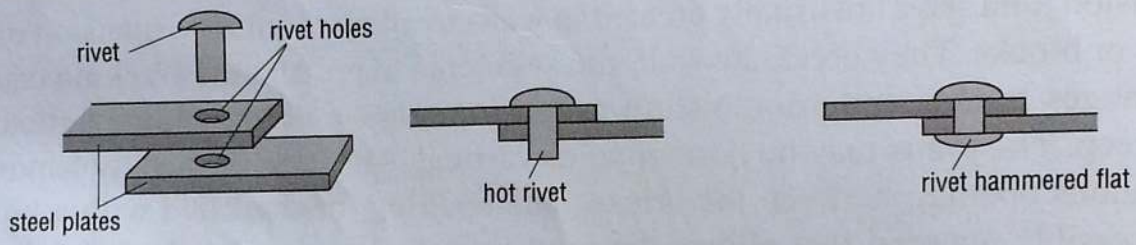


Fig. 1.13: Shrink fitting in rivets

Activity 1.4

Fig. 1.14 shows a bicycle whose pedaling chain system has been removed.

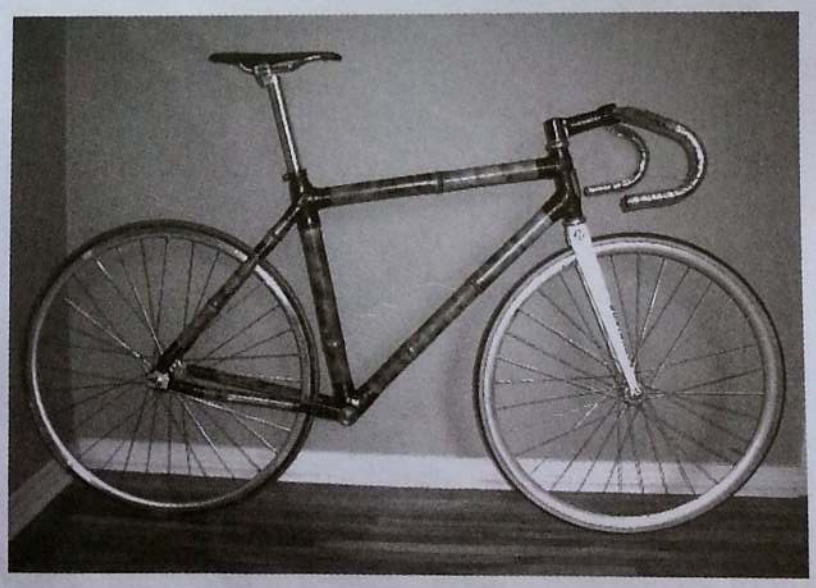


Fig. 1.14: Bicycle frame

Identify all the shrink –fitted joints. How many are they?

Exercise 1.1

1. Define:
   (a) Heat (b) Temperature
   (c) Thermal contraction
2. Differentiate between heat and temperature.
3. Use particles model to explain thermal expansion of solids.
4. Explain why:
   (a) Steel bridges are usually supported on rollers on one loose side.
   (b) Metal pipes carrying steam and hot water are fitted with loops.
5. Describe how shrink fitting is done.
6. State two applications of contraction of solids.
7. Name three physical properties that changes when heating a solid.
8. Describe how the knowledge on thermal expansion is applied in:
   (a) Construction of railway lines (b) Installation of electric cables.
   (c) Tooth filling
9. Sketch a graph of volume against temperature for water in the range between $+10°C - {}^{-}10°C$.

Unit summary

- Expansion is the increase in size (volume) on heating.
- Temperature is the degree of hotness or coldness of a substance.
- Heat is a form of energy which passes from a body of high temperature to a body of a low temperature.
- Contraction is the reduction in size (volume) on cooling.
- Gases expand most followed by liquids then solids.
- Anomalous expansion of water is the unusual (abnormal) behaviour of expansion water in that it contracts on heating from 0°C to 4°C and expands when the converse is done.
- Bimetallic strip is a strip consisting of two metals of different coefficient of expansion welded together so that it buckles on heating.

Unit Test 1

1. Define the following:
   (a) Temperature
   (b) Thermal expansion
   (c) Anomalous expansion of water
2. Show how the combined gas law is obtained.
3. Explain the following observations:
   (a) An inflated balloon hung in the open at a wedding bursts when the temperature of the environment rises.
   (b) Soda bottles are thick.
   (c) Water bubbles seem to increase in size as they rise from the bottom of a tank.
   (d) Electric wires are seen to sag when it's hot but look very straight when its cold.
   (e) Fish living in polar regions such as in Antarctica do not die even when the temperatures fall below 0°C.
4. Give scientific reasons for the following:
   (a) Electricity cables 'sag' in warm weather and tighten in cold weather.
   (b) The mouth of a glass bottle is greatly heated when the glass stopper is rigidly stuck to the mouth so as to remove it.
5. Describe a single experiment to demonstrate that a liquid expands more than a solid.
6. Explain why gaps are left between the railway tracks.
7. Describe a simple experiment to demonstrate expansion and contraction in solids.
8. Explain why:
   (a) iron sheets produce crackling sound when there is a change in weather.
   (b) Soft drinks in the glass bottles are not filled to the brim.
9. Describe how a plumber can join two metallic pipes of the same diameter.
10. How does the volume of a given mass of water change when
    (a) water is cooled from 10°C to 0°C?
    (b) Water is frozen to ice at 0°C?
11. State and explain the effects of anomalous expansion of water.

Mechanics

Outcome

The student will be able to appreciate and demonstrate the use of appropriate quantities to explain various states of motion including the energy interactions and the changes that take place due to forces.

Unit 2: Newton's Laws of motion

Unit 3: Frictional Force

Unit 4: Hooke's Law

Unit 5: Uniform Circular Motion

Unit 6: Moments of Forces

UNIT

2 Newton's Laws of Motion

Success Criteria

By the end of this unit, you must be able to:

- Describe the Newton's laws of motion.
- Describe simple experimentations to illustrate inertia.
- Describe the law of conservation of linear momentum.

Introduction

You may have observed the following: passengers lurch forward when emergency brakes of a car are applied, a group of people are able to push a stalled car to a high speed faster than one person, etc. These observations and similar ones are explained by Newton's laws of motion. In this unit, we shall discuss these laws of motion, linear momentum and their applications.

2.1 Newton's first law of motion

The following experiments will help us to understand the Newton's first law of motion. This law is also called inertia law.

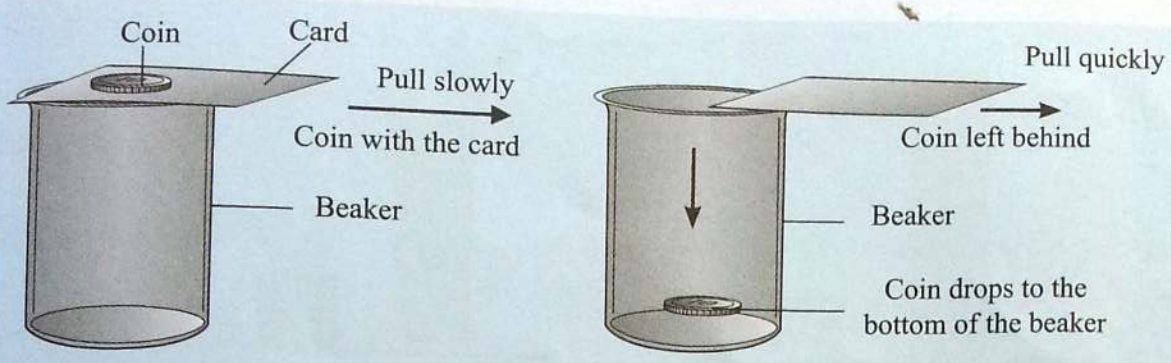
Experiment 2.1: To demonstrate inertia on card being pulled slowly and suddenly

Apparatus

- A coin
- A beaker
- A smooth cardboard

Procedure

1. Place a coin on a smooth cardboard and place it over a beaker. Pull the card away slowly (Fig. 2.1 (a)). Observe what happens to the coin.
2. Repeat the experiment but this time pull the card away suddenly (Fig. 2.1 (b)).



(a) Coin moves with the card (b) Coin left behind

Fig. 2.1: Card with coin pulled (a) slowly (b) suddenly

Observation

When the card is pulled slowly the coin moves together with the card. However, when the card is pulled suddenly, the coin is left behind and drops vertically down into the beaker.

Discussion

When the card is pulled slowly, the frictional force between the card and the coin makes the two to move together. However, when the card is moved suddenly the coin resists motion and does not move with the card and hence drops vertically downwards into the beaker.

The coin resists to change its state of rest but due to lack of support from below, falls into the beaker.

Experiment 2.2: To demonstrate inertia on a pile of wooden blocks pulled slowly and suddenly

Apparatus

- Four wooden blocks

Procedure

1. Place a pile of wooden blocks on a table. Pull the lower block slowly and note what happens (Fig. 2.2 (a)).
2. Repeat the experiment but this time pull the lower block suddenly (Fig. 2.2 (b)).

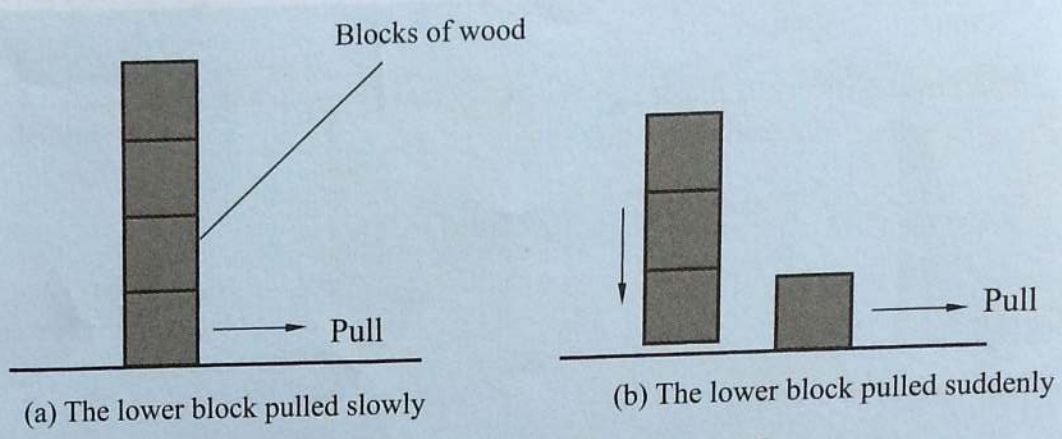


Fig. 2.2: Pulling the blocks of wood

Observation

The whole pile moves when the lower block is pulled slowly but when pulled suddenly the lower block moves leaving the other blocks behind.

Experiment 2.3: To demonstrate inertia on a string pulled slowly and suddenly

Apparatus

- Three 200 g masses
- Six pieces of strings

Procedure

1. Hang a mass as shown in Fig. 2.3 (a).
2. Pull the lower end of the block slowly (Fig. 2.3 (b)) and note what happens to the two strings.
3. Repeat the experiment but now pull the lower end suddenly (Fig. 2.3 (c)).

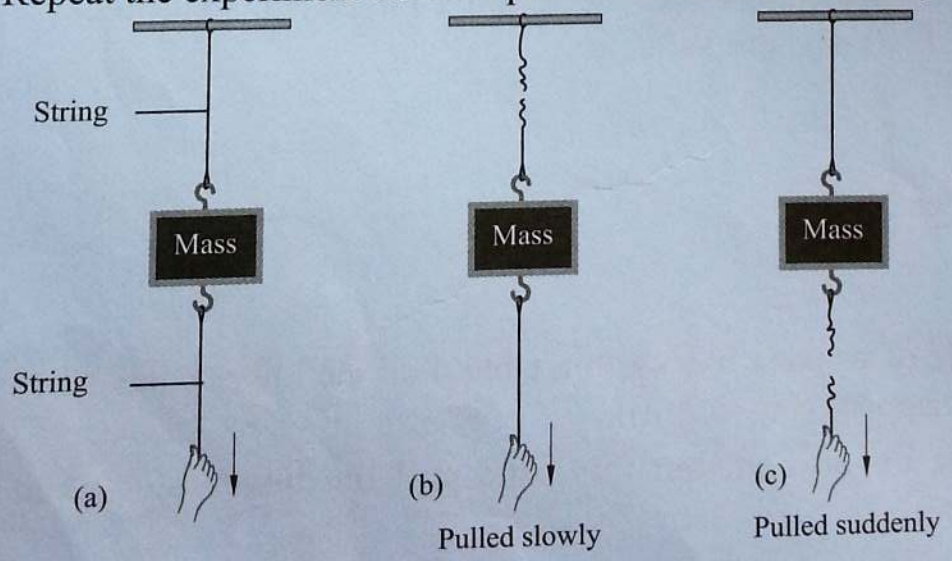


Fig. 2.3: String pulled

Observation

When pulled slowly the upper string breaks. However, when pulled suddenly, the lower string breaks.

From experiments 2.1, 2.2, and 2.3, we can conclude that a *body tends to remain in its state of rest unless acted upon by an external force*. That is, the body once at rest, has a reluctance to move.

Experiment 2.4: To show that bodies will continue in their state of motion unless compelled otherwise

Apparatus

- A wooden block
- A runway
- A trolley

Procedure

1. Place a wooden block on a trolley. Allow the trolley to move down a friction compensated runway as shown in Fig. 2.4 (a).

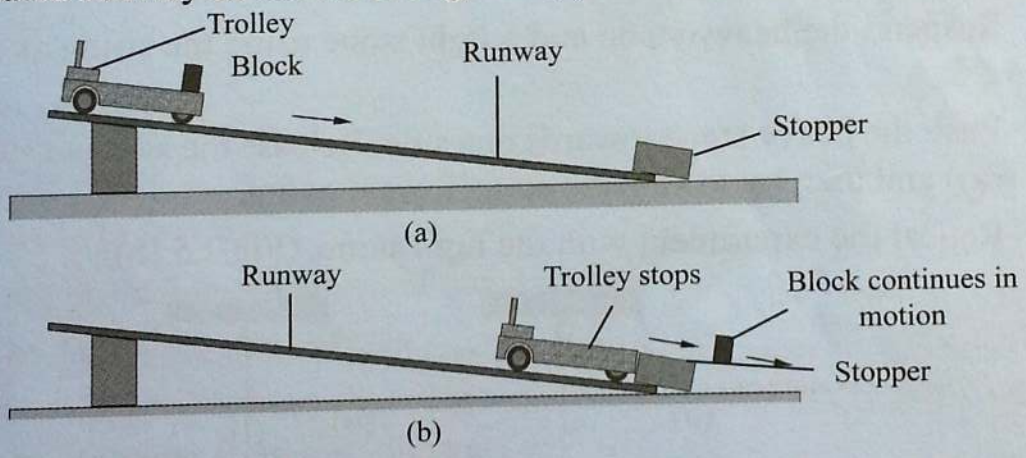


Fig. 2.4: A body is reluctant to stop moving

2. Note what happens to the wooden block once the trolley is stopped suddenly Fig. 2.4 (b).

Observation

The wooden block slides off the trolley and continues moving in the same direction the trolley was moving (Fig. 2.4 (b)) i.e. wooden block is reluctant to stop moving.

Conclusion

The reluctance of a body to change its state of motion i.e. either to remain at rest or to continue moving is called inertia (Latin word meaning laziness).

This observation was summarised by Sir Isaac Newton in his first law of motion, called the law of inertia. The law states that:

A body continues in its state of rest or uniform motion in a straight line unless compelled by some external force to act otherwise.

From this law we can define a *force as that quantity which produces motion of a body at rest or that which alters its existing state of motion.*

2.2 Mass and inertia

Mass is the amount of matter in a substance while inertia is the reluctance of a body to change its state of motion. In this section, we will discuss the relationship between mass and inertia. The following experiment will help us establish their relationships.

Experiment 2.5: To investigate the relationship between mass and inertia of a body

Apparatus

- String
- hook
- heavy stone
- light stone

Procedure

1. Suspend the heavy stone and a light stone using the string as shown in Fig. 2.5.
2. Push the heavy stone towards one side. Release the stone to swing (Fig. 2.5. (a)) and then try to stop the stone from moving.
3. Repeat the experiment with the light stone. (Fig.2.5 (b)).

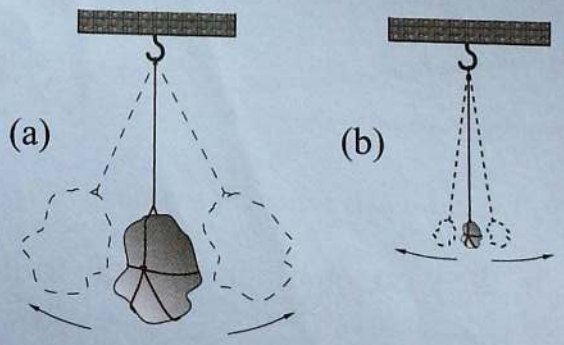


Fig. 2.5: Relationship between mass and inertia.

4. Which stone is easier to start moving and to stop moving?

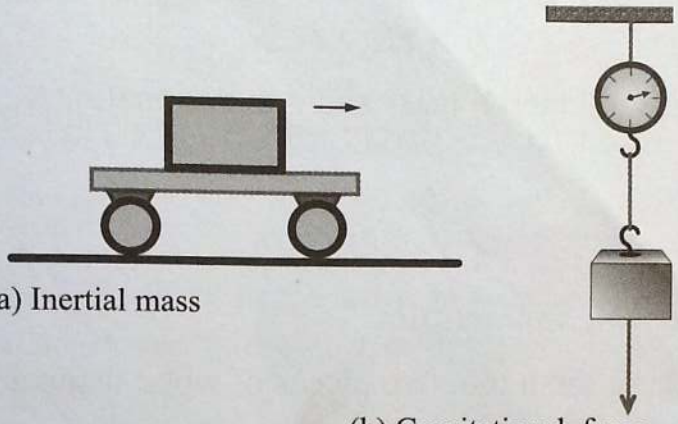
Observation

The lighter stone is easier to start moving and to stop moving. The heavier stone is more difficult to start or stop moving i.e, it requires a larger force.

Conclusion

This experiment shows that the mass of a body is a measure of its inertia. *A body with a large mass has a large inertia* and vise versa.

If the experiment is repeated in a place where there is no gravitational pull e.g. interplanetary space, the same results are obtained. The mass of a body in this case is called *inertia mass* (Fig. 2.6(a)). When the mass of a body is pulled by the force of gravity the mass is called *gravitational mass* (Fig. 2.6 (b)).



(a) Inertial mass

(b) Gravitational force

Fig. 2.6: Inertial and gravitational mass.

Exercise 2.1

1. Explain the term *inertia*.
2. State three practical applications of law of inertia.
3. Explain the following experiences.
   (a) When one alights from a moving bus, he/she is more likely to fall unlike when alighting from a stationary one.
   (b) When a car suddenly stops, the passengers are jerked forward.
4. An umbrella kept upside down can be dried by rapidly closing and opening it. Explain.
5. Explain why safety belts are worn in cars.
6. An object of large mass is suspended by means of a string A from the ceiling. Another similar string, B, is attached to the bottom of the object. Explain which string would break when string B is pulled,
   (a) slowly (b) suddenly
7. Place a coin on a cardboard which is on a table as shown in Fig. 2.7. Move the cardboard backwards and forward several times, moving the cardboard

very slowly in one direction and very quickly in the other. Explain your observation on the movement of the coin.

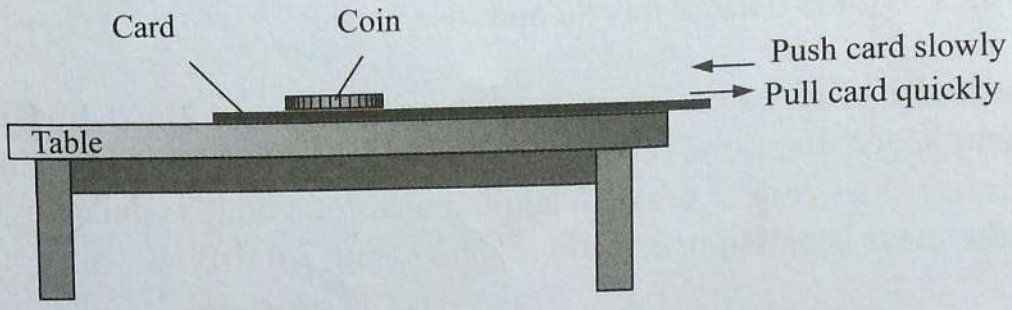


Fig. 2.7

8. Differentiate between inertia mass and gravitational mass.

2.3 Momentum

Activity 2.1: To illustrate momentum

Take two nails and drive them into two pieces of wood using a light hammer. Hit the first one gently and the second nail very hard. What happens in each case? Repeat the experiment using a heavy hammer (Fig. 2.8).

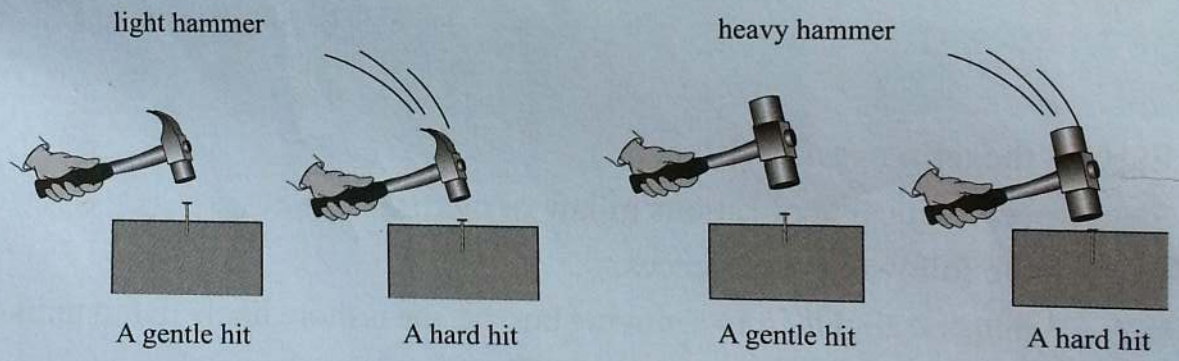


Fig. 2.8: Driving a nail into wood.

From activity 2.1, we note that the nail penetrates into the wood more when the nail is hit hard. A hard hit using a heavy hammer drives the nail deepest into the wood.

To drive the nail into the wood, a certain rate of motion (velocity) and mass of the hammer was required. A quantity involving both motion and mass of a body is called *momentum.*

Momentum of an object is defined as the product of the mass and the velocity of the object. i.e.

Momentum, p = mass, m × velocity, v,

$$p = m \times v$$

The *SI unit of momentum* is *kgm/s*. Momentum is a *vector quantity*. The direction of momentum is the same as that of the velocity.

Example 2.1

A car of mass 600 kg moves with a velocity of 40 m/s. Calculate the momentum of the car.

Solution

Momentum = mass × velocity

= 600 kg × 40 m/s

= 24 000 kgm/s in the direction of velocity

Example 2.2

A body **A** of a mass 4 kg moves to the left with a velocity of 7 m/s. Another body **B** of mass 7 kg moves to the right with a velocity of 6 m/s. (Fig. 2.9).

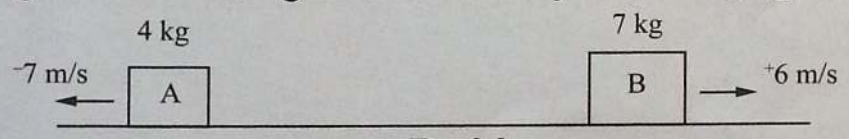


Fig. 2.9

Calculate (a) the momentum of A, (b) the momentum of B, (c) the total momentum of A and B.

Solution

Let us assign positive sign to indicate movement to the right and a negative sign to indicate movement to the left.

(a) Momentum of A = 4 kg × ⁻7 m/s = ⁻28 kgm/s

(b) Momentum of B = 7 kg × ⁺6 m/s = ⁺42 kgms /s

(c) Total momentum = (momentum of A) + (momentum of B)

= ⁻28 kgm/s + 42 kgm/s

= ⁺14 kgm/s

= 14 kgm/s to the right

Impulse

When a force F acts on an object for a very short time t, it produces an impact, usually referred to as *impulse* on the object.

Impulse is defined as the product of force and time i.e.
Impulse = Force (F) × time (t).

Impulse = Ft

SI unit of impulse is the Newton - second (Ns).

When an impulsive force acts on an object it produces a change in momentum of that object. The velocity of that object changes from an initial value (u) to a final value (v) but its mass *m* remains constant.

Experiments have shown that the impulse acting on the object is equal to the change in momentum it produces on the object.

$$\text{Impulse} = \text{Change in momentum}$$
$$Ft = mv - mu$$

Example 2.3

A hammer strikes a metal rod with a force of 20 N. If the impact lasts 0.4 s, calculate the impulse due to this force.

Solution

Impulse = Force × time
= 20 N × 0.4 s
= 8 Ns

The knowledge of impulse will help us to understand the law of conservation of momentum which we shall now discuss.

2.4 Newton's second law of motion

As we already learnt in Form 1, one of the effects of a force is that it changes the state of motion of an object. i.e. it causes a body at rest to move and a moving body to accelerate or come to rest. Any change in the velocity of a body causes a change in its momentum.

Newton summarised this effect on a body in his second law of motion which states that *the rate of change of momentum is directly proportional to the resultant force and it takes place in the direction in which the force acts.*

Mathematically, the law is represented as follows:

$$\text{Force (F)} \ \alpha \ \frac{\text{change in momentum}}{\text{time take}}$$

$$\text{Force (F)} \ \alpha \ \frac{\text{final momentum} - \text{initial momentum}}{\text{time take}}$$

If m is the mass of the body and taking u and v to represent initial and final velocities respectively.

Initial momentum = mass × initial velocity (mu)

Final momentum = mass × final velocity (mv)

Change in momentum = final momentum – initial momentum

$$= mv - mu$$

$$\text{Rate of change of momentum} = \frac{mv - mu}{t}$$

$$= m\left(\frac{v - u}{t}\right)$$

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

Thus F α ma

F = kma where k is a constant of proportionality.

Experiments show that k = 1, Therefore, F = ma

This is the mathematical representation of Newton's second law. The relationship F = ma shows that the greater the force applied on an object the more acceleration it causes on the object.

If mass is 1 kg and acceleration is 1 m/s^2, then the force is 1 N. This is the definition of 1 newton i.e. *1 newton is the force which when it acts on a mass of 1 kg, it gives it an acceleration of 1m/s^2.*

Example 2.4

A truck of mass 2.5 tonnes accelerate at 7.5 m/s^2. Calculate the force generated by the truck's engine to attain this acceleration.

Solution

F = ma $= 2.5 \times 1\,000 \text{ kg} \times 7.5 \text{ m/s}^2$

$= 18\,750 \text{ N}$

Example 2.5

An object of mass 4 kg accelerates to 5 m/s^2. Calculate the resultant force.

Solution

F = ma

$= 4 \text{ kg} \times 5 \text{ m/s}^2$

$= 20 \text{ N}$

Example 2.6

Calculate the acceleration produced by a force of 20 N on an object of mass 300 kg.

Solution

$$a = \frac{F}{m} = \frac{20\ \text{N}}{300\ \text{kg}}$$
$$= 0.066\ 7\ \text{m/s}^2$$

Example 2.7

Table 2.1 shows the values of force, F, and the acceleration, a, for the motion of a trolley on a friction compensated runway.

Table 2.1

Force F (N)	0.2	0.4	0.6	0.8	1.2
Acceleration, a (m/s²)	0.90	1.8	2.7	3.5	5.3

(a) Plot a graph of acceleration, a, against force, F.

(b) Use your graph to determine the force when the acceleration is 4.0 m/s².

(c) Calculate the mass of the trolley, in grams, from your answer in (b).

Solution

(a) The graph is shown in Fig. 2.10.

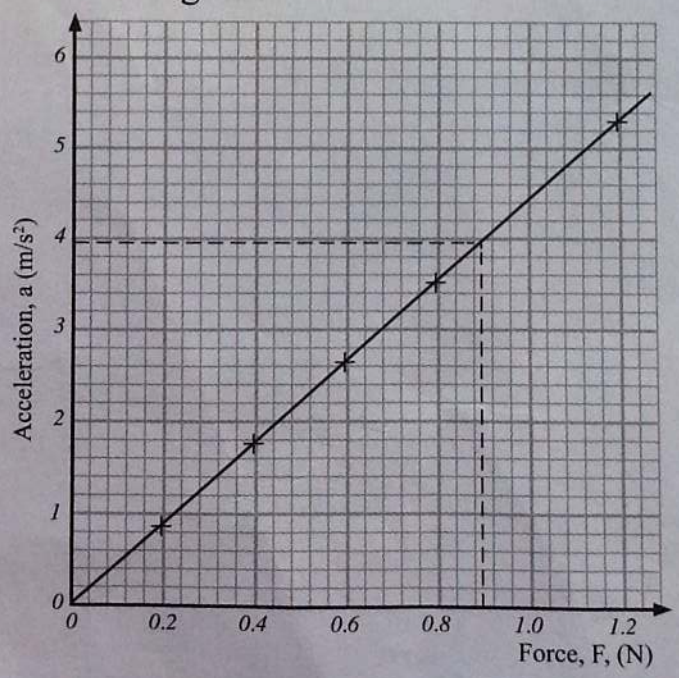


Fig. 2.10: A graph of acceleration against force

(b) As shown in the graph, by extrapolation, force, F = 0.9 N, when acceleration, $a = 4.0\ m/s^2$.

(c) Since F = ma, $m = \frac{F}{a}$

$$= \frac{0.9\ N}{4.0\ m/s^2}$$

$$= 0.225kg$$

The mass of the trolley = 225 g

Example 2.8

A car of mass 900 kg is towed by a breakdown truck along a level road. They accelerates at $0.6\ m/s^2$ (Fig, 2.11). Calculate the tension in the rope.

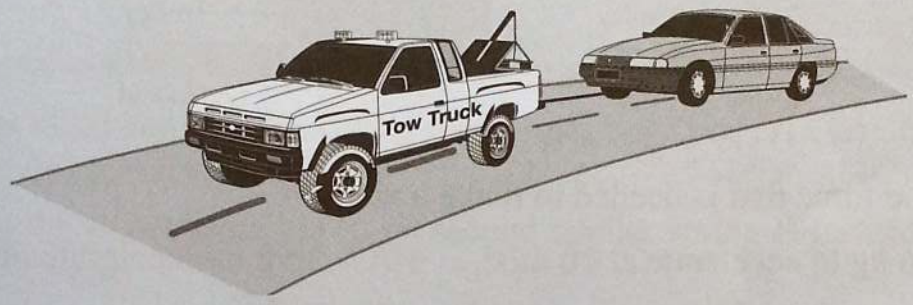


Fig. 2.11

Solution

Tension = resultant force using acceleration

Resultant force, F = ma

$$= 900\ kg \times 0.6\ m/s^2$$

$$= 540\ N$$

Tension = 540 N

Exercise 2.2

1. (a) State Newton's second law of motion.
   (b) Use Newton's second law of motion to derive to the equation F = ma.
   (c) Define the unit of force, 'the newton' using F = ma
2. (a) What is meant by 'impulse of a force'?
   (b) What is the relationship between impulse and the change in momentum?
   (c) When a soccer goalkeeper is being trained on how to catch hard ball(s), he/she is taught how to pull back the hands while catching the ball. Explain how the technique works.

3. A 0.06 kg tennis ball drops freely from the left hand of the player. When in the air, it is hit with a racquet and leaves with a horizontal speed of 58 m/s.

   (a) Calculate the impulse produced on the ball.

   (b) If the time of contact with the racquet is 0.025 seconds, calculate the average force exerted on the ball.

4. A trolley is pulled by three elastic cords in parallel. The acceleration is found to be 15 m/s^2. The elastic cords are then arranged in series and pulled (Fig. 2.12). If the elastic cords are stretched by exactly the same amount of force, find the acceleration of the trolley assuming there are no frictional forces.

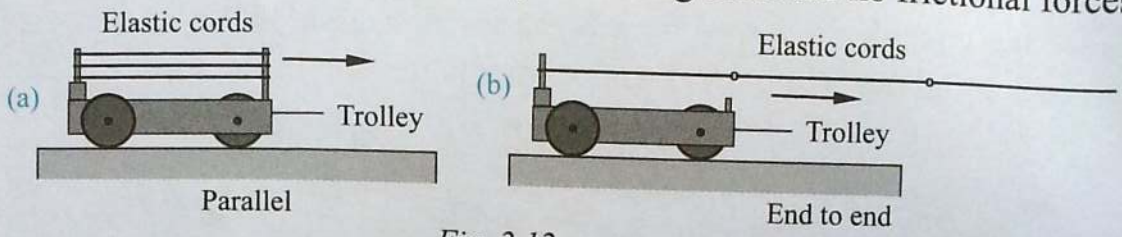


Fig. 2.12

5. Find the force that is needed to make a mass of

   (a) 6 kg to accelerate at 10 m/s^2, (b) 30 g to decelerate at 12 cm/s^2,

   (c) 8 kg to accelerate at 6 m/s^2.

6. Describe an experiment to investigate how the force applied on an object is related to the acceleration it produces. Draw a diagram that you would use, stating the observations expected and explaining how you would use these observations to obtain the relationship between force and acceleration.

7. A bullet of mass 7 g travels with a velocity of 150 m/s. It hits a target and penetrates into it. It is brought to rest in 0.04 s. Find the:

   (a) distance the bullet travels in the target.

   (b) average retarding force exerted on the bullet.

8. Find the force that should be to be applied to an object of mass 8.0 kg to make it an accelerate by 20 m/s^2.

9. A football ball of mass 500 g attains acceleration of 25 m/s^2. Find the average force exerted on the ball.

10. A force of 15 N makes a body of mass 3.0 kg to move. Calculate the average acceleration of the body.

11. A car of mass 800 kg moving with an acceleration of 20 m/s^2 crashes into a wall. Find the average force exerted by the car.

2.5 Newton's third law of motion

It is easier to study the motion of an object by considering one force at a time. However, in reality a single force cannot exist by itself. Two forces always occur when two objects push or pull on each other. These forces are called *action* and *reaction* force. The following experiment will demonstrate action and reaction forces.

Experiment 2.6: To demonstrate action and reaction force

Apparatus

- Two springs
- A rigid support

Procedure

1. Hook one end of a spring balance A to a rigid support.
2. Pull the other end until the spring shows a reading (Fig. 2.13 (a)). Explain what is happening to the wall?
3. Repeat the experiment but use a second similar spring B instead of the wall (Fig. 2.13 (b)).

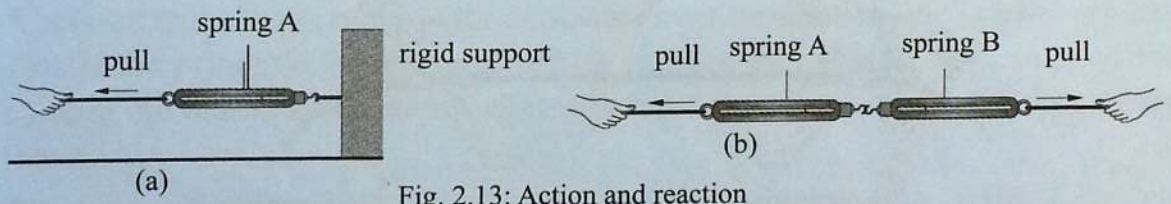


Fig. 2.13: Action and reaction

4. Pull the two springs until the reading on spring A is the same as before.
5. What reading is shown by spring B?

Observation

- The rigid support was being pulled with a certain force, but it was not moving.
- When two springs were pulled they had the same reading.

Conclusion

The reading in spring B is the same as in spring A. The two forces are equal in size but are in opposite direction. This shows that when spring A is pulled to the wall, the wall also pulled the spring A with an equal and opposite force.

Other examples of action and reaction

1. When you push a rigid wall (exert action), the wall pushes back (exerts a reaction). The push of the wall is provided by the contact force which you apply.

2. A book placed on a table provides the action, while the table supports the book by providing a reaction force (Fig. 2.14).

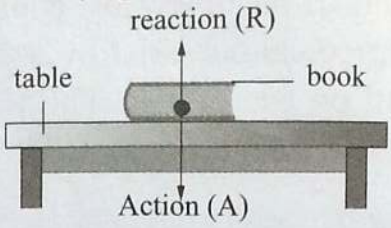


Fig. 2.14: A box resting on a table

3. Charged bodies show two equal but opposite forces (Fig. 2.15).

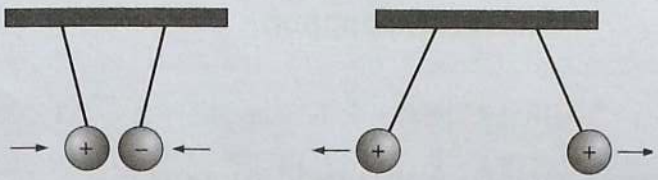


Fig. 2.15: Equal but opposite forces

4. Tug of war (Fig. 2.16).

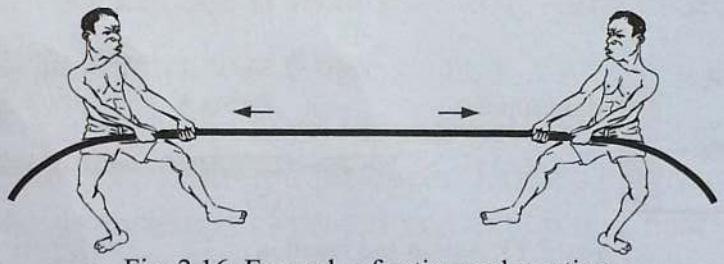


Fig. 2.16: Example of action and reaction

These observations can be summarised by what is called *Newton's third law of motion.*

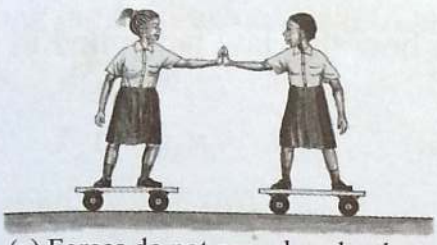
It states that *whenever a body exerts a force on another body, the other body exerts an equal but opposite force on the first body.*

This is sometimes stated as, *to every action there is an equal and opposite reaction.*

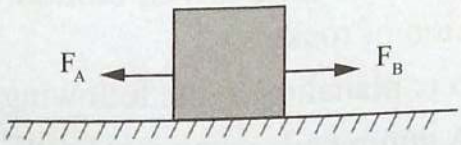
Note

The two forces, action and reaction, act on two different objects. For example in Fig. 2.14 the action force A acts on the table while the reaction force R acts on the book. Consequently, the two forces, although equal and opposite, do not cancel each other; i.e. they do not produce a zero resultant force.

Consider two girls standing on trolleys and pushing each other (Fig. 2.17 (a)). The pushes cause both girls to move away in opposite directions. Compare this with two equal and opposite forces acting on the same body (Fig. 2.17 (b)). The two forces cancel each other and the body remains at the same place.



(a) Forces do not cancel each other



(b) Forces cancel each other

Fig. 2.17: Action and reaction forces

Some common experiences due to Newton's third law of motion

1. When running or walking a person exerts a backward force on the ground. The ground exerts a forward push on the person. This makes walking possible.
2. When a gun is fired, the bullet travels in one direction while the gun recoils backwards (Fig. 2.18). Although the two forces are equal and opposite, the bullet's velocity is greater than that of the gun.

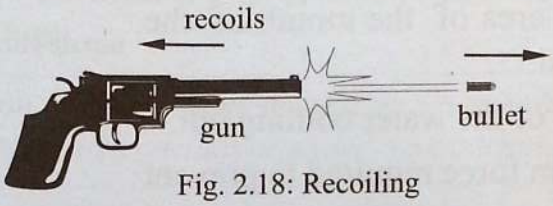


Fig. 2.18: Recoiling

3. A balloon will always move in the opposite direction when the air inside it is released. This is the principle that rockets and jet engines use. The force (action) of the air coming out exerts an equal and opposite force (reaction) on the balloon making it move.
4. The water sprinkler works on action and reaction principle (Fig. 2.19).

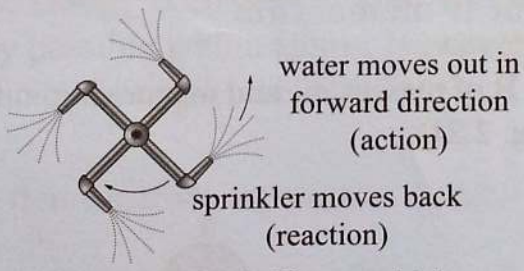


Fig. 2.19: Water sprinkler

The splinkler rotates in the direction opposite to that of the water jet.

Exercise 2.3

1. For each of the following forces, describe the reaction, giving its direction and stating where it acts.
   (a) the push of a boot on a football.
   (b) the push (backwards) of a swimmer on water.
   (c) the pull of gravity on a mango resting on a table.

2. State Newton's third law of motion. Explain how this law is applied in the propulsion of rockets.

3. Give an explanation to the following.
   (a) A gun recoils when it is fired.
   (b) A fireman moves backwards when a water hose he is aiming at a fire is suddenly turned on.

4. A *matatu* accelerates uniformly from rest to 30 m/s in 10 s. Find
   (a) acceleration.
   (b) force the back of a passenger of mass 60 kg would exert on the seat.

5. A garden sprinkler (Fig. 2.20) has three of the four jets blocked. 60 cm^3 of water jets out of the fourth jet every second (density of water is 1 g/cm^3). If the area of the mouth of the jet is 15 mm^2. Find:
   (a) the velocity of the water coming out.
   (b) the minimum force required to prevent the rotation.
   (c) Explain how you would, measure the force in (b).

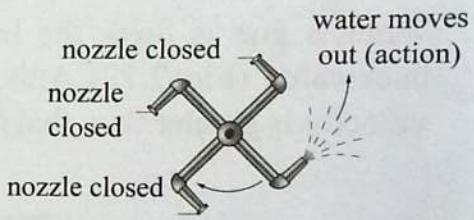


Fig. 2.20: sprinkler moves back (reaction)

6. A rocket pushes out exhaust gas at a rate of 150 kg/s. The velocity of the gas is 250 m/s. Calculate the forward thrust on the rocket.

2.6 Conservation of linear momentum

Consider two objects A and B of masses m_A and m_B moving in the same direction with different velocities (Fig. 2.21).

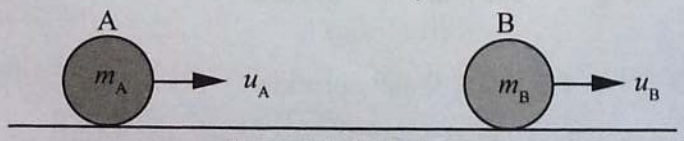


Fig. 2.21: Collisions

On collision, A pushes B with a force F_A and B reacts by pushing A with an equal and opposite force F_B. That is $F_A = {}^-F_B$.

Since the time spent in colliding is the same, A experiences an impulse ${}^-F_B t$ from B while B also experiences an impulse $F_A t$ from A.

Thus ${}^-F_B t = F_A t$ ..... (i)

Impulse = change in momentum = mv – mu

Letting the final velocities of A and B be v_A and v_B respectively

Then, $-F_B t = m_A v_A - m_A u_A$ .....(ii)

$F_A t = m_B v_B - m_B u_B$.....(iii)

Equating (ii) and (iii)

$$-(m_A v_A - m_A u_A) = m_B v_B - m_B u_B$$

$$-m_A v_A + m_A u_A = m_B v_B - m_B u_B$$

$$m_A u_A + m_B u_B = m_A v_A + m_B v_B$$

But $m_A u_A + m_B u_B$ = total momentum before collision

and $m_A v_A + m_B v_B$ = total momentum after collision

$\therefore$ *Total momentum before collision = total momentum after collision*

The momentum has been conserved. This conclusion is summarised as the law of conservation of momentum.

The *law of conservation of momentum* states that *when two or more bodies collide, their total momentum remains constant provided no external forces are acting*.

2.7 Collisions

There are two types of collisions, namely *elastic* and *inelastic* collision.

Elastic collisions

When the total kinetic energy is conserved after collision, the collision is said to be *elastic*. This is only possible within atoms. However, the collision between two smooth marble balls is appropriately elastic.

Experiment 2.7: To demonstrate an elastic collision

Apparatus

- Two trolleys A and B
- A tape
- A ticker timer
- Two carbon papers

Procedure

1. Determine the mass of two trolleys A and B. Compensate the runway for friction.
2. Attach a tape to each of the trolleys. Pass the two tapes through a ticker timer using two carbon papers (Fig.2.22).

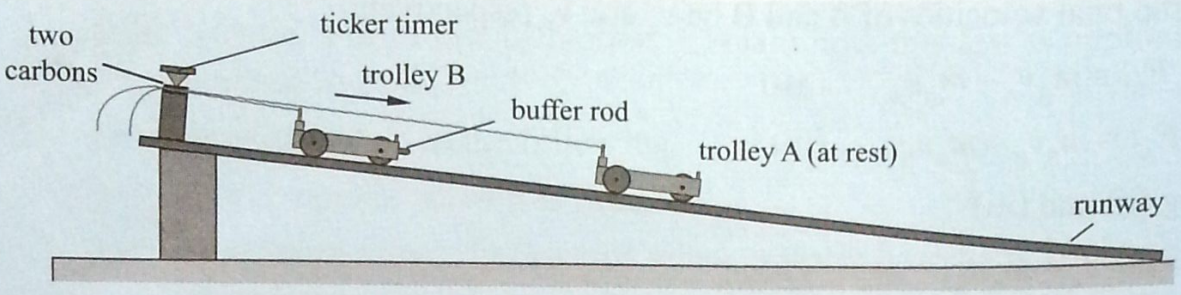


Fig. 2.22: Elastic collision

3. Position trolley A halfway down the runway. Make sure it is stationary.
4. Start the ticker timer and push trolley B aiming its buffer rod towards the trolley A.
5. Allow the two trolleys to continue moving after the collision.
6. Calculate from tapes the velocity of trolley B before collision u_B and the velocity of trolley A and B after collision (v_A and v_B).
7. Repeat the experiment with trolleys A and B loaded with different masses. Record the results in a table (Table 2.2).
8. Determine the total momentum and the total kinetic energy before and after collision. Compare their values before and after collision.

Table 2.2

Before collision								After collision							
Trolley A			Trolley B			Total momentum	Total K.E	Trolley A			Trolley B			Total momentum	Total K.E
m_A	u_A	$m_A u_A$	m_B	u_B	$m_B u_B$	$m_A u_A + m_B u_B$	$\frac{1}{2}m_A u_A^2 + \frac{1}{2}m_B u_B^2$	m_A	v_A	$m_A v_A$	m_B	v_B	$m_B v_B$	$m_A v_A + m_B v_B$	$\frac{1}{2}m_A v_A^2 + \frac{1}{2}m_B v_B^2$

Observation

The tapes appear as shown in Fig. 2.23.

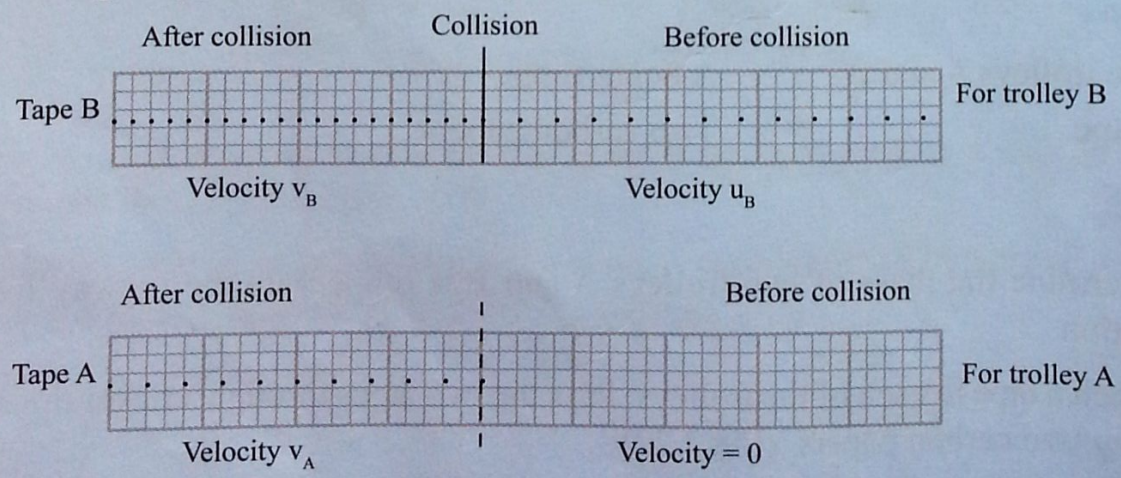


Fig. 2.23: Ticker timer tapes

If no other forces are acting, the total momentum and total energy before and after collision is found to be the same. These types of collisions are not common because in every collision, some energy is always converted to other forms.

Example 2.9

A cannon of mass 800 kg fired a cannon ball of mass 3 kg at a velocity of 120m/s. Find the recoil velocity of the cannon.

Solution

$m_1 = 3$ kg, $u = 0$ m/s, $v_1, = 120$ m/s, $m_2 = 800$ kg, $u_2 = 0$ $v_2 = ?$

Total initial momentum = total momentum

$$m_1u_1 + m_2u_2 = m_1v_1 + m_2v_2$$

$$3 \times 0 + 800 \times 0 = 3 \times 120 + 800 \times v_2$$

$$0 = 360 + 800v_2$$

$$-800v_2 = 360$$

$$v_2 = \frac{360}{800} = -0.45\text{m/s}$$

The cannon recoiled backwards at a velocity of 0.45 m/s. The negative value in the velocity shows that the cannon moved (recoiled) in the opposite direction.

Inelastic collision

We have seen that when the two bodies collide, their total momentum is conserved. The total kinetic energy is however not usually conserved. Some kinetic energy is converted into sound and heat. Collisions where the total kinetic energy is not conserved are called *inelastic collisions*. A *completely inelastic* collision is one *which two bodies stick together after collision.*

Experiment 2.8: To demonstrate inelastic collision

Apparatus

- Two trolleys A and B
- A cork
- A pin or a sharp buster rod

Procedure

1. Determine the mass of two trolleys A and B. Raise the runway to compensate for friction.
2. Attach a cork at the back of trolley A position trolley A halfway down the runway. Make sure it is stationary.

3. Attach a pin or a sharp buster rod at the front of trolley B and a tape to pass through the ticker timer.
4. Start the ticker timer. Push the trolley B aiming the pin towards the cork on trolley A (Fig. 2.24).

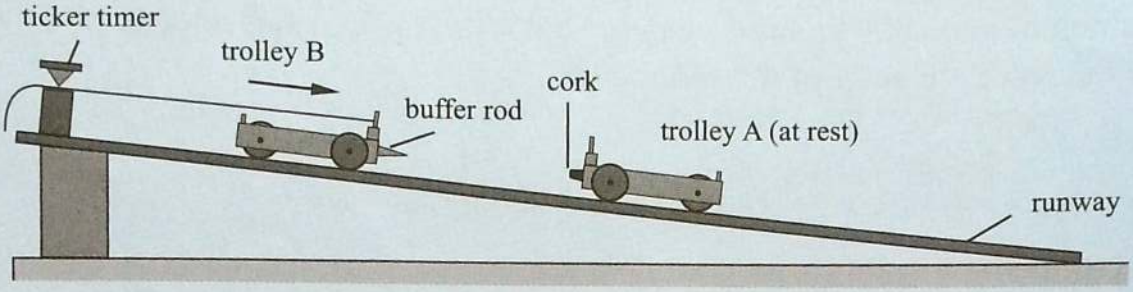


Fig.2.24: Inelastic collision

Allow the trolleys to move together after collision.

Observation

- Repeat the experiment with trolleys A and B loaded with different masses. Record the results in a table (Table 2.3).
- Determine the total momentum and the total kinetic energy before and after collision. Compare these quantities before and after collision.

Table 2.3

Before collision					After collision			
Trolley B			Total momentum	K.E			Total momentum	Total K.E
m_B	u_B	$m_B u_B$	$m_B u_B$	$\frac{1}{2} m_B u_B^2$	m_{AB}	v_{AB}	$m_{AB} v_{AB}$	$\frac{1}{2} m_{AB} v_{AB}^2$

From the experiment, we observed that only momentum is conserved, but there is a loss of kinetic energy.

The tapes appear like the ones shown in Fig. 2.25.

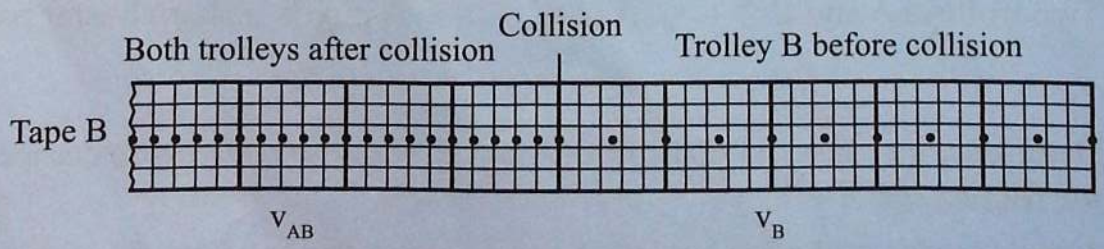


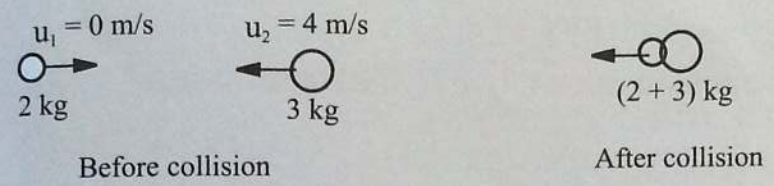
Fig. 2.25: Ticker timer tape

From the tapes, measure the velocity (u_B) of trolley B before collision, and then velocity (v_{AB}) of trolley A and B after collision.

Example 2.10

A mass of 3 kg moving with a velocity of 4 m/s collides with another mass of 2 kg which is stationary. After collision the two masses stick together. Calculate the common velocity for the two masses.

Solution



Momentum before collision $= m_1u_1 + m_2u_2 = (2 \times 0) + (3 \times 4)$

$= 12$ kgm/s

Momentum after collision $= (m_1 + m_2)v = (3 + 2)v = 5v$

Momentum before collision = momentum after collision

$$12 \text{ kgm/s} = 5v$$

$\therefore$ Common velocity, $v = 2.4$ m/s

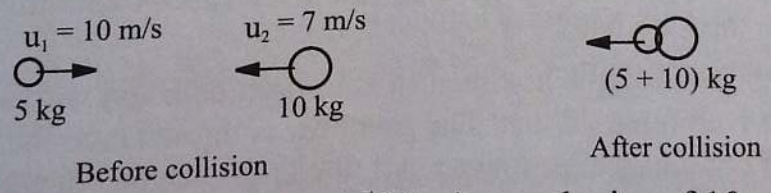
Example 2.11

A 5 kg mass moving with a velocity of 10 m/s collides with a 10 kg mass moving with a velocity of 7.0 m/s along the same line. If the two masses join together on impact, find their common velocity if they were moving

(a) in opposite direction **(b)** in the same direction

Solution

(a)



Velocity of 5 kg mass = $^{+}10$m/s ; velocity of 10 mass = -7 m/s

Momentum before collision = momentum after collision

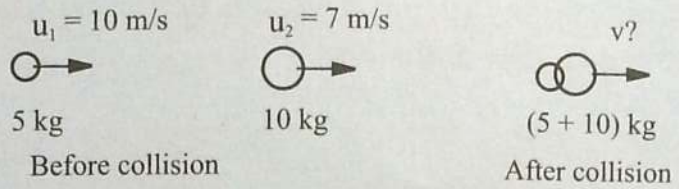
$$(5 \times 10) + (10 \times -7) = (5 + 10)\,v$$

$$50 + (-70) = 15v$$

$$v = -1.33 \text{ m/s}$$

The minus sign means that the joined mass moves to the left.

(b)



Momentum before collision = momentum after collision

$$(5 \times 10) + (10 \times 7) = 15 \times v$$

$$50 + 70 = 15\ v$$

$$v = +8.0 \text{ m/s}$$

The plus sign means that the joined mass move to the right.

Exercise 2.4

1. A mass of 8 kg travelling to the right at 2.5 m/s collides with a 2 kg mass travelling to the left at 3.0 m/s. Find
   - **(a)** the momentum of each mass.
   - **(b)** their total momentum.
2. An object of mass 20 kg collides with a stationary object of mass 10 kg. The two objects join together and move at a velocity of 5 m/s. Find the original velocity of the moving object.
3. A car of mass 600 kg travels at 20 m/s towards a stationary pick-up of 1 200 kg. After colliding the two stick and move together. Find their common velocity.
4. A truck of mass 3 000 kg moving at 3 m/s collides head on with a car of mass 600 kg. The two stop *dead* on collision. At what velocity was the car travelling before collision?
5. If a 2 kg ball travelling north at 6 m/s collides with 4 kg ball travelling in the same direction at 4 m/s, the velocity of the 4 kg ball is increased to 5.5 m/s to the north. What happens to the 2 kg ball?
6. A small car of mass 500 kg is involved in a head-on collision with a heavy car of mass 4 000 kg travelling at 20 m/s. The small car is thrown onto the bonnet of the heavy car which continues after impact at 4 m/s in the original direction. How fast was the small car moving?
7. A bullet of mass 10g is shot from a gun of mass 20kg with a muzzle velocity of 100m/s. If the bullet is 20 cm long determine:
   - **(a)** the acceleration of the bullet.
   - **(b)** the recoil velocity of the gun.

Unit Summary

- Newtons first law of motion states that a body continues in its state of rest or uniform motion in a straight line unless compelled to by some external force to act otherwise
- Momentum is the product of mass and velocity of a body.

$$P = m \times v$$

- Newton's second law of motion states that the rate of change of momentum is directly proportional to the resultant force and take place in the direction in which the force act .
- Impulse = Ft = force (N) × time(s)
- Impulse = change in momentum

$$\mathbf{Ft = mv - mu}$$

- The law of conservation of momentum states that when one or more bodies collide, their total momentum remain constant provided no external forces are acting.

$$\mathbf{m_A u_A + m_B u_B = u_A v_A + m_A v_B}$$

- In an elastic collision two or more bodies separate after colliding. Both momentum and kinetic energy are conserved.
- In an inelastic collision, two or more bodies fuse and move together after colliding. Momentum is conserved but kinetic energy is not.
- $F = ma$, is the mathematical statement of Newton's second law of motion.
- Newton's third law of motion states that for every action there is an equal and opposite reaction.

Unit Test 2

1. (a) Explain why Newton's first law of motion is also called the law of inertia.

   (b) Describe an experiment to illustrate the Newton's first law of motion.

2. Table 2.4 shows the values of the resultant force, F, and time, t, for a bullet travelling inside the gun barrel after the trigger is pulled.

Table 2.4

Force, F (N)	360	340	300	240	170	110
Time, t (s) × 10^{-3}	3	4	8	12	17	22

(a) Plot a graph of force, F, against time, t.

(b) Determine from the graph;

(i) the time required for the bullet to travel the length of the barrel. (Assume that the force becomes zero just at the end of the barrel.)

(ii) the impulse of the force.

(c) Given that the bullet emerges from the muzzle of the gun at a velocity of 240 m/s, calculate the mass of the bullet.

3. A block of mass of 3 kg is pulled by a spring balance that records a force of 10 N. The ticker tape (Fig. 2.26) attached at the back of the mass shows a group of 10 spaces between them having the lengths as shown in Figure. The ticker timer makes 50 dots per second.

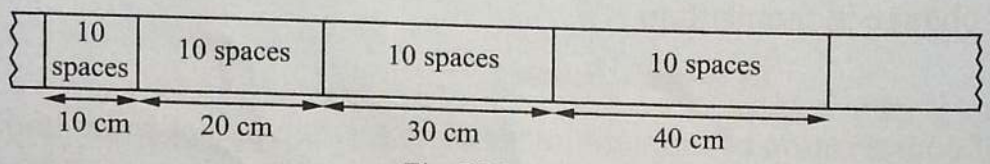


Fig. 2.26

(a) Draw and show how the dots are spaced out on the tape.

(b) Find (i) the acceleration of the block

(ii) the balanced force acting on the block.

4. The graph in Fig. 2.27 shows how the force applied on a 20 kg mass varies with time.

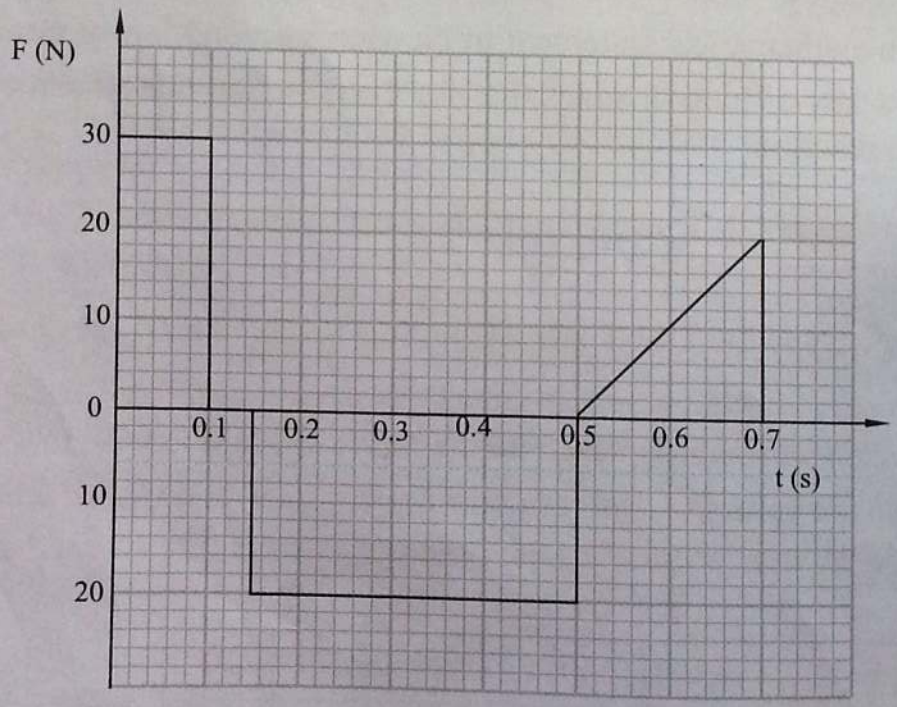


Fig. 2.27 A graph of F against t

(a) Find the total impulse after 0.7 s.

(b) If the body starts from rest, draw the;

(i) acceleration-time graph.

(ii) velocity-time graph.

(iii) momentum-time graph.

5. A ball of mass of 2.0 kg, travelling at 1.5 m/s catches up and collides with another ball of mass 3.0 kg travelling at 0.8 m/s in the same direction. If they stick and move together, calculate;

(a) the velocity after collision for each ball.

(b) the change in momentum for each ball.

6. A rugby player of mass 75 kg, running east at 8.0 m/s, collides with another player of mass 90 kg and who is running directly towards him at 5.0 m/s. If the two players cling together after the tackle, what will be their common velocity?

7. Fig. 2.28 is a graph of acceleration against applied force.

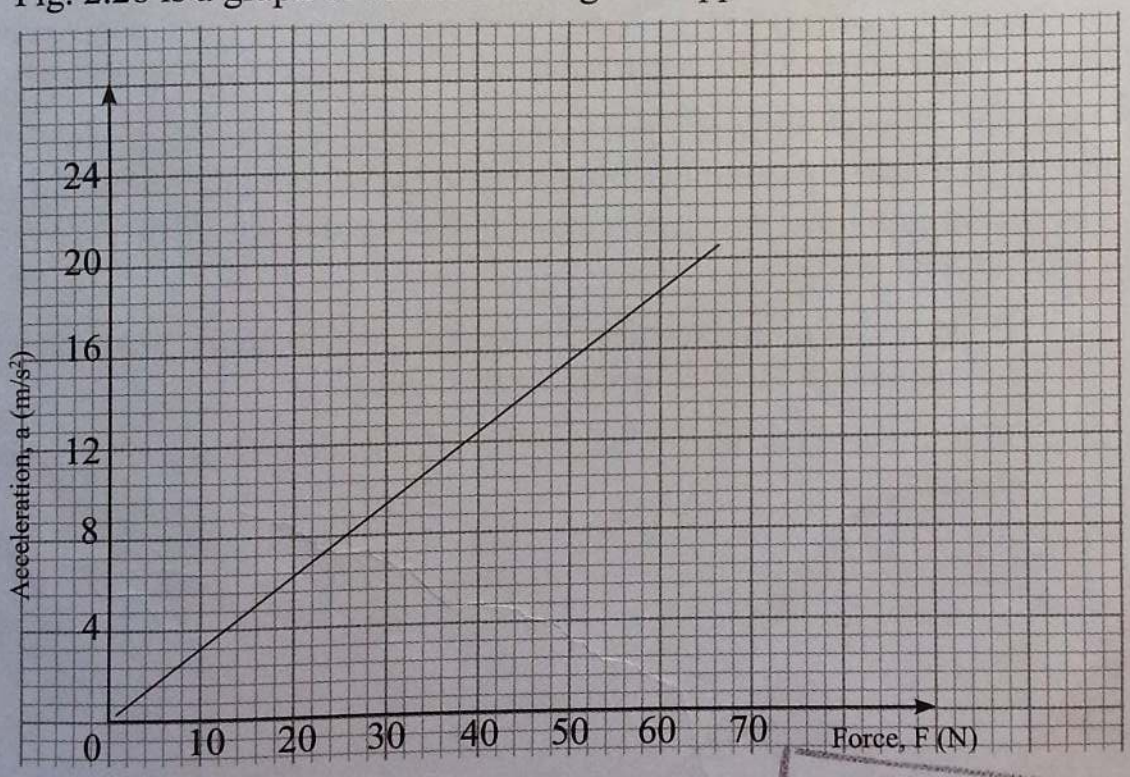


Fig. 2.28 A graph of acceleration against force

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Find:

(a) the force that results to acceleration of 14 m/s²

(b) the gradient and state its unit

8. A bullet of mass 15 g travelling at 400 m/s becomes embedded onto a block of wood of mass 300 g which is at rest. Calculate the initial speed of the block immediately after collision.

9. A bullet of mass 20 g travelling horizontally at a speed of 200 m/s embeds itself in a block of wood of mass 850 g suspended from a light inexensible string so that it can swing freely. Find:

   (a) The velocity of the bullet and block immediately after collision.

   (b) The height through which the block rises.

10. Two ice hockey players travelling in opposite directions get entangled and move while locked together. Player A has a mass of 120kg and is travelling at 5m/s. Player B has a mass of 90kg and is travelling at 4 m/s. Calculate.

   (a) the intial momentum of player A.

   (b) the initial momentum of player B.

   (c) the speed with which they both move with after being locked together.

   (d) In which direction did they move after collision?

11. A trolley of mass 2 kg travelling from left to right at 4 m/s collides elastically with another trolley of mass 4 kg travelling from right to left at 1m/s. If the speed of the 2 kg trolley after collision is 0.8 m/s, what is the speed of 4 kg trolley?

12. A satellite is travelling in an orbit around the earth. The scientists controlling it need to reduce its speed by firing a small rocket motor to collide with it. The rocket motor moves at a speed of 4 000m/s and ejects its fuel at a rate of 2.0kg per second.

   (a) If the rocket motor acts for 5.0 seconds, calculate the total change in momentum of the fuel ejected in this time.

   (b) If the mass of the satellite is 2.0×10^3 kg, calculate the change in speed of the satellite.

UNIT

3 Frictional Force

Success criteria

By the end of this unit, you must be able to:

- Describe applications of frictional force
- Explain terminal velocity

Introduction

In Form 1, we were introduced to frictional force. We defined friction as the force that oppose the relative motion of two surfaces that are in contact. We also learnt that the two factors that affect the friction between two surfaces are the nature of the surfaces and the normal reaction (R).

In this unit, we will learn how to determine the coefficient of friction between two surfaces and discuss friction in fluids.

3.1 Coefficient of solid friction

Look at Fig. 3.1. A solid block is being pulled over a horizontal surface by an applied force, F, frictional force (F_r) acts in the opposite direction to oppose the movement of the block.

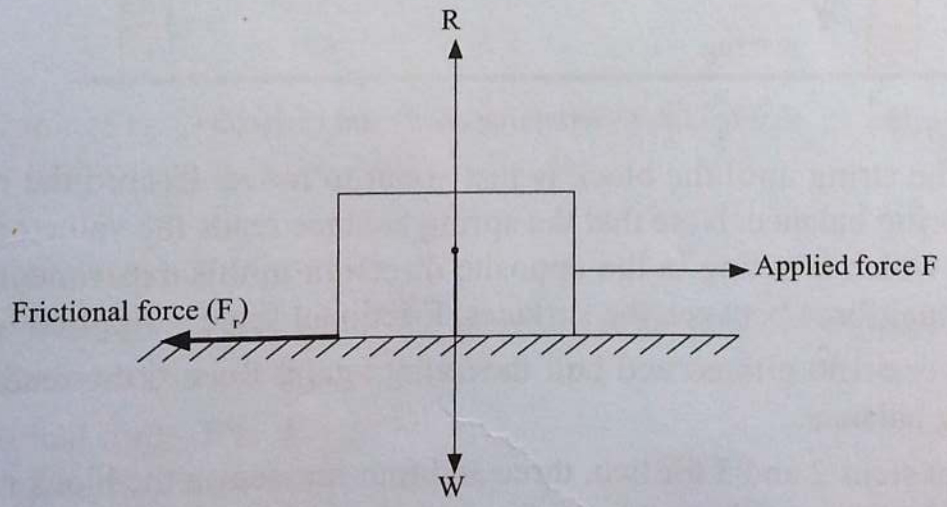


Fig. 3.1 Forces acting on a solid block on a horizontal surface

When the block is just about to move, the solid friction is called *static friction*. Static friction is the force opposing motion between surfaces when the surfaces are just about to move. When the block is moving, friction force is reduced and is called *dynamic friction*. Dynamic friction is the force opposing motion when there is relative motion.

Suppose some weights are placed on top of the block, would the frictional force remain the same? In other words, what is the relationship between the frictional force and the normal reaction (R)?

The following experiment will help us establish the relationship between frictional force and normal reaction.

Experiment 3.1: To establish the relationship between frictional force and normal reaction

Apparatus

- A 50 g wooden block with rough surface.
- A rough bench
- Four 150 g masses
- A spring balance

Procedure

1. Set up the apparatus as shown in Fig. 3.2.

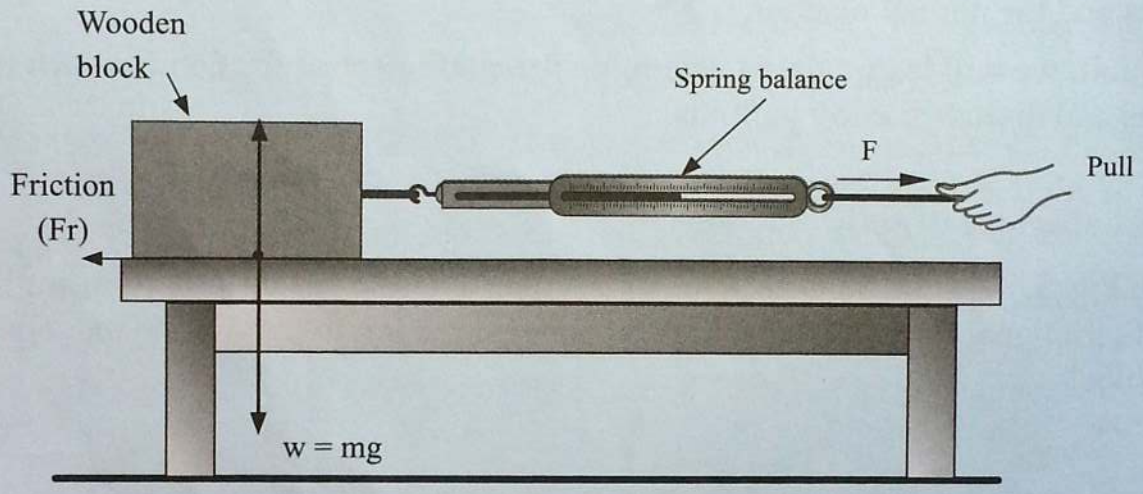


Fig. 3.2: Determining coefficient of friction

2. Pull the string until the block is just about to move. Record the reading on the spring balance. Note that the spring balance reads the value of frictional force which is acting in the opposite direction in this experiments. F is the frictional force between the surfaces. Frictional force = Applied force F.
3. Place one 150 g mass and pull the string again. Record the reading on the spring balance.
4. Repeat steps 2 and 3 for two, three and four masses on the block masses and the record the reading of force, F on the spring balance in Table 3.1.

Table 3.1

Mass (g)	50	100	150	200	250
Reaction, R (N)					
Spring reading, F (N)					

5. Draw a graph of F(N) against R(N).

Observation

From Table 3.1, we note that the readings on the spring balance increase with increase of the mass. If a column of $\frac{F}{R}$ is added and completed in Table 3.1. We will notice that the value of $\frac{F}{R}$ is constant.

Discussion

When a graph of F against R is plotted, a straight line that is passing through the origin is obtained (Fig. 3.3).

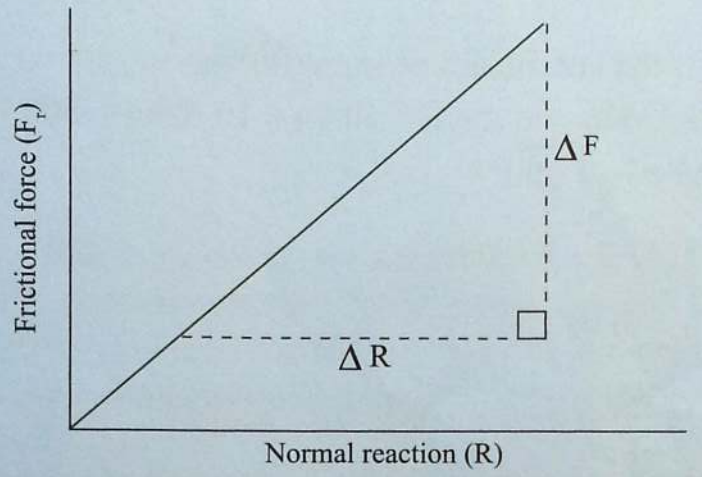


Fig. 3.3 A graph of F against R

The gradient of the line gives:

$$\text{Gradient} = \frac{\text{change in F}}{\text{change in N}} = \frac{\Delta F}{\Delta R}$$

From the graph (Fig. 3.3), we conclude that, frictional force in solid is directly proportional to the weight of the solid i.e. F α W.

From Newton's third law of motion:

Weight (W) of an object placed on the bench is equal and opposite to the normal reaction (R) between the surface of the bench and the block in contact.

Frictional force, F α W
Therefore, F α Normal reaction (R)

Therefore, $F = \mu_s R$, where μ_s is a constant called the coefficient of static friction.

The coefficient of static friction, μ_s, is the ratio of static frictional force to the normal reaction R.

$$\mu_s = \frac{F}{R}$$

Coefficient of static friction, μ_S, has no unit since it is a ratio of forces.

One has to apply a force larger than the limiting *static frictional force (F_s)* for a body to move. When the body is sliding along the bench with a constant velocity, the frictional force is now called *kinetic or dynamic friction (F_k)*. It is calculated as $F_k = \mu_k R$ where R is the normal force and μ_k is the coefficient of kinetic friction.

Example 3.1

A force of 25 N limits the motion of a block of mass 50 kg which is being dragged on the horizontal ground. Calculate the coefficient of static friction force.

Solution

$F_s = \mu_s R$ where μ_s is the coefficient of static friction

Weight of the block = Normal force = 50 kg × 10 N/kg = 500 N

$$\therefore \; 25 = \mu_s \times 500$$

$$\mu = \frac{25}{500} = 0.05$$

$$\mu_s = 0.05$$

Example 3.2

Fig. 3.4 shows a block of mass 200 kg being dragged at constant velocity with a force 40 N at angle 60° to the horizontal.

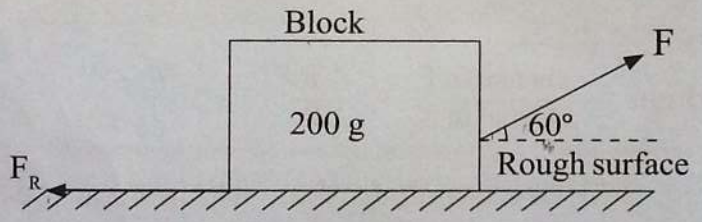


Fig. 3.4: A block being dragged at a constant velocity horizontally

Determine the coefficient of kinetic friction (μ_k).

Solution

$F = \mu_k R$

Since F is acting at an angle, we find its horizontal component.

$$F_H = F\cos\theta$$

$$= 40 \times \cos 60 = 40 \times 0.5 = 20 \text{ N}$$

Substituting this in, $F = \mu_k R$, we get:

$$20 \text{ N} = \mu_k \times 200 \text{ kg} \times 10 \text{ N/kg}$$

$$\mu_k = \frac{20}{2000} = 0.01$$

The coefficient of kinetic friction is 0.01

Exercise 3.1

1. Define the terms static friction and kinetic friction.
2. A force of 2000 N limits the motion of a car of mass 1.2 tonnes. Calculate the coefficient of friction between the road and the tyres in contact.
3. A child was pushing a block of mass 500 kg along a horizontal rough surface with a force 800 N at an angle 30° to the horizontal. Calculate the coefficient of static friction.
4. A body of mass 90 kg moving at a constant speed along a rough surface of $\mu_k = 0.8$. Calculate the friction force limiting the motion.
5. Explain what would happen if $\frac{F}{R}$ is more than 1.

3.2 Viscosity

Fluids particles also offer opposition to the motion of a body through the fluid. In this section, we shall study this resistive force in fluids (liquids and gases).

Activity 3.1: To show that fluids offer resistance to motion of objects through them

- Allow identical ball bearing to fall though a certain height *h* in air, water and glycerine (Fig. 3.5).

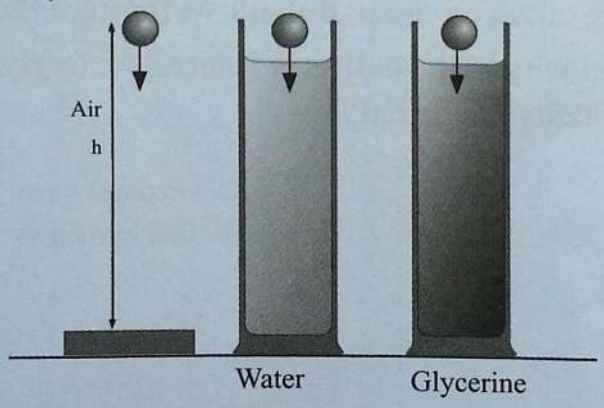


Fig. 3.5: Frictional forces in fluids

- Measure the time taken for the ball bearing to move through this height, *h*. Compare the times in the three cases.

From Activity 3.1, we observe that, the time taken by the ball to fall in air is shorter than the time it takes to fall in water. The time taken for the ball to fall in water is shorter than in glycerine.

This shows that liquids *offer resistance to the movement of objects* in them. *This resistance differs from liquid to liquid.*

Frictional force in liquids is due to the *viscocity* of the liquid. *Viscosity is the measure of how easily a fluid flows*. If the frictional force is comparatively low, as in water, the viscosity of the liquid is low. If the frictional force is large as in glycerine, the viscosity of the liquid is high. Air has a very low viscosity. The resistance due to fluids is called the *viscous drag*.

Terminal velocity

We were introduced to terminal velocity in Form 3. We defined terminal velocity as the maximum downward velocity possible for a body falling through a fluid. The following experiment will help us determine terminal velocity in a fluid.

Experiment 3.2: To determine terminal velocity

Apparatus

- A long tube filled by a fluid (Glycerine)
- Ball bearing
- Stop watch

Procedure

- Fix some rubber bands around a long tube at equal distances. Drop a small steel ball bearing into the long tube containing glycerine (Fig. 3.6).
- Measure the time taken by the ball to move through the equal intervals.
- Determine the velocity of the ball as it descends into glycerine. What can you say about the velocity of the ball?

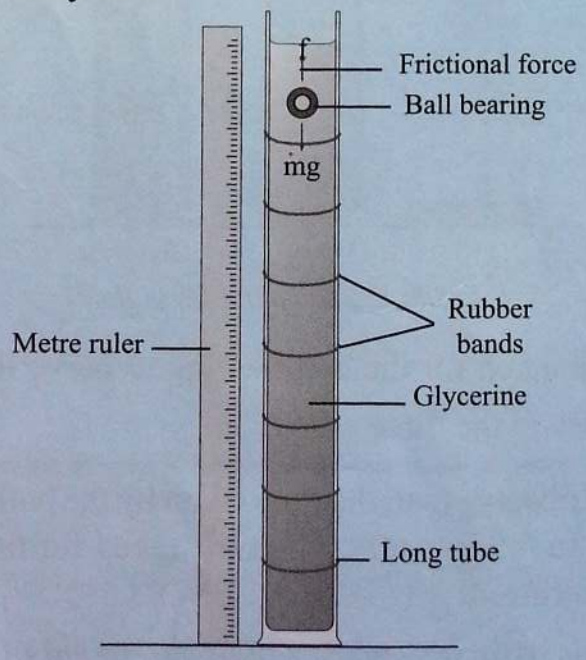


Fig. 3.6: Determination of terminal velocity

Observation

You must have observed that the velocity of the ball starts from zero and accelerates to a maximum value and then remains constant at this value, as the ball continues falling.

Discussion

When a body is falling in a fluid, three forces act on it (Fig. 3.7).

These forces are:

(i) weight of the body (W)

(ii) upthrust (U)

(iii) viscous drag (fluid friction F).

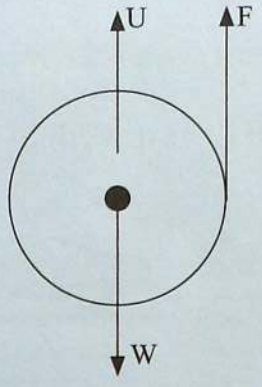


Fig 3.7 A body falling in a fluid

The fluid friction increases with increase in speed of the falling body.

Initially, W > (U + F) hence the body accelerates downwards.

As fluid friction (F) increases, it reaches a point where U = F = W

There being no resultant force, the body moves at uniform (constant) velocity. This constant velocity is called *terminal velocity.* (V_t).

Terminal velocity is therefore defined as the maximum downward velocity possible for a particular object falling through a fluid.

If the velocity of the object is plotted against time, a graph similar to the one in Fig. 3.8 is obtained.

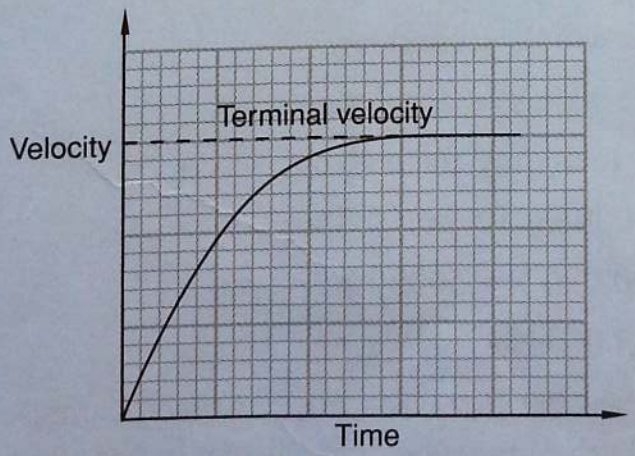


Fig. 3.8: Graph of velocity against time

Air resistance

When running, we experience the backward pushing by air even without the pressure of wind. The same resistance is experienced by moving vehicles. Thus, air offers resistance to movement. Air resistance is also referred to as air friction. i.e. friction opposing a moving body in air. It is a form of dynamic friction. Moving objects waste a lot of energy in overcoming air resistance. For a vehicle, this leads to high fuel consumption. To reduce air resistance, bodies of cars and planes are streamlined. i.e they have smoothened, rounded and pointed bodies.

Example 3.3

A car of mass 1000 kg is travelling under the action of forces as shown in Fig 3.9.

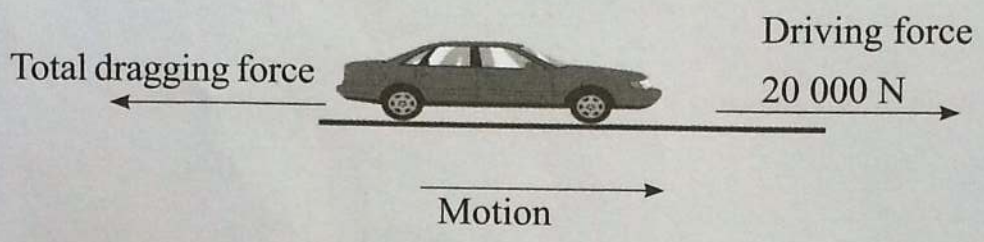


Fig. 3.9 Forces on a moving car

(a) State the size of the drag force when the car is travelling at a constant speed.

(b) If the car accelerates at 5 m/s^2, work out the total dragging force.

(c) The car continues accelerating at 5 m/s^2 but eventually reaches the highest constant speed. Explain.

Solution

(a) At constant speed, Resultant force = 0 N.

$\therefore$ Total dragging force = Driving force = 20 000N

(b) According to Newton's second law,

Resultannt force = mass × acceleration

Driving force – total drag force = ma

$20\,000 - F = 1\,000 \text{ kg} \times 5 \text{ m/s}^2$

$F = 20\,000 \text{ N} - 5000 \text{ N}$

$= 15\,000 \text{ N}$

(c) As the speed of the car increases, air resistance increases. At some point the total drag equals the highest driving force, hence the car cannot accelerate any further.

Resistive media

Air resistance is just one example of the resistive or viscous forces which objects experience when they move through a fluid i.e a liquid or a gas. If you have ever run down the beach and into the sea, or tried to wade quickly through the water of a swimming pool, you experience the viscous drag. Gases have very low viscosities compared to liquids.

3.3 Free fall in vacuum

An object falling in a vacuum does not experience air resistance and upthrust force opposing its motion.

The body accelerates downwards due to its weight i.e. acceleration due to gravity. The only force acting on the body is its weight. (see Fig. 3.10).

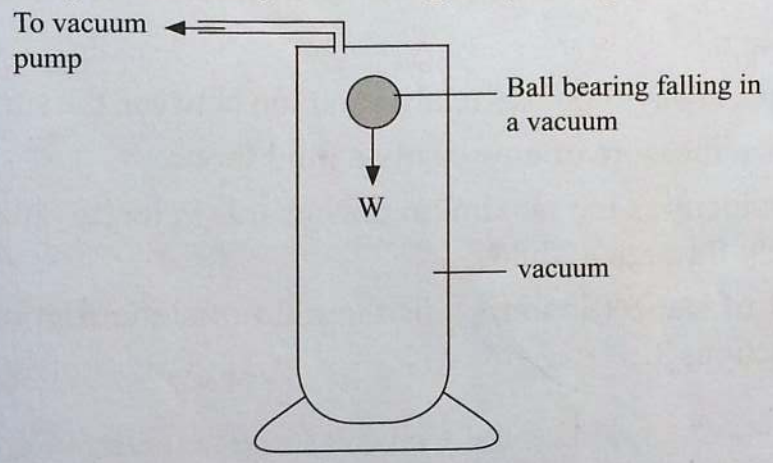


Fig. 3.10: A body falling in a vacuum

Since weight is the only force acting on the ball bearing (Fig. 3.10), the acceleration of the ball bearing is equal to the acceleration due to gravity i.e. a = g

The velocity – time graph of the motion of the ball bearing is a straight line as shown in Fig 3.11. We assume the motion starts at rest.

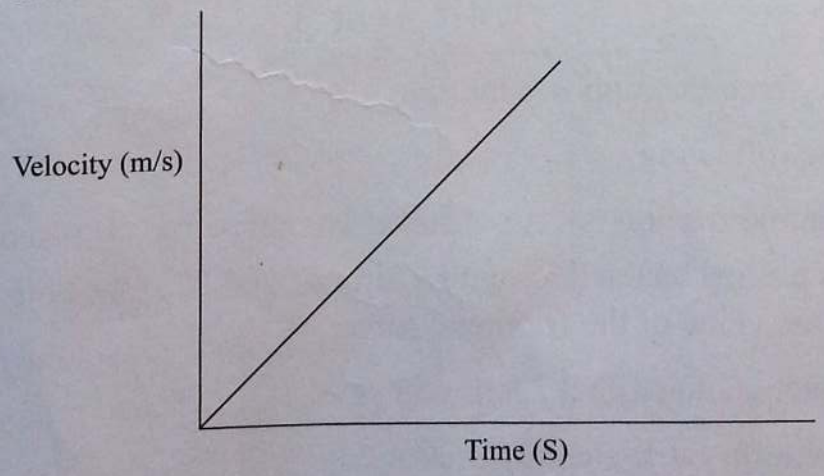


Fig. 3.11: Velocity – time graph of a motion of a body ball falling in a vacuum

Applications of friction force

(i) The brakes in a car use pads made of material that offer alot of friction.
(ii) The friction between the soles of our shoes and tyres of cars provide a grip on the ground.
(iii) The conveyor belts in factories do not slip because of friction between them.
(iv) Nails are able to hold the pieces of wood.
(v) Writing on paper, chalkboard etc utilises friction.

Disadvantages of friction

As parts rub against each other in machines, they tear and wear.
To reduce this we use lubricants such oil and ball bearings between the parts in machines.

Unit Summary

- Friction force always opposes relative motion between the surfaces in contact.
- Viscosity is a measure of how easily a fluid flows.
- Terminal velocity is the maximum downwards velocity attained by a body falling freely through a fluid.
- Coefficient of static friction, μ_s is the ratio of static frictional force to the normal reaction, R.

$$\mu_s = \frac{F_s}{R}.$$

- Coefficient of kinetic friction (μ_K) is the ratio of dynamic frictional force to the normal reaction.

$$\mu_K = \frac{F_K}{R}.$$

Unit Test 3

1. Name the force that opposes motion.
2. Define the following:
   (a) dynamic friction (b) static friction (c) viscous drag
3. A body is pushed on the floor with a force of 200 N. If the body did not move, estimate the value of the frictional force.
4. Explain factors that affect friction in solids.
5. Define the term coefficient of friction.

6. A force of 2 500 N limits the motion of a motorcycle of mass 500 kg on a horizontal flat road. Calculate the coefficient of friction of the surfaces in contact.

7. The Fig. 3.12 shows a 3 kg block attached to a 2 kg mass by a light inextensible string passing over a pulley. The frictional force between the horizontal bench and the block is 5.0 N. When the 2 kg mass is released from rest, both the masses move through a distance of 0.54 m and stop.

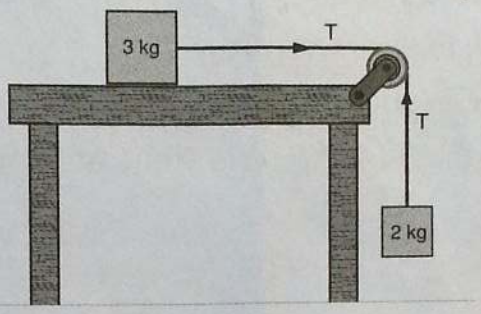


Fig. 3.12:

Friction in solid

(a) Calculate:

(i) the net acceleration of the system.

(ii) the velocity of the string at the end of the motion.

(iii) the work done against friction.

(iv) the kinetic energy of the 2 kg block when it has moved through a distance of 0.54 m.

(b) State the energy changes which occur from the time when both the masses were at rest till the 2 kg mass hits the ground.

8. Fig. 3.13 is a block of wood of mass 35 kg being dragged by a force F on a rough horizontal surface of coeffiecient of friction is 0.2.

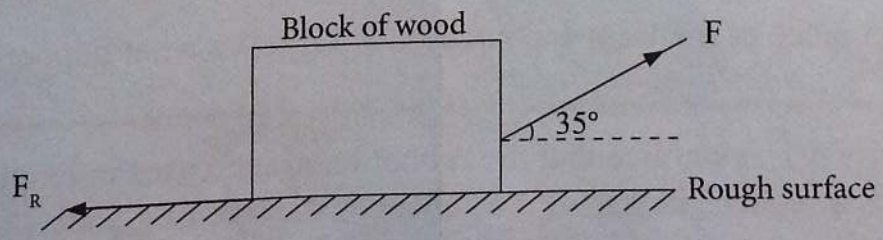


Fig. 3.13: A block being dragged on a horizontal surface

(a) Determine the value of F.

(b) How can one reduce friction between surfaces?

UNIT

4 Hooke's Law

Success Criteria

By the end of this unit, you must be able to:

- Explain the effects of a force.
- Verify Hooke's Law experimentally.
- Apply Hooke's Law in solving related problems.
- Explain the significance of the term limit of proportionality for an elastic solid.

Introduction

In Form one, we defined force as a pull or a push. We also learnt the effects of force on objects such as force causes change in motion, change in shape, size and direction.

In this unit, we will study the stretching and compressing effects of forces. The knowledge of stretching of materials when forces are applied is important particularly in the construction industry. It helps the engineers to determine the strength of the materials to be used for any specific work.

4.1 Effects of force

We already know that force applied can cause change in shape and size of a body. The following activity will help us demonstrate effects of forces on objects.

Activity 4.1: To demonstrate effects of forces on bodies

1. Take a rubber band and pull its two ends and see what happens.
2. Take a piece of mattress and squeeze it. Observe what happens.

From Activity 4.1, we notice that the rubber band increases in length and the piece of the mattress reduces in size. Force changes the size of a body.

We conclude that force can cause change in size and shape of an object.

When elastic materials are compressed by a force, their sizes reduce and when acted upon by tensional forces, their size increases (they stretch). When the force is withdrawn, an elastic material regains its original shape and size.

4.2 Stretching of materials

Robert Hooke did a lot of research work on stretching of materials. He performed different experiments involving:

1. stretching of spiral springs,
2. stretching of wires, and
3. loading horizontal beams fixed at one end.

From these experiments, he discovered the relationship between the *applied force* and *the extension* of the material used. This relationship is referred to as *Hooke's law*.

Experiment 4.1: To investigate the relationship between the extension produced in a spring and the force applied

Apparatus

- A metre rule
- A stand with clamp
- A spiral spring
- Seven, 50 g masses

Procedure

1. Set up the apparatus as shown in Fig. 4.1. Note the initial position (x) of the pointer before the weight is loaded.

   The initial pointer reading x = _____ cm

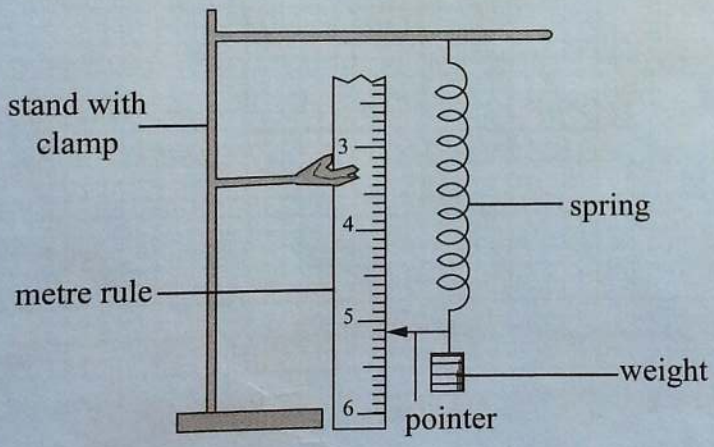


Fig. 4.1: Stretching a spring.

2. Load the spring with a 50 g mass and record the new pointer reading. Unload the spring and observe what happens to the pointer.
3. Repeat Step 2 with 100 g, 150 g, 200 g, 250 g, 300 g, 350 g masses and record the readings in a table (Table 4.1).

Mass (g)	Force (N)	Final reading y (cm)	Extension, e = y – x (cm)
50			
100			
150			
200			
250			
300			
350			

Table 4.1

5. Draw a graph of applied force against extension produced.

Discussion

Fig. 4.2 is the graph of Force (N) against extension (cm) obtained in the experiment.

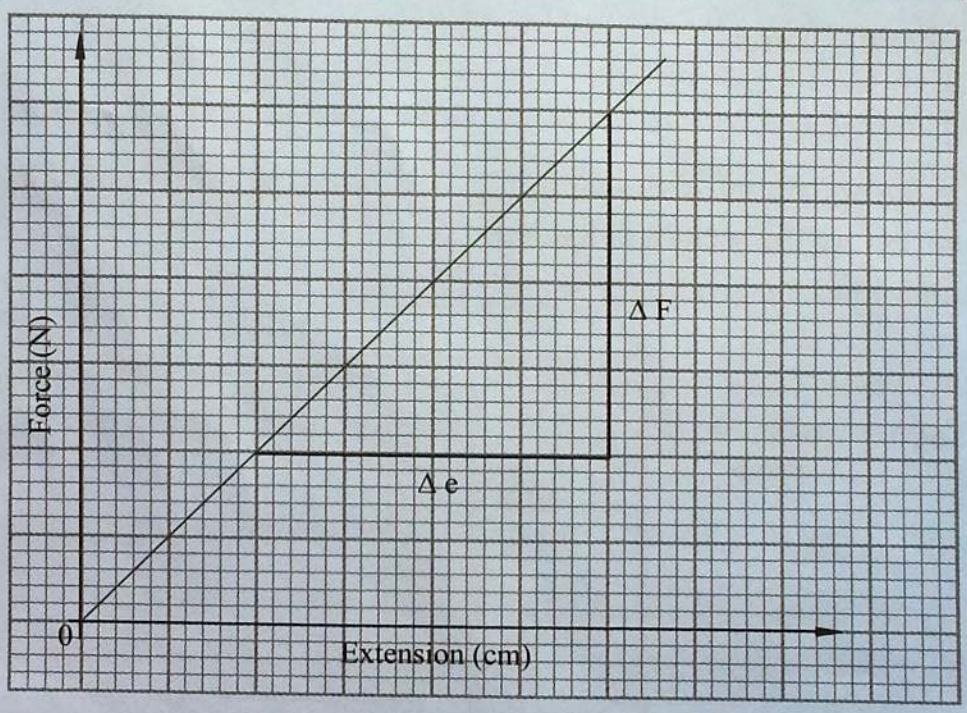


Fig. 4.2: Force-extension graph for a spring.

The graph of force against extension gives a straight line graph passing through the origin. $\frac{\Delta F}{\Delta e}$ = gradient of a graph of force against extension.

$\therefore$ The spring constant, (k) = $\frac{\Delta F}{\Delta e}$ gradient of a graph of force against extension.

Conclusion

It can be seen from the graph that *the extension produced is directly proportional to the force applied*. Each time the spring is unloaded the pointer returns to its original position.

Materials that are able to recover their original shape and size after unloading are said to be *elastic*.

If more weights are added to the spring in Experiment 4.1, a point is reached where the extension is no longer proportional to the applied force. This point is called *the elastic limit* (Point E in Fig. 4.3).

The pointer does not return to the original position when the load is removed once the elastic limit is exceeded. The spring is said to have been *permanently deformed* i.e. it acquires a permanent extension.

Fig. 4.3 shows a graph of force against extension after the spring has been permanently deformed.

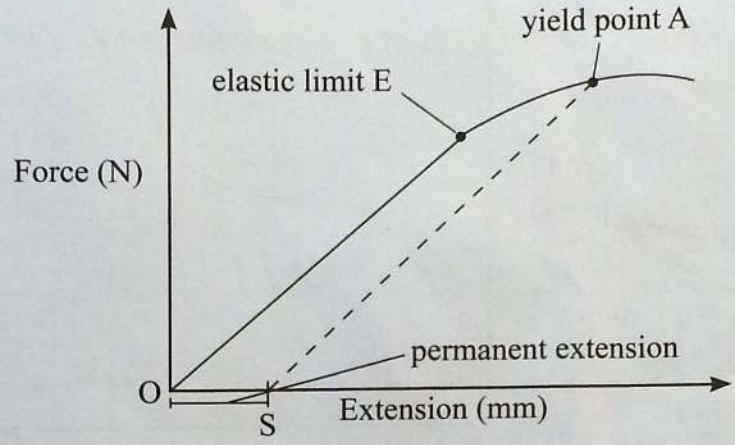


Fig. 4.3: Force-extension graph showing permanent deformation

The spring is said to undergo *elastic deformation* along OE. When a material is undergoing elastic deformation it is said to be obeying Hooke's law.

The spring is said to undergo *plastic deformation* along EA. Hooke's law is no longer obeyed beyond point E. If the weights are further added, a point is reached beyond which the material loses its elasticity. This is called the *yield point* (Point A in Fig. 4.3).

Hooke's law states that provided the elastic limit is not exceeded, the extension of a spring is directly proportional to the load applied on the spring.

Mathematically, the applied force, F, is directly proportional to the extension, e, i.e. $F \alpha e$.

Therefore:

$$F = ke$$

where k is a constant of proportionality called *the spring constant*. Hence

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

The SI unit of the spring constant, k, is the *newton-metre* N/m.

If Experiment 4.1 is repeated with a spring of different number of turns the spring constant changes. Springs of different materials or dimensions have different spring constants. When experiment is repeated by compressing the elastic material, similar results are attained where the compression force is directly proportional to the compression.

The spring constant is a measure of *the stiffness* of the spring; the stiffer the spring is the larger the value of its *spring constant*.

If Experiment 4.1 is repeated with a *rubber band*, by increasing the load (forces), a graph shown in Fig. 4.4 is obtained. The graph is not a straight line showing that rubber does not obey Hooke's law.

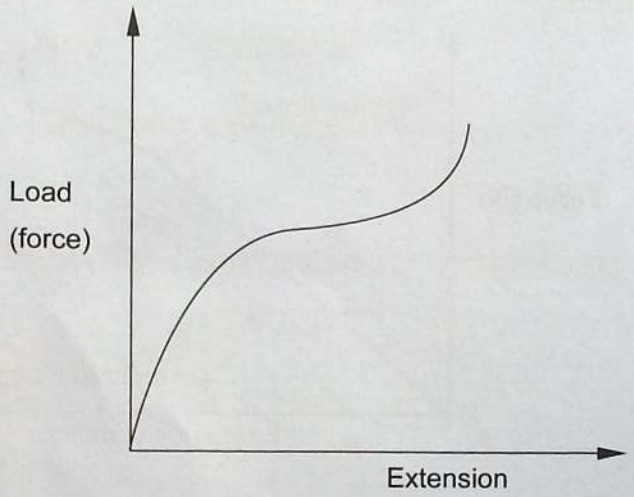


Fig 4.4: A load aganinst extension of rubber band

Example 4.1

A sack containing drugs and narcotic substances intercepted by the police, was weighed on the spring balance and the spring balance stretched by 3 cm. The owner was arrested and finally jailed after a court case. If the sack had a mass 200 g, calculate the spring constant of the spring balance.

Solution

$$F = ke \Rightarrow k = \frac{F}{e} = \frac{mg}{e}$$

$$= \frac{(200 \div 1\,000) \times 10}{(3 \div 100)} = 66.67 \text{ N/m}$$

Avoid drugs and narcotic substances. They are addictive and harmful to your health. Besides, taking them is a criminal offence punishable by the law.

Example 4.2

A spring has a spring constant of 200 N/m. If it is compressed by 0.06 m. Calculate the compressing force.

Solution

$k = 200N/m$, $e = 0.06m$

$F = ke = 200\ N/m \times 0.06\ m$

$= 12\ N$

Example 4.3

Fig. 4.5 is a graph of force against extension drawn from an experiment to verify Hooke's law.

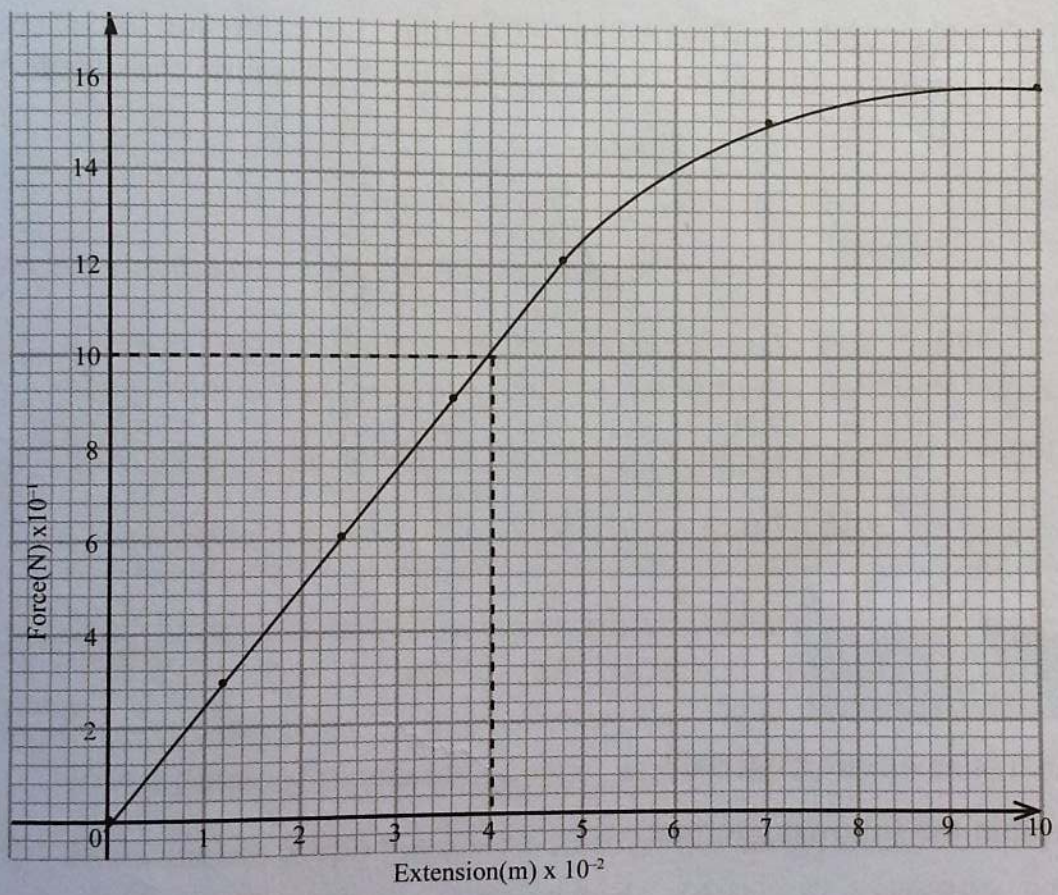


Fig. 4.5: A graph of force against extension

(a) Use the graph to determine the spring constant.

From Hooke's law, $k = \frac{F}{e}$. Thus, in a graph of F against e,

Spring constant = Gradient of the graph

$$= \frac{(10-0) \times 10^{-1}N}{(4-0) \times 10^{-2}m} = 25\ N/m$$

(b) Use the graph to find the length of the spring when a mass of 0.05 kg is hung from it.

Extension for 0.05 kg = 2mm

Length of spring = 80 mm + (0.02 × 1 000)

= 100 mm

(c) State with a reason whether or not Hooke's Law is obeyed.

Hooke's Law is obeyed up to the 12 N force because the graph is a straight line from the origin. It is not obeyed beyong 12 N.

Example 4.4

A force of 12 N extends a spring by 8 mm. Calculate the extension that is produced by the same spring if a force of 25N is hanged on it. (Assume the elastic limit is not exceeded.)

Solution

$$k = \frac{F}{e} = \frac{12N}{8\ mm}$$

$$= 1.5\ N/mm$$

$$\text{Extension, } e = \frac{F}{k} = \frac{25N}{1.5\ N/mm}$$

$$= 16.67\ mm$$

Exercise 4.1

1. What is an elastic material?
2. Explain the following terms:

   (a) Stiffness **(b)** Extension **(c)** Springs constant
3. State Hooke's Law.
4. A force of 20N is used to compress a spring through 0.25 cm. Calculate the spring's constant in SI unit.
5. A spring of a force constant of 100 N/m stretches through 0.5 m. Calculate the force causing the stretch.

6. Fig. 4.6 shows a spring balance. Its spring constant is 50 N/m. The scale extends over a distance of 10 cm.

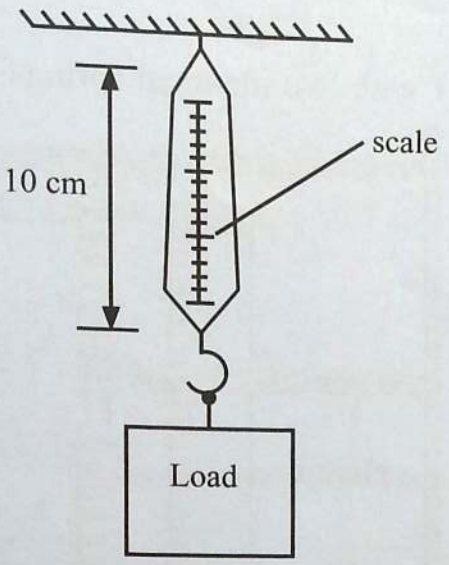


Fig. 4.6 Measuring weight using a spring balance

What is the maximum weight that it can measure

7. (a) Draw a labelled diagram of the apparatus to be used to investigate how the extension of a spiral spring varies with the stretching force.

(b) In such an experiment, the following reading were taken (Table 4.2).

Table 4.2

Force (N)	1	2	3	4	5	6	6.5
Extension, *e* (mm)	20	40	60	80	104	122	174

(i) Plot a graph of extension (y-axis) against the force (x-axis).

(ii) Mark on the graph the elastic limit of the spring used.

(iii) Use the graph to determine the force required to produce an extension of 48 mm.

(iv) A similar spring is used to make spring balance. What is the maximum weight that could be measured with this balance?

4.3 Combination of springs in series and parallel

Experiment 4.2: To determine the spring constant of two springs arranged in series

- Repeat Experiment 4.1 with two identical springs in series (Fig. 4.7).

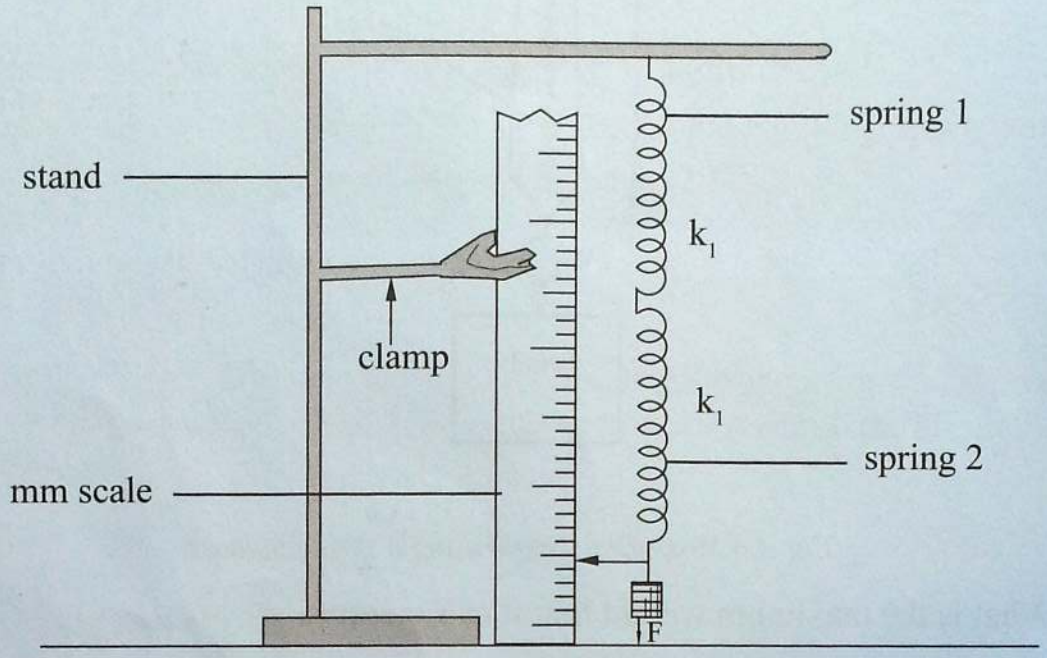


Fig. 4.7: Springs in series

- From the results,` draw a graph of the force applied against the extension and use your graphs to determine the spring constant for the two springs in series.

Discussion

You should have observed that while a single spring produces an extension, e, two identical springs arranged in series produce an extension of $2e$ for the same force.

Applying Hooke's law,

$F = k_1 e$ .....for the single spring

$F = k_s \times 2e$ .....for the two springs in series

where F is the applied force, k_1 is the spring constant for the single spring, and k_s is the spring constant for the two springs connected in series.

Since the same force is used,

$$k_s \times 2e = k_1 \times e$$

$$\therefore \quad k_s = \frac{k_1 e}{2e} = \frac{1}{2} k_1$$

This experiment shows that the spring constant for two identical springs in series is equal to half of the spring constant of one spring.

In general the spring constant, k_s, for n identical springs in series is given by the expression

$$k_s = \frac{k_1}{n}$$

Where k_1 is the spring constant for one spring and $n = 1, 2, 3, 4, \ldots$ n is the number of springs. This arrangement produces a less stiff spring system than one spring.

Activity 4.2: To determine the spring constant for two springs in parallel

- Repeat Experiment 4.1 with the two springs connected in parallel as shown in Fig. 4.8.

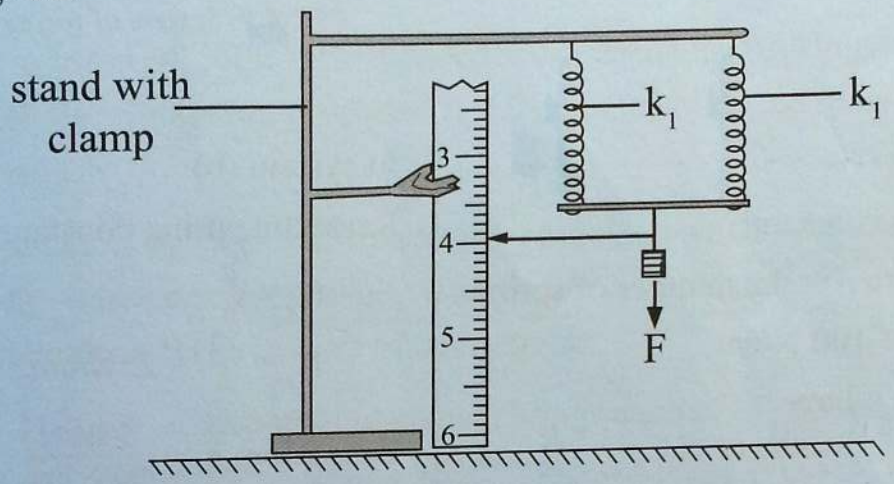


Fig. 4.8: Two identical springs in parallel.

You should observe that while a single spring produces an extension, e, two identical springs produce an extension $\frac{1}{2}e$, for the same force.

Applying Hooke's law,

$F = k_1 e$ .....for a single spring

$F = k_p \times (\frac{1}{2} e)$ .....for the parallel springs

$$\therefore \quad k_1 e = \frac{1}{2} k_p e$$

$$k_p = 2k_1$$

In general, $k_p = nk_1$ where $n = (1, 2, 3, \ldots n)$ is the number of springs and k_p is the spring constant for n springs in parallel. This arrangement produces a *stronger* or stiffer spring system than a single spring.

Example 4.5

Fig. 4.9 shows two system of identical springs. If each spring has a spring constant of 50 N/cm. Calculate the total extension produced by the load attached in each system. (Assume the springs are weightless).

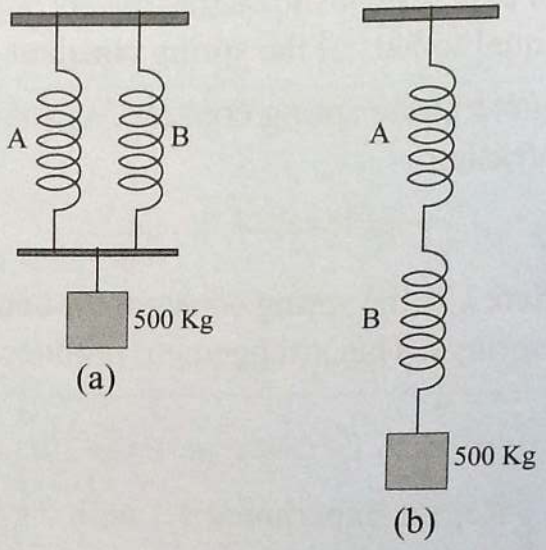


Fig. 4.9: System of springs

Solution

In system (a)

Total springs constant,

$K_p = nk$ where n is the number of springs

$K_p = 2 \times 50 = 100$ N/cm

From Hooke's Law,

$F = Ke$

$e = \frac{F}{K}$, but $F = W = 500 \times 10 = 5\,000$ N

$= \frac{5000N}{100N/cm} = \frac{50}{1} = 50$ cm

In system (b)

Resultant spring constant,

$K_s = \frac{k}{n}$

$K_s = \frac{50}{2} = 25N/cm$

Extension, $e, = \frac{5000\ N}{25\ N/cm}$

$= 200$ cm

Example 4.6

Fig. 4.10 shows three identical springs with a spring constant of 5 N/cm each. A weight of 30 N is hung on the lower springs set up. Find the total extension of the set up.

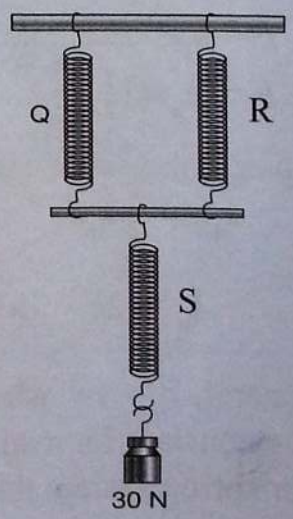


Fig. 4.10

For spring S

$F_S = 30$ N, $k = 5$ N/cm, $e_1 = ?$

$F_S = ke_1$

$30 = 5e_1$

$e_S = 6$ cm

Spring Q and R share the load

$F_q = \frac{30}{2} = 15$ N, $k = 5$ N/cm, $e_q = ?$

$F_q = ke_q$

$15 = 5e_q$

$e_q = 3$ cm

Total extension $= e_s + e_r = 6 + 3 = 9$ cm

Exercise 4.2

1. When a mass of 100g is suspended from two spiral springs connected in parallel, the elongation produced is 2.0 cm. Calculate the spring constant of the spring.

2. Four identical springs were arranged parallel to each other and a mass of 1000 kg was hanged on them. If each has a spring constant of 100 N/m. Calculate the total extension of the system.

3. Fig. 4.11 shows a system of identical springs each of of constant of 20 N/cm.

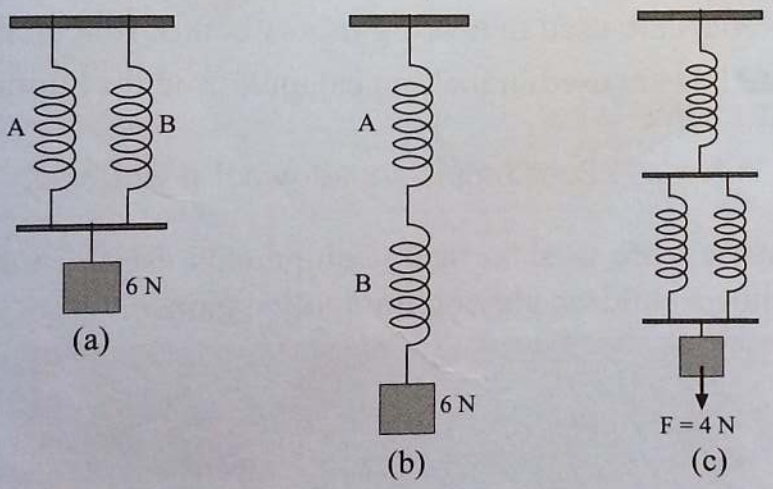


Fig. 4.11: Spring in series and parallel arrangement

Calculate the extension in spring 1 and 2 in set up *(a)* and *(b)* respectively

4. A spiral spring produces an extension of 6 cm when a force of 4 N is applied to it. Calculate the spring constant in newtons per metre for a system when three such identical springs are arranged in: (a) series (b) parallel.

4.4 Application of Hooke's law

Calibration of spring balance

Hookes's law is applied in the making of spring balances which are used to measure weights of various substances. (Fig. 4.12).

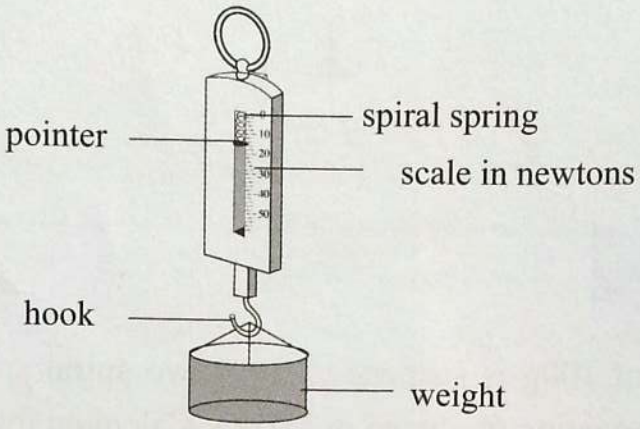


Fig. 4.12: A spring balance

Other applications of Hooke's law include:

- Elasticity in materials e.g springs is applied in making spring beds, diving boards etc.
- Stretching and compressing of spiral springs helps in designing spring shock absorbers or shock breakers used in car suspensions.
- Elastic materials are used in making rubber bands, rubber shoes etc.
- Elastic materials are used in making catapult used for hunting birds.

> ⚠ **Warning!** Poaching is not allowed! it is illegal.

- Elastic materials are used to make equipments used in trampoline games. Fig. 4.13 shows children playing trampoline games.

Fig. 4.13: Children playing on a trampoline

Unit summary

- Some materials stretch when subjected to a force and regain their original state after the force is removed. Materials that behave in this manner are called elastic materials.
- The extension (e) produced in elastic materials is directly proportional to the force applied (F) within the elastic limit. This is called Hooke's law; mathematically expressed as $F = ke$, where k is the spring constant.
- The spring constant of an elastic material is force per unit extension.
- Elastic limit is a point beyond which a material loses its elasticity.
- When springs are connected in series the value of the spring constant is reduced while when in parallel the value of the spring constant is increased .
- Hooke's law is applied in the making of spring beds, diving boards, car suspension etc.
- The resultant spring constant K_s and K_p for n identical springs in series and parallel respectively are given by $K_s = \frac{k_1}{n_1} =$ and $K_p = nk_1$ where K_1 is the spring constant for one spring .

Unit Test 4

1. Define the following terms:
   (a) elastic material (b) elastic deformation
   (c) plastic deformation (d) spring constant
2. State Hooke's law.
3. Describe an experiment to verify Hooke's law.
4. Show graphically the relationship between the extension of a spiral spring and the force applied to it. Label the axes of the graph and point out the main features shown by the curve.
5. A spring of spring constant 0.073 N/mm produces an extension of 3 mm when a certain force is applied to it. Find the magnitude of the force applied.
6. A spiral spring produces an extension of 6 mm when a force 0.3 N is applied to it. Calculate the spring constant for a system when two such springs are arranged in: (a) series (b) parallel
7. The following readings (Table 4.3) were obtained when masses were hung on a certain spring.

UNIT

5 Uniform Circular Motion

Success criteria

By the end of this unit, you must be able to:

- Differentiate angular displacement and angular velocity.
- Describe simple experimentation to illustrate centripetal force.
- Apply principles of uniform 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 horizontal 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. The physics behind these observations will be understood after going through this unit, where we shall consider the motion of particles describing a circular path.

5.1 Illustrating circular motion

The following activities illustrate some cases of circular motion.

Activities 5.1: Motion of mud on a rotating bicycle wheel

Apparatus

- A bicycle with dry mud stuck on the tyres.

Procedure

- Place a bicycle, which has been ridden on a muddy road, on its stand and rotate the pedals.
- Rotate the pedals faster and watch the motion of the rear wheel and the mud stuck to the tyre. What happens to the mud as the wheel starts rotating faster? Why?

From Activity, we observe that initially the mud stuck to the tyre moves in a circular motion along with the wheel. This is because of the force of adhesion between the mud and the tyre. As the speed of the wheel increases, the adhesive force of mud *'gives up'* and the mud breaks off and flies away along the tangent of the rim of the tyre.

Activities 5.2: Motion of drops of water on a rotating umbrella

Apparatus

- A wet umbrella

Procedure

Take an umbrella that is wet with water. With the umbrella open and its handle horizontal, rotate the handle in a circular manner, as shown in Fig. 5.1.

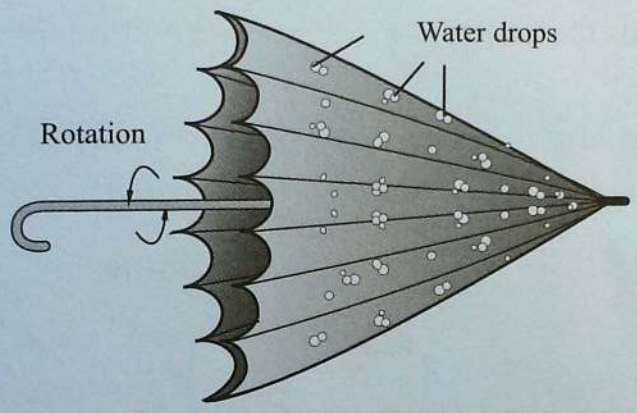


Fig. 5.1: An umbrella rotated in a circular motion

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 5.3: Motion of a rotating mass attached to a spring balance

Procedure

- 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 a 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. 5.2.

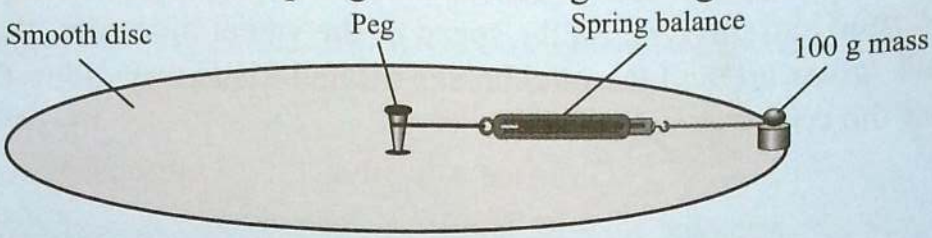


Fig. 5.2: A disc in a circular motion

- Rotate the disc and observe what happens to the reading of the spring balance. What happens to the mass? Why?

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 5.4: Motion of a rotating ball attached to a string

Apparatus

- A small ball
- A string

Procedure

- 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. 5.3 (a)).

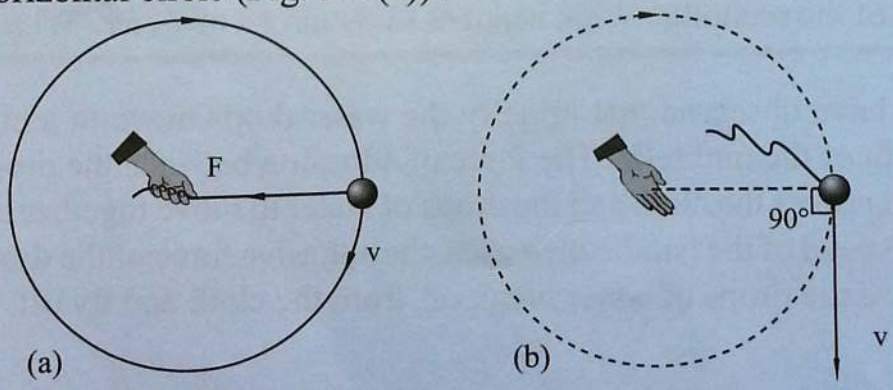


Fig. 5.3 Rotating ball attached to string

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

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

We 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, at the point of release (Fig. 5.3(b)).

All the activities discussed 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*.

5.2 Angular displacement and angular velocity

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. 5.4), the line OA (radius r) joining the particle to the centre of the circle sweeps through an angle θ.

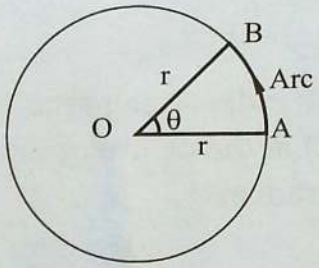


Fig. 5.4: Angular displacement

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

In Fig.5.5(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. 5.5(b)).

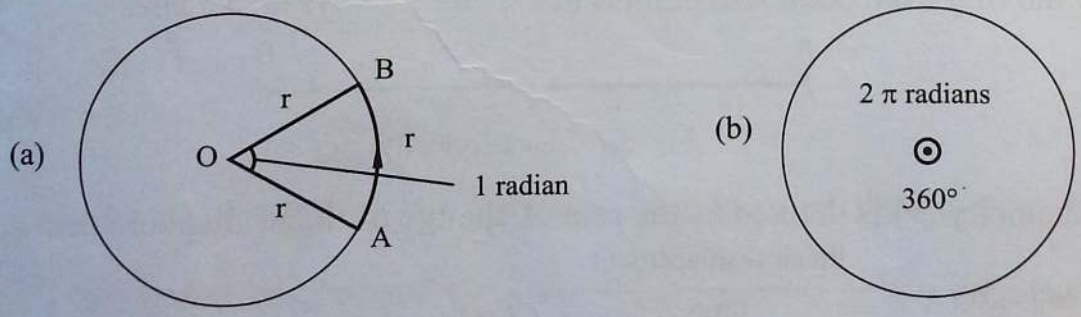


Fig. 5.5: The radian measure

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,

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

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. 5.6), the length s of the arc AB of the circle is given by

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

Arc length $s = r\theta$

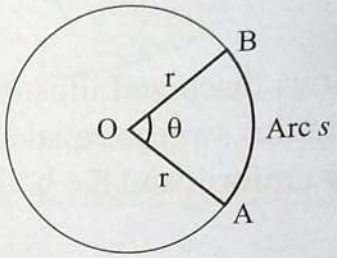


Fig. 5.6: Arc length s

Example 5.1

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

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

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

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

Angular velocity

A body moving from point A to point B in a *straight line* (Fig. 5.7) has *linear velocity*.

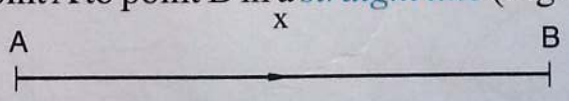


Fig. 5.7: Linear velocity

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. 5.8). The angular displacement of the radius OA is in the same time t. Such a body is said to have has angular velocity (ω).

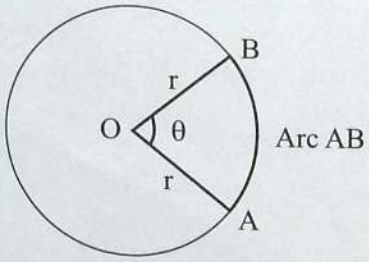


Fig. 5.8 Angular velocity

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

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

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

Relationship between angular velocity and frequency

For one complete circular motion, $\square = 360 = 2\pi$ 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 $\omega = 2\pi f$.

Angular velocity= $2\pi \times$frequency *(f)* or $\omega = 2\pi f$

Relationship between the angular velocity and the linear velocity

We have seen that when a body is whirled around 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.

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 $\frac{r\square}{t}$ is its angular velocity, . Therefore,

Linear speed, v = radius(r) × angular velocity (ω)

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

Example 5.2

Fig. 5.9 shows the motion of the second hand of a clock. Calculate its angular velocity.

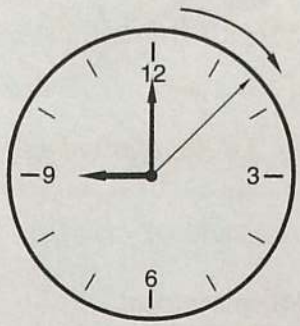


Fig. 5.9 Motion of the second hand of a clock

Solution

Angular velocity $\omega = \frac{\square}{t}$

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 5.3

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 $= 2\pi$ rad

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

$= 10\pi$ rad

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

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

Example 5.4

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,

$$\omega = \frac{\square}{t} = \frac{2\pi}{(24 \times 60 \times 60)}$$

$$= \frac{2\pi}{86\,400}$$

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

Example 5.5

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

Example 5.6

The wheel of a car of radius 20 cm is rotating at a frequency of 20 Hz. Calculate the linear speed of the car.

Solution

Angular velocity of the wheel

$$\omega = \frac{\theta}{t} = \frac{2\pi}{T} = 2\pi f.$$

Therefore $\omega = 2 \times \pi \times 20 = 40\,\pi$ rad/s

Linear speed v = radius (r) × angular velocity (ω), hence

$$= 0.20 \times 40\pi$$

$$= 25.14 \text{ m/s}$$

The speed of the car = 25.14 m/s

Exercise 5.1

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 a frequency of 2 Hz in a circle of radius 2 m. Calculate its (a) angular speed. (b) linear velocity.

5.3 Circular motion and centripetal force

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.

Experiment 5.5: To investigate the relationship between the force (F) and the speed of revolution (v) of a body undergoing circular motion

Apparatus

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

Procedure

- Obtain a glass or plastic tube of length 15 cm and diameter about 1 cm, (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.
- 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. 5.10).

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.

- 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. 5.10)

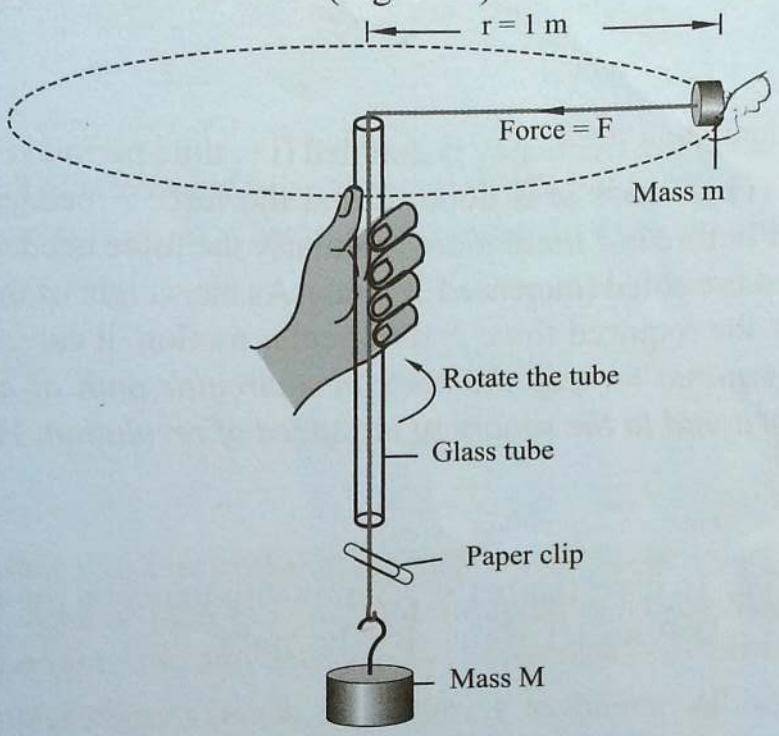


Fig. 5.10: A mass moving in a horizontal circle

- 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, $v = 2\pi r/T$.
- 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 revolution and the speed, v of mass m. Record your observations in a table (Table 5.1.)

Table 5.1

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)

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

Discussion

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.

Conclusion

It is seen 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 trebled (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

$$F \alpha v^2$$

Experiment 5.6: To investigate the relationship between the force (F) and the radius (r) of the circular path

Apparatus

- 1.5 m long string
- A glass tube
- A mass

Procedure

- Keeping the mass m constant, and adding the slotted masses M in turn to the hanger, repeat the Experiment 5.1.
- By trial and error, make the frequency of revolution of the mass m the same for each added mass M.
- Measure the radius r of the circular path. Record your observations in a table (Table 5.2).

Table 5.2

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

- Determine the relationship between the values of mass M and radius r.

Discussion

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 is *inversely proportional to the radius r of the circular path, when the speed of revolution of the body is constant*. Hence

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

Experiment 5.7: To investigate the relationship between the force (F) and mass (m) of a body undergoing circular motion

Apparatus

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

Procedure

- Attach a known mass m to the string and repeat Experiment 5.1 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.
- 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 2 M.
- 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.
- 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 5.3).

Table 5.3

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)

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

Discussion

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 is directly proportional to the mass undergoing circular motion. Hence

$$F \alpha m$$

From Experiments 5.1, 5.2 and 5.3 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

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

Centripetal force

Centripetal force *is a force that constrains an object in motions to move in a circular motion.*

In Experiments 5.1, 5.2 and 5.3, an external force acts towards the centre of the circle and keeps the body of mass m at a fixed distance from the centre. This force is called *centripetal force*. Centripetal is a Greek word meaning 'seeking centre'. So this force is also called *the centre seeking force*.

The experiment showed that centripetal force $F \alpha v^2$, $F \alpha \frac{1}{r}$ and $F \alpha m$ 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 alonf the circular path in m/s

r is the radius of the circular path

Centripetal force in terms of angular velocity

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

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

$$F = \frac{m(rw)^2}{r} = \frac{m(rw)^2}{r} = mrw^2$$

$$F = mrw^2$$

What happens when the centripetal force fails?

In Activity 5.1 and 5.2 , the force of adhesion between the mud particles and the tyre or 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 5.4, 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. 5.3(b). For any circular motion, there should be a centripetal force towards the centre of the circle, provided by an external agent.

5.4 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. 5.11.

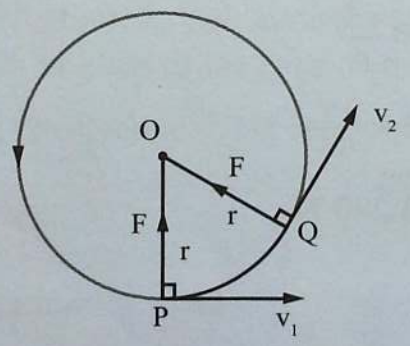


Fig. 5.11: Centripetal acceleration

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 only direction changes continously. 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.

Example 5.7

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 5.8

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 5.2

(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". Justify the statement.
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

5.5 Applications of uniform circular motion

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. 5.12).

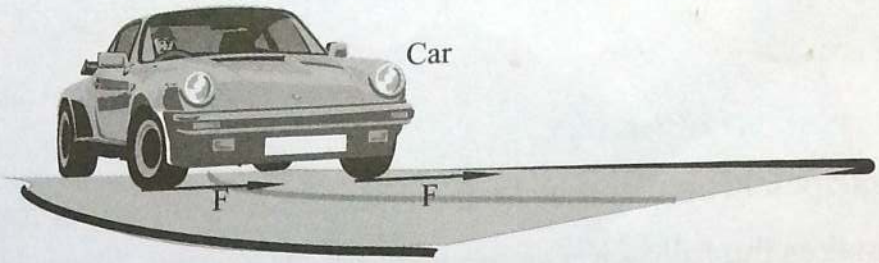


Fig. 5.12: A car going round a curve on a level road.

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.

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. 5.13 shows a part of the contact force R (the normal reaction force) acting towards the centre of the circle providing the required centripetal force.

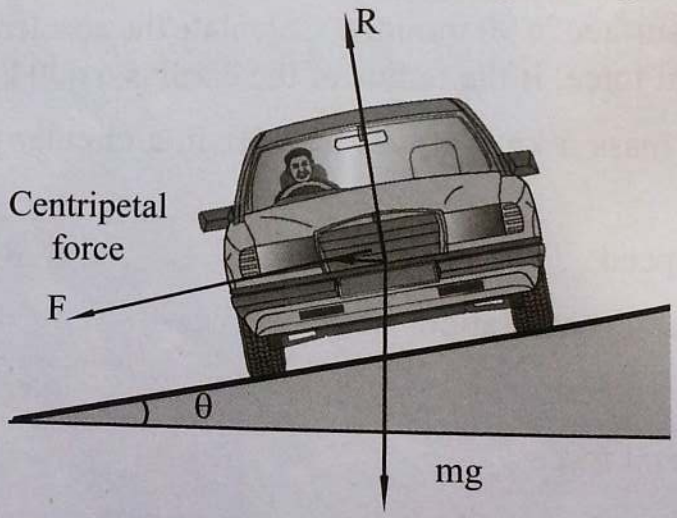


Fig. 5.13 Car on a banked road

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. 5.14.

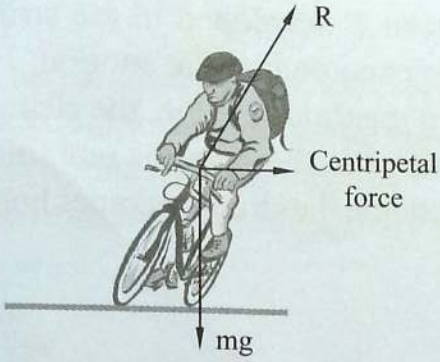


Fig. 5.14: A cyclist leans inwards when going round a curved track

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. 5.14, in order to successfully negotiate the curved path.

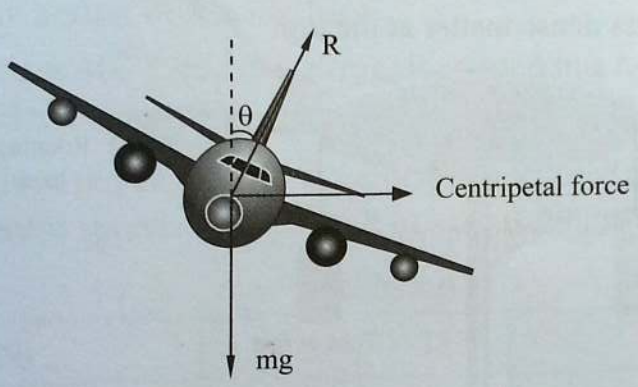


Fig. 5.14: An aircraft tilted inwards while taking a circular turn

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. 5.15.

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

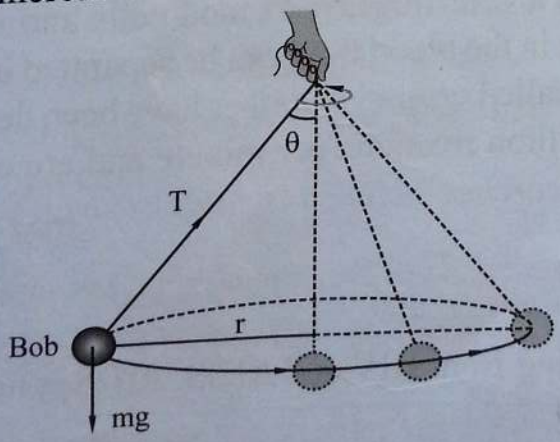


Fig. 5.15: A conical pendulum

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, $T = m\frac{v^2}{r}$.

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. 5.16. The matter of low density moves inwards towards the centre of rotation. On stopping the rotation, tube returns to the vertical position with less dense matter at the top.

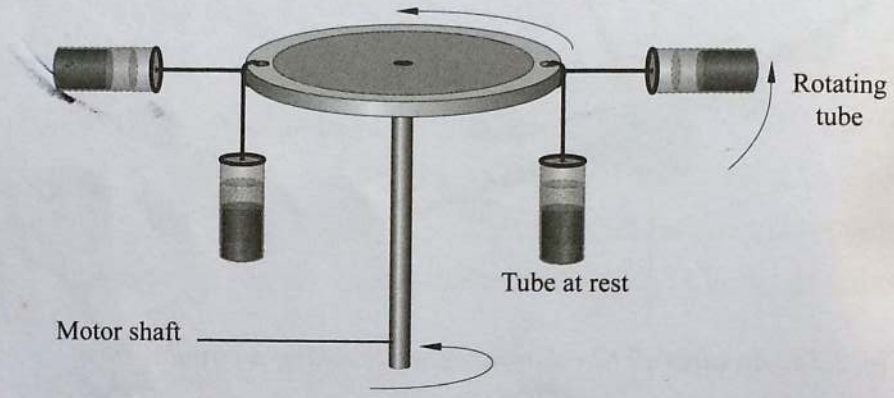


Fig. 5.16: Centrifuge

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!

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 5.3

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 5.6 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 5.6

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.

Unit 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 and keeps 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.

Unit Test 5

(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 5.3 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 5.3

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. 5.17.

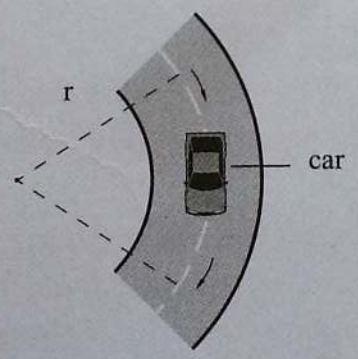


Fig. 5.17: A car moving at a bend

   (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 5.4 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 5.4

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.

UNIT 6

Moments of Forces

Success Criteria

By the end of this unit, you must be able to:

- Describe moment of a force.
- Apply principle of moments in everyday life.

Introduction

As we learnt in Form 1, one of the effects of a force is that it produces a turning effect on body. But how can we quantify the turning effect? What are some of the applications of this effect in our daily lives? In this unit, we will seek answers to these questions.

6.1 Moment of a force

A number of simple machines like levers, pliers, spanners and so on do work when a force produces a turning effect on some of their parts. It is important to know where the force should be applied for the machine to be more efficient in doing work.

The following experiment will help us to investigate the turning effect of a force.

Experiment 6.1: To investigate the turning effect of a force

Apparatus

- A metre rule
- A knife edge
- A mass

Procedure

- Balance a metre rule on a knife edge. Apply a force F_1 at a point A at a distance d_1 from the knife edge as shown in Fig. 6.1(a). Observe what happens to the rule.
- Repeat the experiment by applying another force F_2 on the other end B of the metre rule at a distance d_2 from the knife edge as shown in Fig. 6.1(b). Observe what happens to the metre rule.

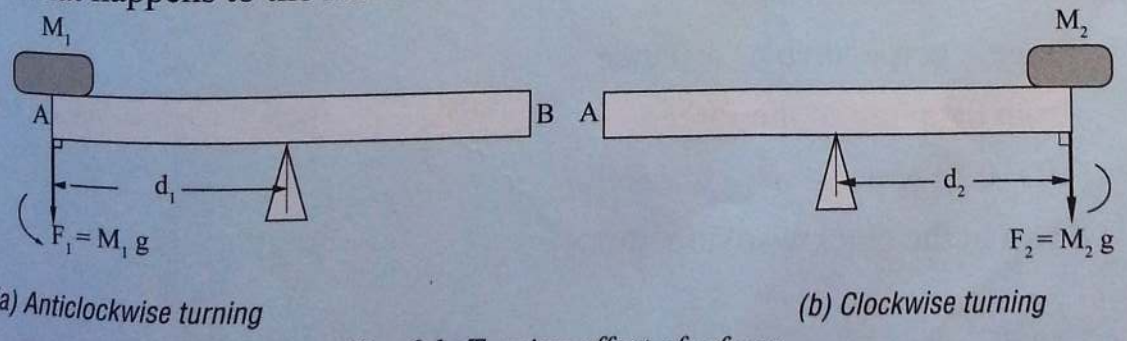


Fig. 6.1: Turning effect of a force.

Discussion

In both cases, the metre rule turns about the knife edge. When the force F_1 is applied at A, the metre rule turns in *anticlockwise direction* about the knife edge. When the force F_2 is applied at B, the metre rule turns in the *clockwise direction*. Both F_1 and F_2 produce a turning effect on the metre rule about the knife edge.

The turning effect of a force about a point is called the *moment of the force about that point*. This moment depends on the force applied and its distance from the point.

Conclussion

The moment of a force about a point *is the product of the force and the perpendicular distance from the point to the line of action of the force.*

The moment of a force about a point is either clockwise or anticlockwise about the point.

In Fig. 6.1(a), the anticlockwise moment about the knife edge is $F_1 \times d_1$. In Fig. 6.1(b), the clockwise moment about the knife edge is $F_2 \times d_2$.

Moment of a force about a point = Force × Perpendicular distance from the point to the line of action of the force

$= F \times d$

SI unit of moment of a force

Moment of a force = Force (N) × Perpendicular distance (m).

Therefore, the *SI unit* of moment is *newton metre (Nm)*.

Moment of a force is a *vector quantity* since it has both magnitude and direction.

Example 6.1

A student applies a force of 10 N to the handle of a door, which is 0.8 m from the hinges of the door (Fig. 6.2). Calculate the moment of the force.

Solution

Moment of a force about a point

= Force × perpendicular distance from the point to the force.

= (10 × 0.8) Nm

= 8 Nm in the clockwise direction.

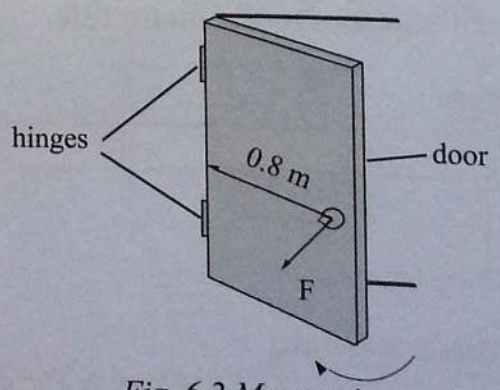


Fig. 6.2 Moment in opening the door

Example 6.2

Calculate the moment of the force about the fulcrum when a pet dog of mass 10 kg is at a distance of 1.2 m from the fulcrum of the seesaw as shown in Fig. 6.3.

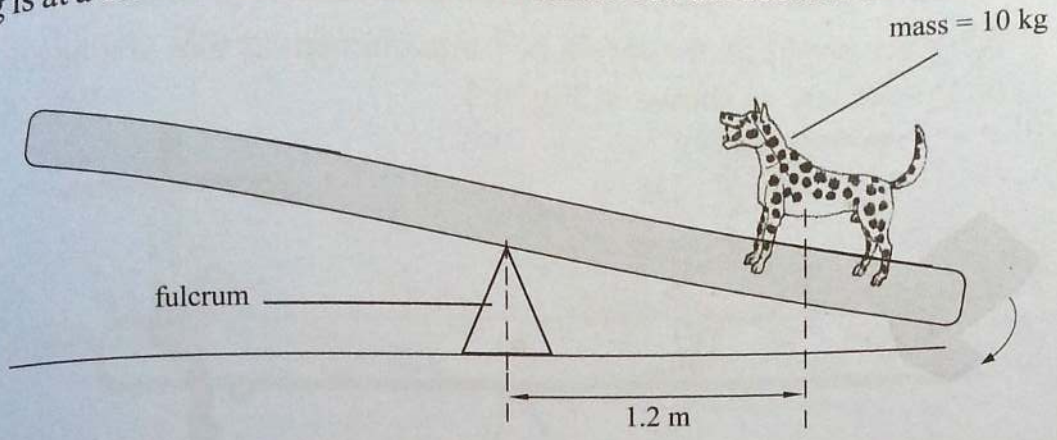


Fig. 6.3 Moment of force

Solution

$$F = \text{Weight of dog} = mg = 10\ \text{kg} \times 10\ \text{N/kg}$$
$$= 100\ \text{N}$$

Moment of the force about the fulcrum

= Force × perpendicular distance from the fulcrum

= 100 N × 1.2 m

= 120 Nm in the clockwise direction.

Exercise 6.1

1. Define 'moment of a force' and state its SI unit.
2. A force of 20 N is applied to open the gate of a fence as shown in Fig. 6.4. Calculate the moment of the force about the hinges if the force is applied at the edge of the gate.

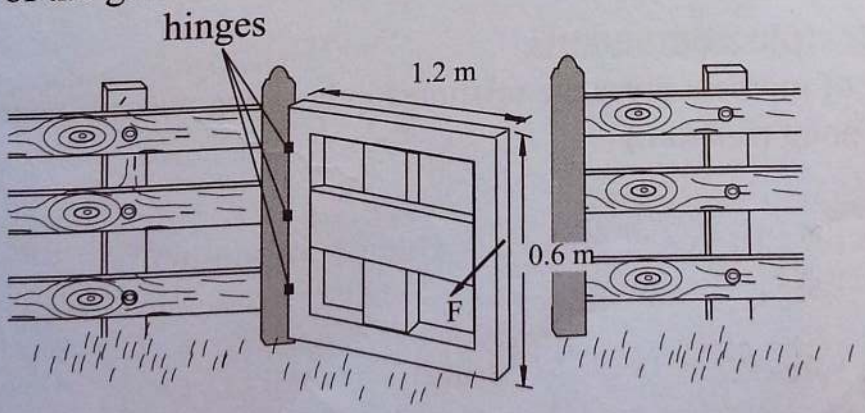


Fig. 6.4 Moment in opening the gate

3. Give the scientific reasons for the following:
   (a) The handle of a door is fixed far from the hinges.
   (b) A pair of garden shears has small blades and long handles.
   (c) A lighter boy is able to produce same moment as that of a heavier girl on the seesaw as shown in Fig. 6.5.

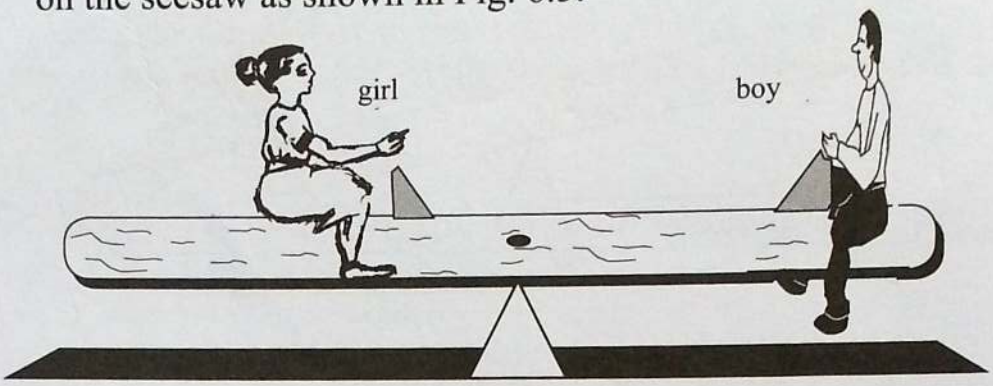


Fig. 6.5: Moment on a seesaw

4. A person applies a force of 500 N and produces a moment of force of 300 Nm about the wheels of a wheel cart (Fig. 6.6). Calculate the perpendicular distance, d, from the line of action of the force to the wheels.

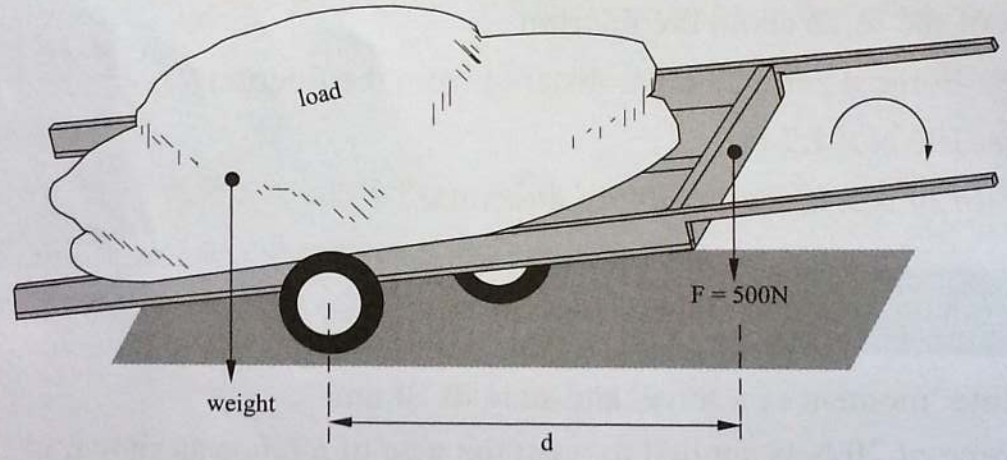


Fig. 6.6 Moments in a wheelcart

6.2 The principle of moments

The principle of moment gives the relationship between two moments that are at the same turning point (fulcrum).

Experiment 6.2: To investigate the principle of moments

Apparatus

- A metre rule
- Three 100 g mass
- string
- support e.g. clamp

Procedure

1. Suspend a uniform metre rule from a firm support e.g. clamp, at the 50 cm mark, i.e. at its mid point G as shown in Fig. 6.7 (a) using a string.
2. Suspend a 100 g mass at a point A as shown in Fig. 6.7 (b). Observe what happens.

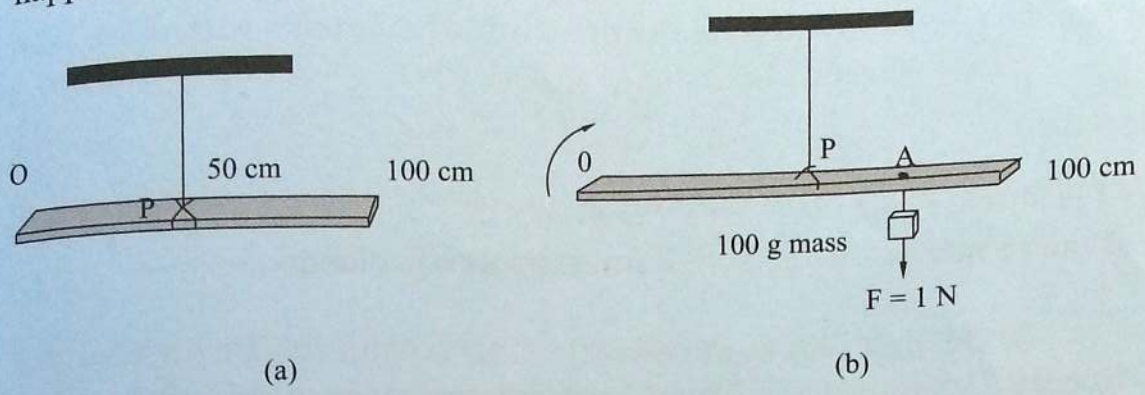


Fig. 6.7: Principle of moments.

Observation

The metre rule turns in the clockwise direction. There is a moment of force in the clockwise direction due to the force acting vertically downwards at point A.

Discussion

Moment of the force in the clockwise direction = Force × perpendicular distance = 1.0 × PA

3. Now suspend a 200 g mass at a point B near the 0 cm mark (Fig. 6.8 (a)). What has happened? The system turns in the anticlockwise direction. Now adjust the position of B till the system balances horizontally as shown in Fig. 6.8 (b).

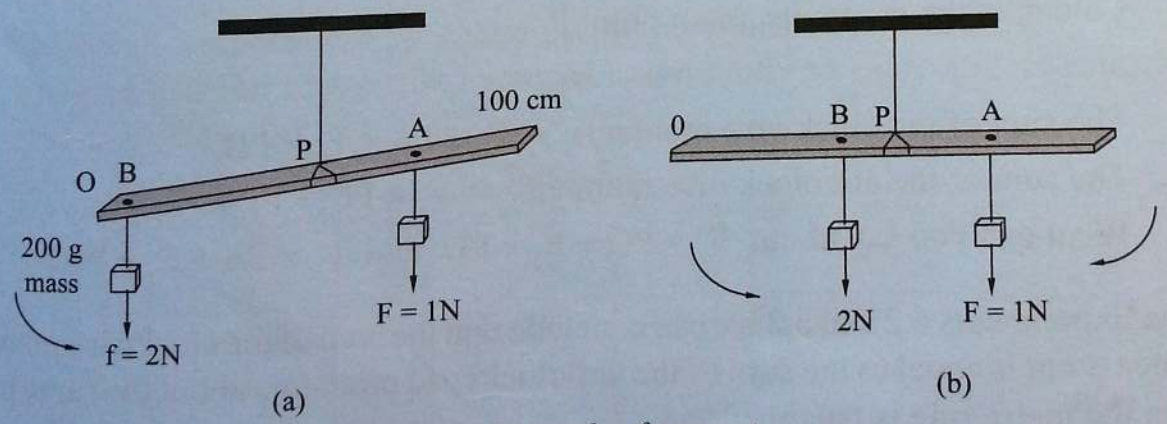


Fig. 6.8: Principle of moments.

Moment due to the 2 N force about P is 2.0 × PB in the anticlockwise direction.

Measure the distance PA and PB. Compare the values of $1.0 \times PA$ and $2.0 \times PB$. What can you say about these values?

We note that the two moments are equal in magnitude and opposite in direction. The clockwise moment of the 1 N force about point P is equal to the anticlockwise moment of the 2 N force about point P.

Experiment 6.3: To investigate the principle of moments with more than two forces

Apparatus

- Four mass
- A metre rule
- string
- Firm support e.g. clamp

Procedure

- Repeat Experiment 12.1 using 4 masses, two on each side of G as shown in Fig. 6.9. Move the masses until the rule balances horizontally.

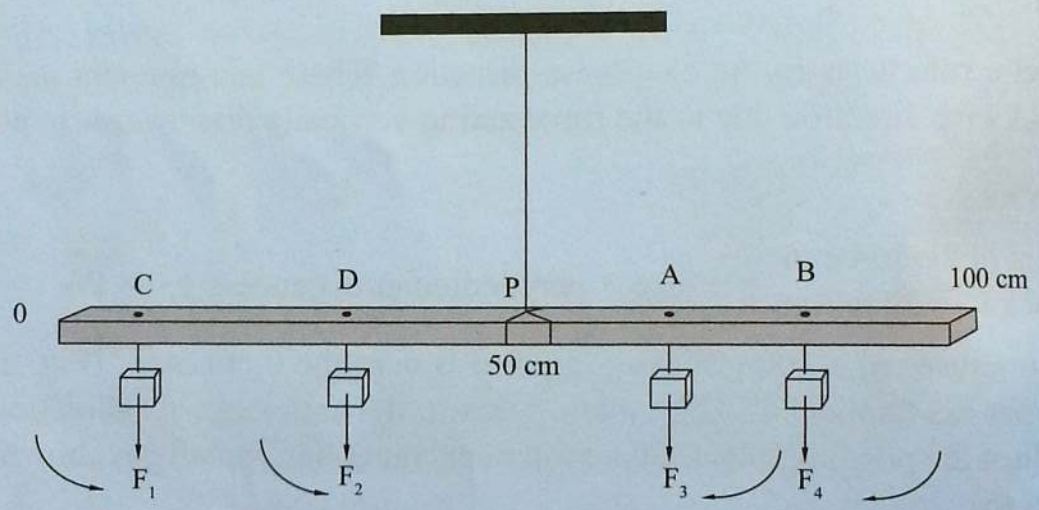


Fig. 6.9: Balanced metre rule under action of forces.

- Calculate the moments about point P.

Results

The sum of the clockwise moments $= F_3 \times PA + F_4 \times PB$.

The sum of the anticlockwise moments $= F_1 \times PC + F_2 \times PD$.

What can you say about $F_1 \times PC + F_2 \times PD$ and $F_3 \times PA + F_4 \times PB$?

From Experiments 6.2 and 6.3 we can conclude that the sum of the clockwise moments about a point is equal to the sum of the anticlockwise moments about the same point, when the metre rule is balanced.

In Experiment 6.3, we saw how a body can be balanced by a number of forces. *When a body is balanced under the action of a number of forces*, it is said to be in *equilibrium*.

The results of Experiments 6.2 and 6.3 are summarised in what is known as *the principle of moments*.

It states that, *when a body is in equilibrium under the action of forces, the sum of clockwise moments about any point is equal to the sum of anticlockwise moments about the same point.*

Experiment 6.4: To verify the principle of moments

Apparatus

- A metre rule
- Seven, 50 g masses

Procedure

- Consider a uniform metre rule suspended at its mid point P, which is the 50 cm mark. Suspend 3 masses; 200 g, 100 g and 50 g and adjust their positions A, B and C till the system is in equilibrium as shown in Fig. 6.10.
- Calculate the distances PA, PB and PC in metres and enter the values in a table.

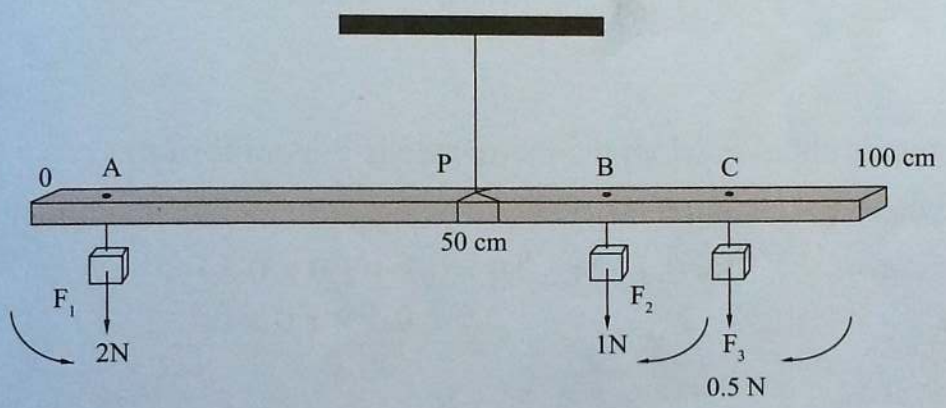


Fig. 6.10: Verifying the principle of moments.

- Repeat the experiment by changing the positions of A or B or C or all the three so that the metre rule balances horizontally in each case. Record the results in Table 6.1.

Table 6.1

	PA (m)	PB (m)	PC (m)	$F_1 \times PA$ (Nm)	$F_2 \times PB + F_3 \times PC$ (Nm)
1					
2					
3					
4					
5					

Discussion

It is seen that the last two columns are equal for each set of results proving that the sum of the clockwise moments is equal to the sum of the anticlockwise moments about point P.

$$F_2 \times PB + F_3 \times PC = F_1 \times PA$$

Example 6.3

A uniform metre rule is pivoted at its centre P, and 3 masses are placed at A, B and C as shown in Fig. 6.11. Find the value for the weight W of the mass M placed at C so that the metre rule is balanced horizontally.

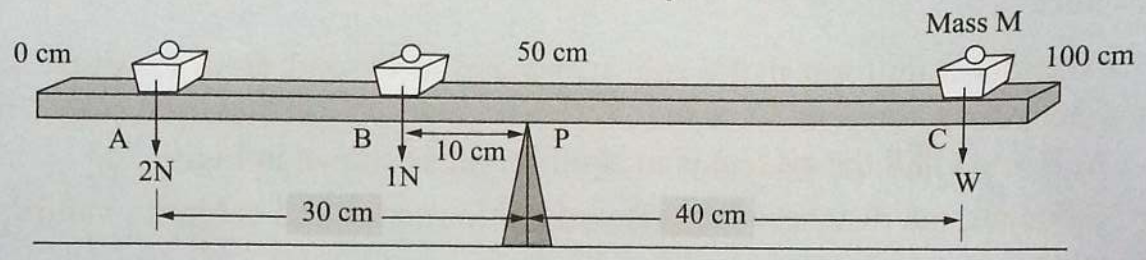


Fig. 6.11: Principle of moment

Solution

Taking moments about P, when the metre rule is in equilibrium.

Sum of the clockwise moments = Sum of the anticlockwise moments

$$W \times 0.4 = 2.0 \times 0.3 + 1.0 \times 0.1$$

$$W = \frac{2.0 \times 0.3 + 1.0 \times 0.1}{0.4}$$

$$= 1.75 \text{ N}$$

Example 6.4

John, Joyce and Janet sat on a seesaw as shown in Fig. 6.12. Where is John, whose mass is 60 kg seated so that the seesaw is balanced horizontally if the masses of Joyce and Janet are 50 kg and 20 kg respectively?

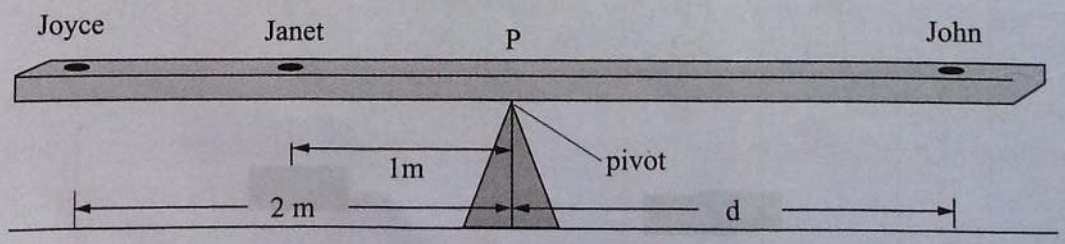


Fig. 6.12: See saw at balance

Solution

John's weight = 600 N, Joyce's weight = 500 N, Janet's weight = 200 N

Taking moments about the pivot,

Sum of clockwise moments about the pivot = Sum of the anticlockwise moments about the pivot

$$600 \times d = 500 \times 2 + 200 \times 1$$

$$600\ d = 1\ 000 + 200$$

$$d = \frac{1\ 200}{600} = 2 \text{ m}$$

John should sit at a distance of 2 m from the pivot.

Example 6.5

The uniform plank of wood in Fig. 6.13 is balanced at its center by the forces shown. Determine the value of W in kg.

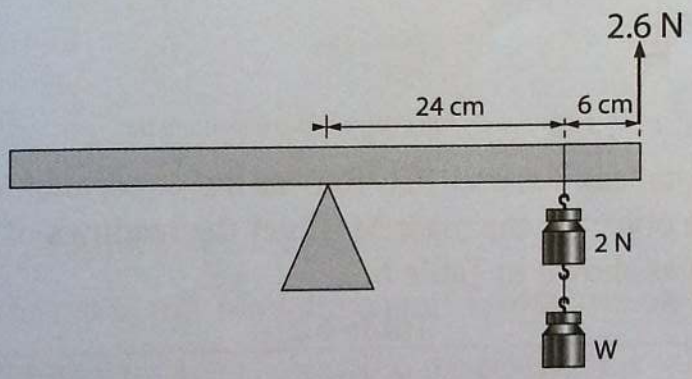


Fig. 6.13

Solution

Note that the 2.6 N produces an anticlockwise moment.

Sum of clockwise moments = Sum of anticlockwise moments

$$0.24 \times (2 + W) = 2.6 \times 0.30$$

$$0.48 + 0.24W = 0.78$$

$$\Rightarrow W = \frac{0.78 - 0.48}{0.24} = 1.25 \text{ N}$$

$$= 0.125 \text{ kg}$$

Experiment 6.5: To determine the mass of an object using the principle of moments

Apparatus

- A metre rule
- A known mass
- An unknown mass
- Support

Procedure

- Suspend a uniform metre rule at its mid point P. Suspend the object of mass m, using a string, from a point A. Suspend a known mass M on the other side of the metre rule and adjust the position of the mass M till the metre rule is horizontal as shown in Fig. 6.14.

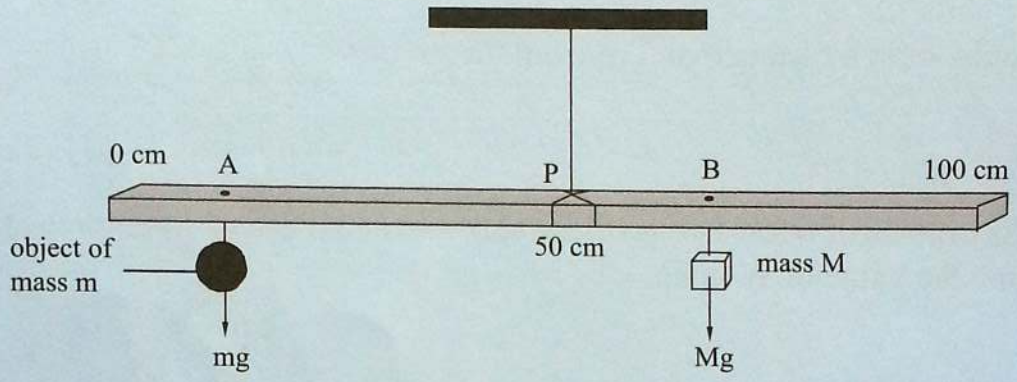


Fig. 6.14: Finding unknown mass m.

- Record the distances PA and PB. Repeat the experiment by changing the position of the object or the mass M. Enter the readings of M, PA and PB in a tabular form as shown in Table 6.2.

Table 6.2

	Mass M(g)	PA(cm)	PB(cm)	$m = \frac{M.PB}{PA}$ (g)
1				
2				
3				
			Mean *m*	

- Calculate the mean value for the mass of the object from the last column.

Discussion

Taking moments about P,

$$(mg) \times PA = (Mg) \times PB,$$

$$m \times PA = M \times PB, \quad \text{(g cancels out)}$$

$$\therefore m = \frac{M \times PB}{PA}$$

Exercise 6.2

1. State the principle of moments.
2. A boy of mass 20 kg sits on one side of a log of wood and 10 m away from the pivot. A girl of mass 30 kg sits on the opposite side of the log. How far is the girl from the pivot.
3. State two conditions for a system to be in a state of equilibrium.
4. Weights of 25 N, 28 N and 8 N were suspended on a uniform plank of wood pivoted at its center on a knife-edge. Fig. 6.15 shows the plank immediately after it was placed on a knife-edge.

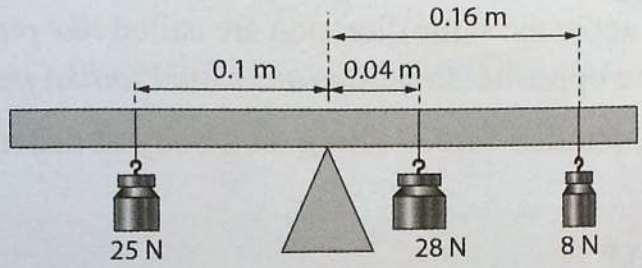


Fig. 6.15

(a) Work out:

(i) Sum of Clockwise moments

(ii) Sum of Anticlockwise moments

(b) Is the bar in a state of equilibrium? Give a reason for your answer.

5. A uniform metre rule is pivoted at the center. It is balanced by weights of 8 N, F and 24 N suspended at 34 cm, 46 cm and 60 cm marks respectively (Fig. 6.16). Calculate the value of F.

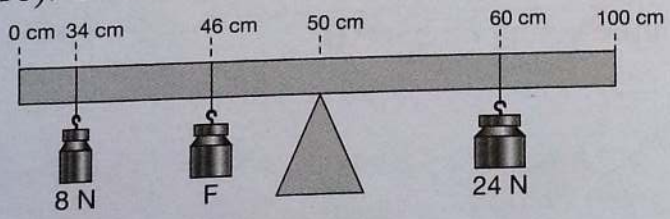


Fig. 6.16

6. Fig. 6.17 below shows a modern bar balanced by forces of 210 N, 100 N and 25 N. Calculate the distance *d*.

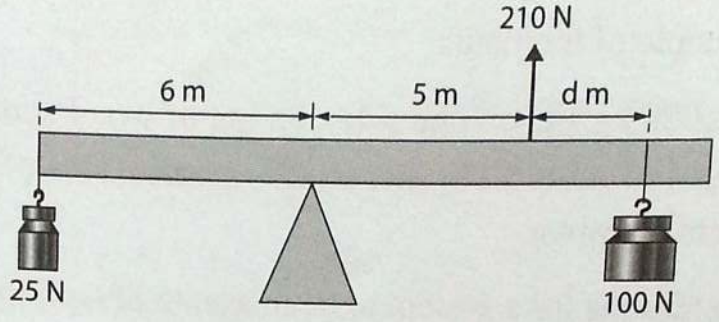


Fig. 6.17

6.3 Couple

Parallel forces which act in the same direction are called *like parallel forces*. Parallel forces which act in the opposite directions are called *unlike parallel forces*.

Two equal and unlike parallel forces acting on a body at different points form a *couple*. (Fig. 6.18).

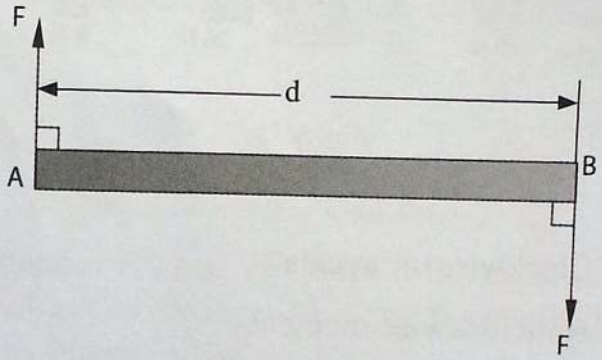


Fig. 6.18: A couple

A couple produces a turning effect on a body.

Moment of a couple

Fig. 6.19 shows a couple acting on bar AB.

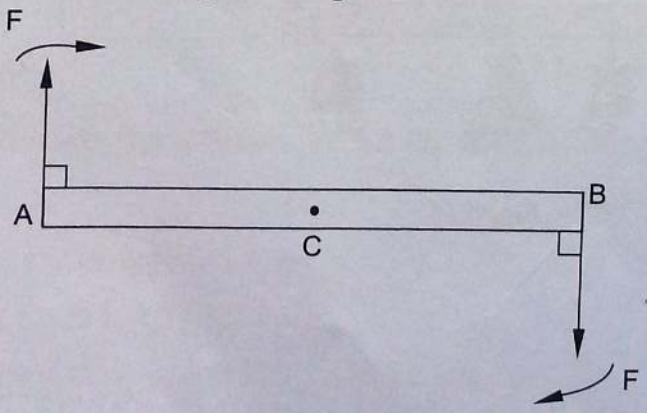


Fig. 6.19: Moment of a couple

Since the pivot is at C, the moment of the force F acting at point A = F × AC, in the clockwise direction.

Similarly, the moment of the force, F acting at point B = F × BC, also in the clockwise direction.

□ The moment of the couple = (F × AC) + (F × BC)

= F (AC + BC), but AB = BC + BC

= F × AB = F × Arm of the couple.

The moment of the couple, called the *torque* which is defined as the *total rotating effect* of a couple and is given by the product of one of the forces and the perpendicular distance between the forces.

Hence, in Fig. 6.19,

Torque = F × perpendicular distance AB.

SI unit of torque is the *newton-metre (Nm)*

Example 6.6

In Fig. 6.20, each force is 4 N and the arm of the couple is 20 cm. Calculate the moment of the couple.

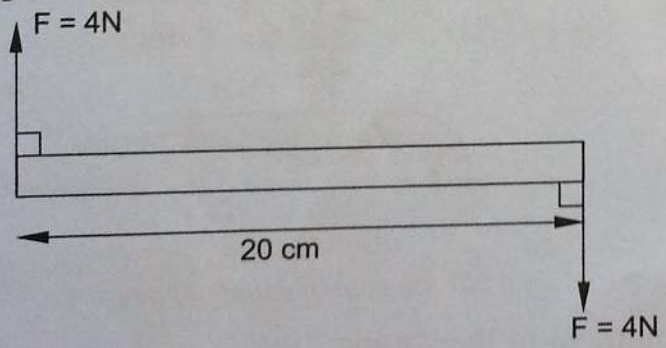


Fig. 6.20: Moment of a couple

Solution

The moment of the couple = F × perpendicular distance

= 4 N × 0.20 m

= 0.80 Nm.

Some common real life examples of a couple are observed when:

- Forces are applied by hands to turn a steering wheel of a motor car (Fig. 6.21 (a)) or the handle bars of a bicycle.

- A water tap is opened or closed (Fig. 6.21 (b)).
- A cork is removed from the mouth of a bottle using a cork-screw (Fig. 6.21 (c)).

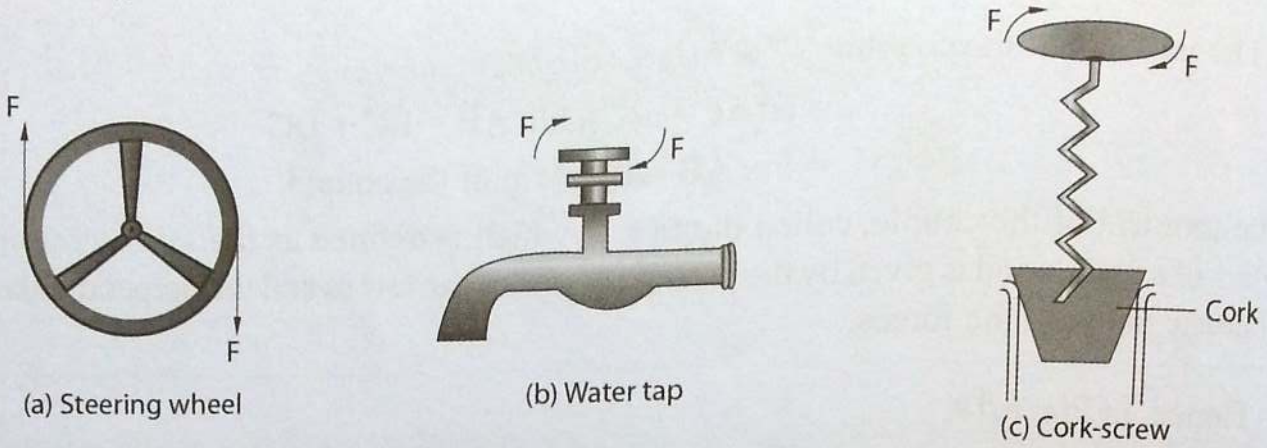
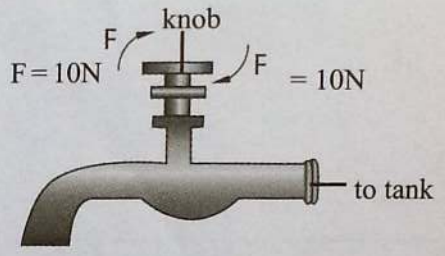


Fig. 6.21 Moment of couple

Exercise 6.3

1. Fig. 6.22 is a water tap in use. If the diameter of a circular path made by the tap (knob) when is open and closed is 20 cm.



(b) Water tap

Fig. 6.22: Moment of couple of a tap

Calculate the moment of the couple.

2. Calculate the torque in Fig. 6.23.

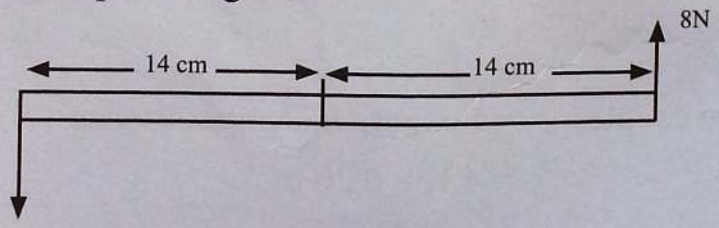


Fig. 6.23: Torque

3. A steering wheel of a truck has a diameter of 60 cm. If the driver is holding the wheel with both hands, while negotiating a corner, calculate the force applied by the right hand if the left hand is pulling the wheel by a force equal to 200 N.

6.4 Centre of mass of a body

In one of his experiments, Sir Isaac Newton showed that bodies experience a force of gravity exerted on them by the earth. This force of gravity is always directed towards the earth's centre and is called the *weight of the body*. How is this weight distributed throughout the body? The answer to this question is found in the following experiment.

Experiment 6.6: To investigate where the weight of a body acts from

Apparatus

- A table
- A thin rectangular card

Procedure

- Place a thin rectangular cardboard near the edge of the bench top.
- Pull the card slowly away from the bench until it is just about to topple over when released as shown in Fig. 6.24 (a).
- Using a ruler, mark and draw the line AB along which the card balances.
- Repeat the experiment with the other side of the card, mark and draw the line CD along which the card balances. The line AB and CD intersect at a point M (Fig. 6.24(b)).

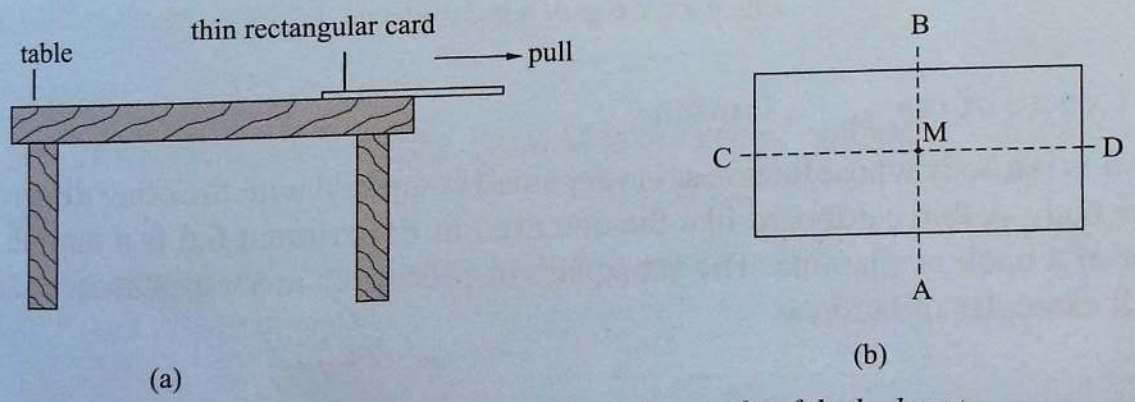


Fig. 6.24: Location of a point where the weight of the body acts

- Now try to balance the card with the point M placed at the tip of your fore finger. The card is observed to balance horizontally on the finger.

Observation

The cardboard balances horizontally at a certain point only.

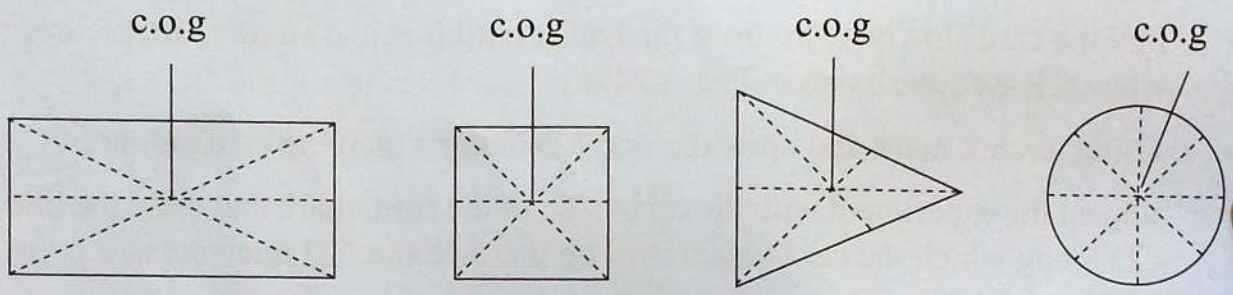
Discussion

Experiment 6.6 shows that although the mass of the cardboard is distributed over the whole body, there is a particular point, M, where the whole mass of the cardboard appears to be concentrated. When pivoted at this point the cardboard balances horizontally. This point, M, is called *centre of mass* of the cardboard.

> The centre of mass of a body is the point where the whole mass of the body appears to be concentrated.

Experiments show that bodies with *uniform cross section area* and *density* have their centres of mass located at their *geometrical centres.* For example, a metre rule of uniform cross-sectional area and density has its centre of mass located at the 50 cm mark.

Fig. 6.25(a) - (d) shows the centre of gravity of rectangular, square, triangular, and circular laminae.



(a) rectangle (b) square (c) isosceles triangle (d) circle

Fig. 6.25: c.o.g. of regular lamina

6.5 Centre of mass of a lamina

A *lamina* is a body whose thickness is very small compared with the other dimensions of the body. A thin cardboard like the one used in Experiment 6.6 is a lamina. The cover of a book is a lamina. The set square or protractor in your mathematical set are all examples of laminae.

Experiment 6.7: To determine the centre of mass of an irregular lamina using a plumbline

Apparatus

- An irregular lamina
- Plumbline
- A drawing pin

Procedure

- Make three holes P, Q and R on an irregularly shaped lamina as close as possible to the edges and far away from each other. The holes should be large enough to allow the lamina turn freely when supported by a drawing pin.
- Suspend the lamina on the clamp using the drawing pin each hole at a time.
- Suspend a plumbline (a thin thread with a small weight at one end) from the point of support, P as shown in Fig. 6.26(a) and draw the line of the plumbline on the lamina by marking two points A and B far apart and joining them.
- Repeat the procedure with the support Q and mark the point M where the two lines intersect.
- Check the accuracy of your method by suspending the lamina at R.

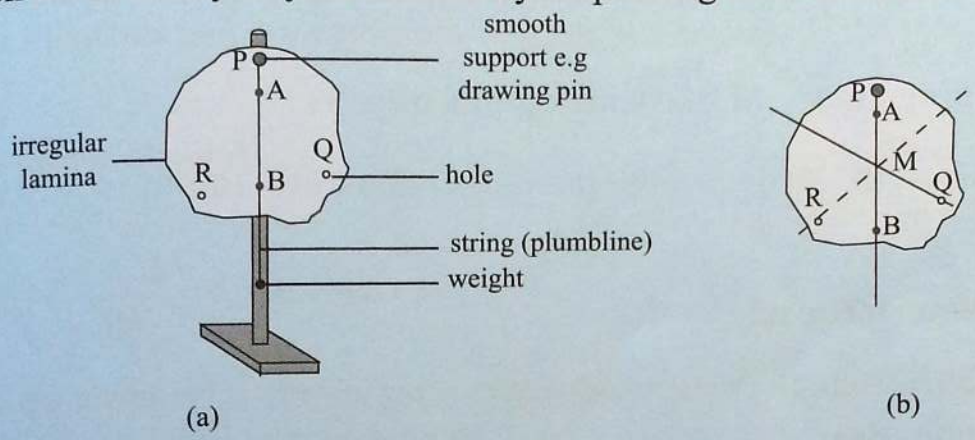


Fig. 6.26: Locating centre of mass of a lamina using a plumbline

The plumbline pass through M (Fig. 6.26 (b)). Check the results again by balancing the lamina about point M.

Observation

The lamina balances horizontally. Point M is the centre of mass of the lamina.

Conclusion

The experiment above also proves that *when a body is freely suspended it rests with its centre of mass vertically below the point of suspension.*

Experiment 6.8: To find the centre of mass of a lamina using a straight edge

Apparatus

- An irregular lamina
- A prism

Procedure

- Balance a lamina on the edge PQ of a prism as shown in Fig. 6.27. Mark the points A and B on the lamina and join them.

- Repeat the experiment for another position and note the points C and D on the lamina. Join C and D.

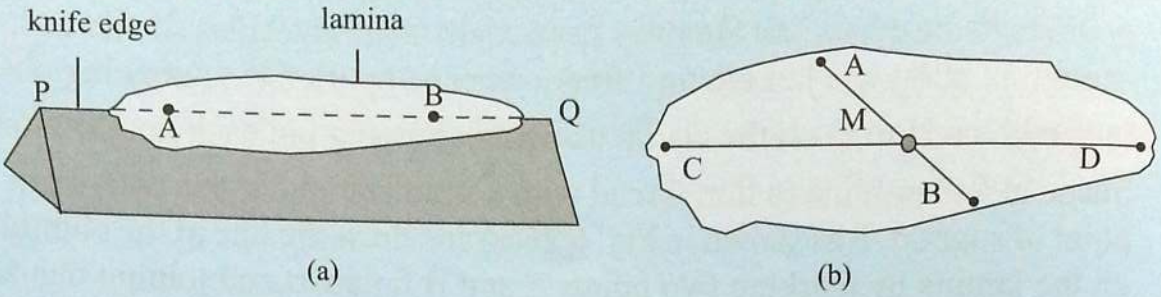


Fig. 6.27: Locating the centre of mass of a lamina using a straight edge

Conclusion

The lines AB and CD intersect at M, the centre of gravity of the lamina.

Determining centre of mass of regular objects

Experiment 6.9: To determine the weight of a beam (uniform metre rule)

Apparatus

- Uniform metre rule
- A mass, m
- A knife edge

Procedure

- Balance a uniform metre rule of mass *m* on a fulcrum and adjust its position until the metre rule is horizontal. Note the position P, where it is pivoted (Fig. 6.28(a)).
- Displace the fulcrum to a point A, say to the right of *P*. Observe what happens.
- Place a mass M between A and 100 cm mark and adjust its position B until the metre rule is horizontal (Fig. 6.28(b)).

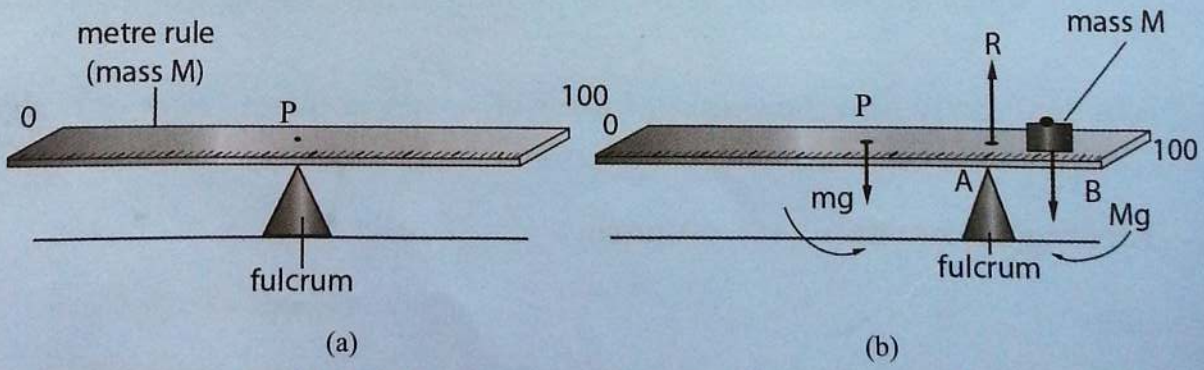


Fig. 6.28: Determination of mass of a uniform metre rule

- Find the lengths PA and BA. Repeat the experiment by changing the position of A or the mass M.
- Record the mass of M, length PA and length BA in a table (Table 6.4).

Table 6.4

	Mass M(g)	BA(cm)	PA(cm)	$m = \frac{M.BA}{PA}$ (g)
1				
2				
3				
			Mean m =	

- Take moments and determine the value of m (the mass of the metre rule).

Discussion

Taking moments about A

$mg \times PA = Mg \times BA$

$$m = \frac{M \times BA}{PA} \text{ (g cancels out)}$$

Calculate the mean value for the mass of the metre rule from the last column of Table. 6.4. The weight of the metre rule = mg.

Example 6.7

A uniform metre rule pivoted at the 60 cm mark is kept horizontal by placing a 50 g mass on the 80 cm mark. Calculate the mass of the metre rule (Fig. 6.29).

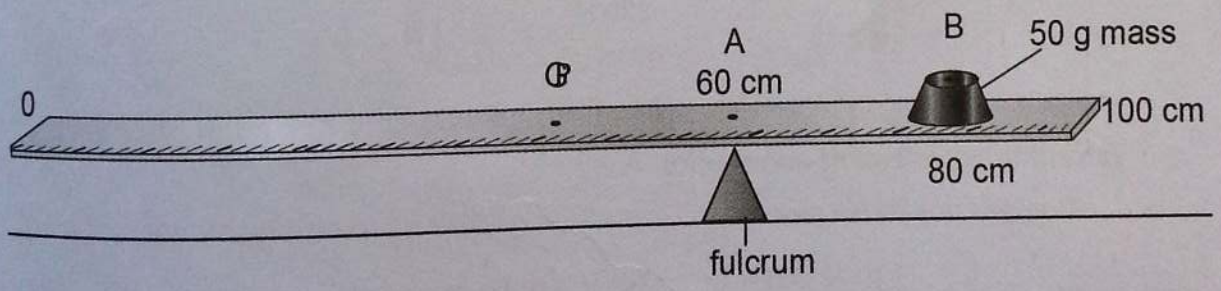


Fig. 6.29: Determining the mass of the metre rule

Solution

Let the mass of the metre rule be m

Force due to m = $m \times g$ where g = 10 N/kg

= 10m newtons

Force due to 50 g mass = $\frac{50}{1\,000} \times g = 0.05 \times g = 0.50$ N.

PA = 10 cm = 0.1 m

AB = 20 cm = 0.2 m

By the principle of moments, taking moments about point A,

$$10 \text{ m} \times 0.1 = 0.50 \times 0.2$$

$$m = \frac{0.50 \times 0.2}{10 \times 0.1} = \frac{0.10}{1}$$

$$= 0.1 \text{ kg or } 100 \text{ g}$$

Example 6.7

A coffee table of mass 22 kg and length 1.6 m long is to be lifted off the floor on one of its shorter sides to slip a carpet underneath. Calculate the maximum force needed to lift the table.

Solution

Fig. 6.30 shows the forces acting on the table where F is the lifting force and 220 N is the weight of the table acting at the center.

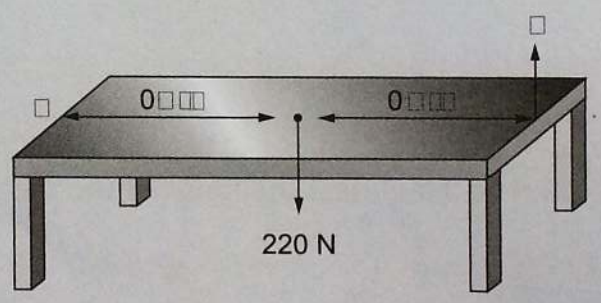


Fig. 6.30

Taking the movement about point A

Sum of Clockwise moments = *Sum of Anticlockwise moments*

$$220 \text{ N} \times 0.8 \text{ m} = F \times 1.6 \text{ m}$$

$$\Rightarrow F = \frac{220 \times 0.8}{1.6}$$

$$= 110 \text{ N}$$

$\therefore$ The minimum force required = 110 N

Exercise 6.4

1. A uniform metre rule of uniform width 2.5 cm and thickness 0.5 cm is suspended at the 78 cm mark and kept balanced by hanging a mass of 150 g at the 100 cm mark (Fig. 6.31). Calculate, (a) the mass of the metre rule, (b) the density of the material of the metre rule, (c) the tension T in the string.

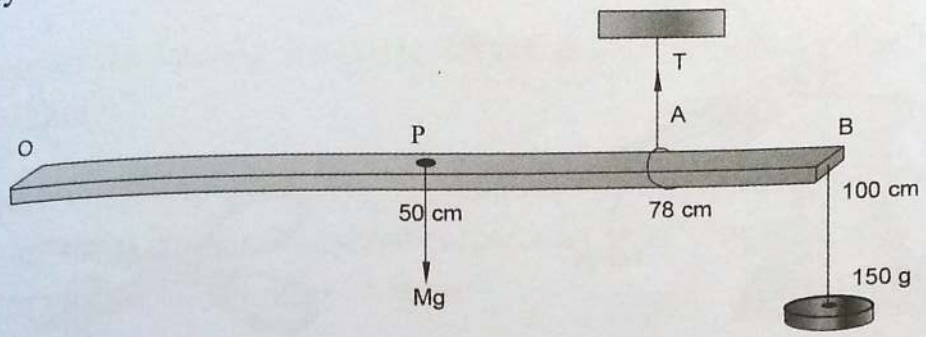


Fig. 6.31: A system at balance

2. A uniform metre rule is balanced at the 20 cm mark by a mass of 240 g placed at one end. (a) Draw a diagram to show the state of balance of the metre rule (b) Determine the weight and mass of the metre rule.

3. A non-uniform plank AB shown in Fig. 6.32 is balanced when a force of 200 N is applied at the end B. The centre of gravity, G, is shown.

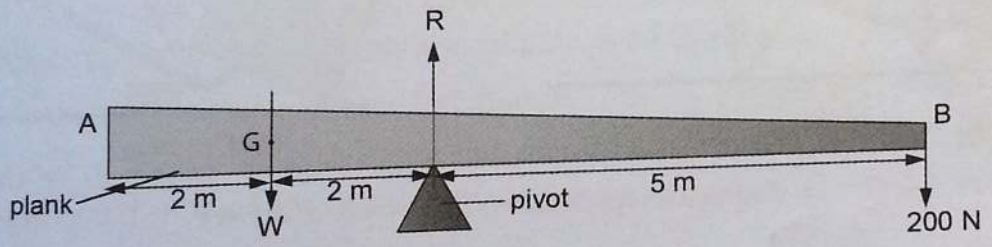


Fig. 6.32: Centre of mass of a plank

Calculate the:

(a) weight and

(b) mass of the plank.

6.6 Applications of moment of a force

The following are some of the common examples which illustrate the turning effect of a force i.e moment of a force:

1. Opening or closing a door.
2. Opening a bottle using a bottle opener (Fig. 6.33(a)).
3. A pair of scissors or garden shears in use (Fig. 6.33(b)).

4. Children playing on a "see-saw".
5. A wheelbarrow being used to lift some load (Fig. 6.33(c)).
6. A wheel cart being used to lift heavy loads.
7. A screwdriver being used to tighten/loosen a screw.
8. A crowbar being used to move large object (Fig. 6.33(d)).

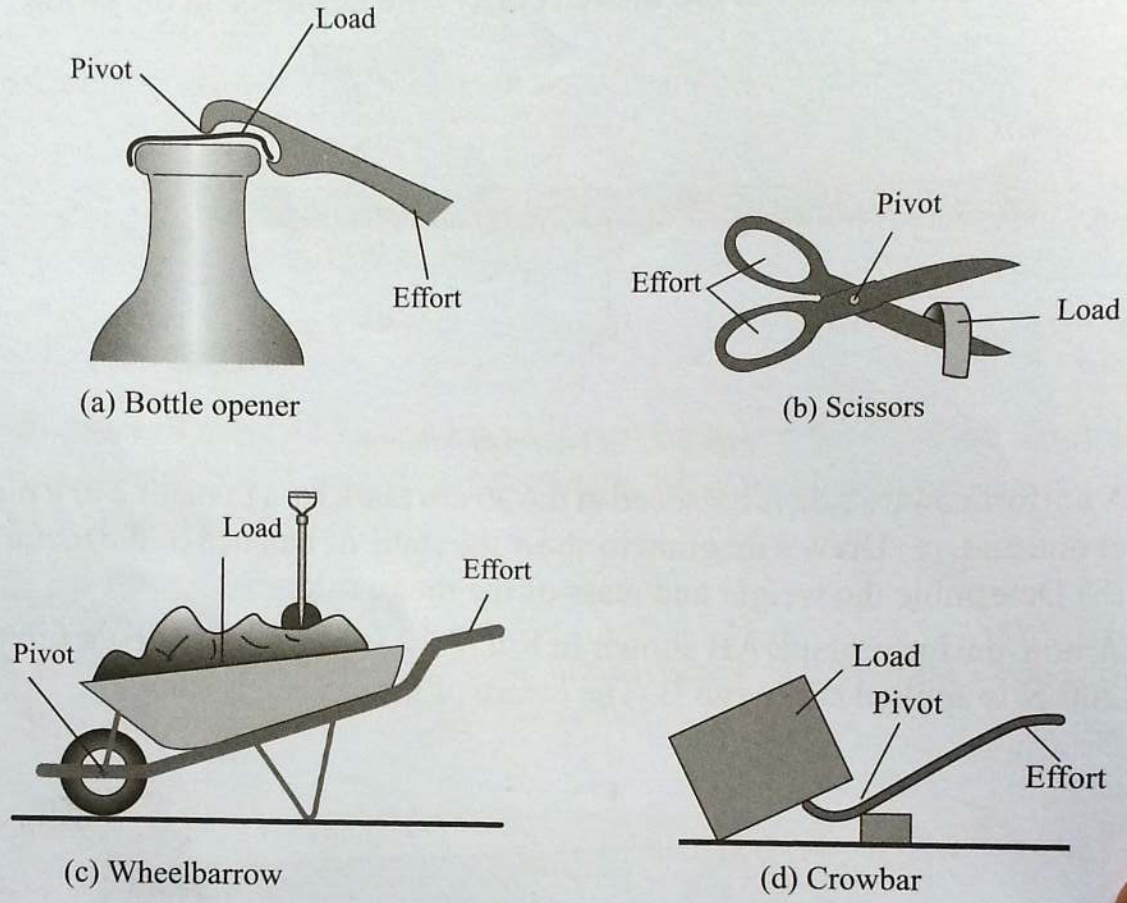


Fig. 6.33: Applications of moment of a force

Note

In all these tools the length of the handle determines the amount of effort to be used. Activity 6.1 will help us to understand this.

Activity 6.1: To investigate the effect of length to the effort needed in using a tool

- Remove the bottle top using a bottle opener with a short handle. Repeat the same with a bottle opener with a long handle.
- Open the classroom door with your hand near the door hinge. Now, open the same door with your hand far away from the door hinge. Of the activities above, when do you use less effort?

From Activity 6.1, we notice that, we use less effort when using a bottle opener with a longer handle to remove bottle top and when our hands are far away from the hinge to open the door.

Several experiments have been done on several tools and machines and proved that:

(a) The longer the handle, the lesser the effort used when using the machines.

(b) The shorter the handle, the more the effort used while working with the tools and machines.

Therefore, the manufacturers always design tools and machines such as bottle openers, see-saw, water taps, spanners and wheelbarrows with longer handles so that very little effort be used in working with them.

Unit summary

- The moment of a force about a point is the turning effect of the force about the point.
- The turning effect of the force depends upon the magnitude of the force applied and the perpendicular distance from the pivot.
- The moment of a force is the product of the force applied and the perpendicular distance from the pivot to the line of action of the force.
- The moment of a force is a *vector* quantity and its SI unit is Newton metre.
- Principle of moments states that the sum of the clockwise moments about a point is equal to the sum of the anticlockwise moments about the same point, when the system is in equilibrium.

Unit Test 6

1. (a) State the principle of moments.
   (b) Describe an experiment to prove this principle using two known masses and a uniform metre rule.
2. A uniform metre rule is suspended at the 50 cm mark and a stone at the 0 cm mark. The metre rule is balanced horizontally when a mass of 100 g is suspended at the 60 cm mark. Calculate the weight of the stone.

3. In the diagram shown (Fig. 6.34), calculate the value of the unknown mass M, when the plank is balanced horizontally.

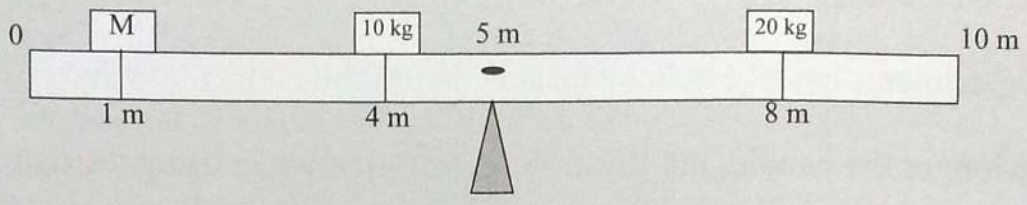


Fig. 6.34: A plank at balance

4. Jane and James are seated at 3 m and 2 m respectively from the centre of a seesaw on one side and Jack at 4 m from the centre on the other side. The seesaw is balanced horizontally. Find the weight of Jack, if the masses of Jane and James are 40 kg and 30 kg respectively.

5. Fig. 6.35 shows a uniform plank pivoted at its centre. Where should a 5 kg mass be attached if the plank is to be perfectly horizontal?

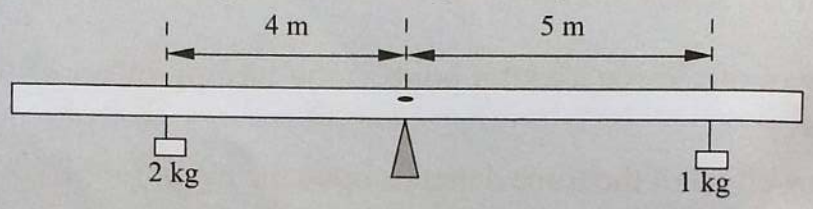


Fig. 6.35: A uniform plank at balcon

6. A uniform metre rule is balanced horizontally at its centre. When a mass of 5 g is suspended at the 4 cm mark, the rule balances horizontally if a mass M is suspended at 60 cm mark. Calculate M.

7. Fig. 6.36 shows a uniform metallic metre rule balanced when pivoted at the 30 cm mark under the conditions shown on the diagram.

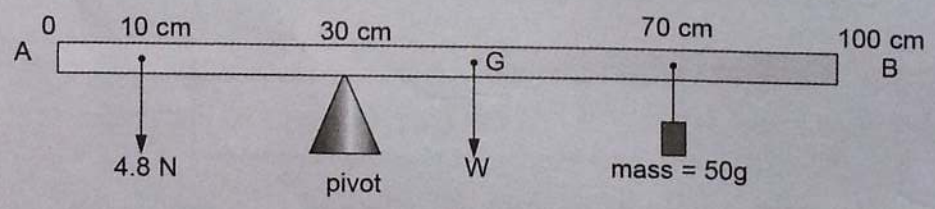


Fig. 6.36: Moments in a uniform rule

(a) Redraw the diagram showing all the forces acting on the metre.

(b) Calculate the weight W of the metre rule.

8. Name four importance of moments in our daily life.

9. Fig. 6.37 represents a type of safety valve that can be fitted to the boiler of a model steam engine.

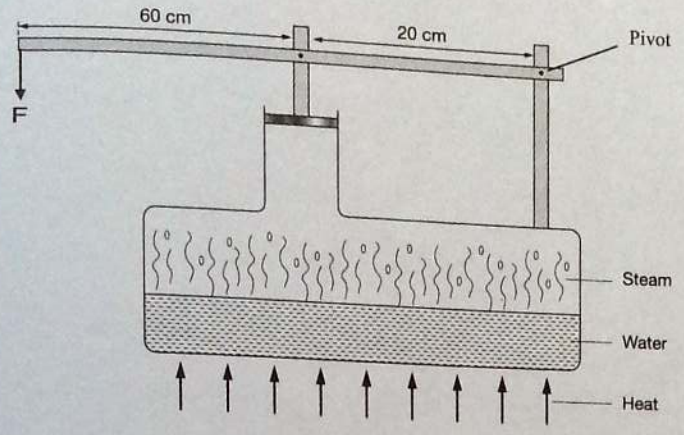


Fig. 6.37

(a) Briefly explain how the system works..

(b) What minimum pressure should the steam have in order to escape through the plate which has a cross sectional area 10.6 cm^2? (Take atmospheric pressure = 10^5 Pa)

Electricity and Magnetism

Outcome

The students will be able to understand the laws and principles of electricity, magnetism and then apply this knowledge in areas such as analogue and digital electronic systems.

Unit 7: Magnetism

Unit 8: Electromagnetism

Unit 9: Electromagnetism Induction

Unit 10: Introduction to Digital Electronics

UNIT

7 Magnetism

Success criteria

By the end of this unit, you must be able to:

(a) Describe magnetisation and demagnetisation.

Introduction

In Form 1, we discussed a few facts on magnetism. We learnt that some materials like iron, nickel and cobalt are magnetic materials while others like glass, wood and plastic are non-magnetic materials.

We also learnt that a magnet has two poles: North and South poles, where magnetic force is concentrated. The magnetic force between the poles was summarised in the law of magnetism which states that *like poles repel while unlike poles attract.* We also discovered that repulsion is the sure test for magnetic poles.

In this section, we will learn how to make magnets, demagnetise a magnet and study the domain theory.

7.1 Magnetisation

In the second century A.D, the Chinese found a method of making magnets by rubbing pieces of common iron against lodestone. Nowadays, magnets are made using various methods. Some of these methods include stroking or touching method, electric method, hammering and induction method.

(a) Stroking or touching method

There are two ways of magnetising an object by stroking method: single stroke and double stroke methods.

(i) Single stroke method

A piece of steel e.g. steel needle placed near a magnet becomes magnetised. However, the magnetism acquired usually disappears quickly when the magnet is removed. This magnetism may be enhanced by stroking as illustrated by Experiment 7.1.

Experiment 7.1 : To make a magnet by single stroke method

Apparatus:

- A steel needle
- bar magnet

Procedure

1. Place the steel needle on the bench.
2. Stroke the steel needle with the south pole of the bar magnet along the whole length of the steel needle.
3. Once at the end, lift the magnet well away from the steel needle i.e. make a wide sweep as shown in Fig. 7.1.

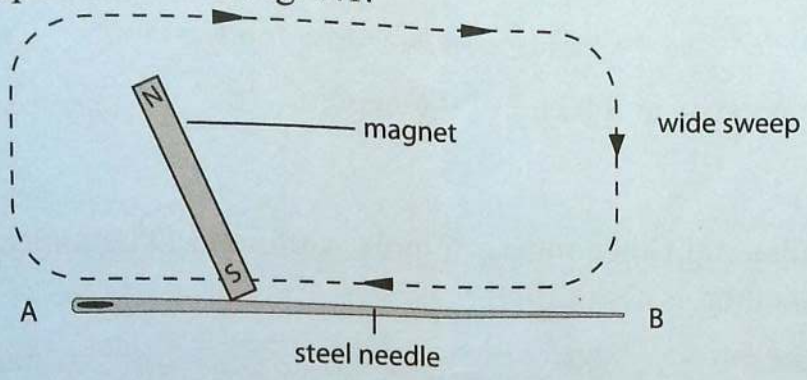


Fig. 7.1: Making magnets by single stroke method

4. Repeat the process several times.
5. Test the polarity of the steel needle by the repulsion method.

Observation

It is observed that the steel needle becomes magnetised with end B becoming a S-pole and end A becoming a N-pole.

Conclusion

The end of the magnetic material last touched by the magnet acquires a polarity opposite to the one touching it.

(ii) Double stroking or Divided stroking

Experiment 7.2: To make a magnet by double stroking.

Apparatus

- 2 bar magnets
- steel needle

Procedure:

1. Stroke a steel needle using two magnets as shown in Fig. 7.2.
2. The stroking should begin at the middle of the steel needle each time making sure that the two bar magnets are lifted far away from the steel needle once you reach the ends.

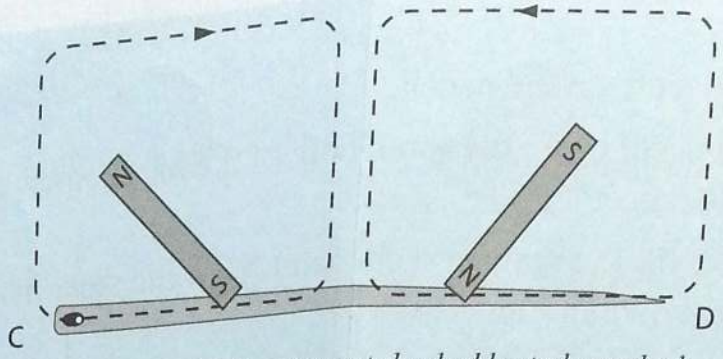


Fig. 7.2: Making magnets by double stroke method

3. Test for the polarity at the end of the needle.

Observation

It is observed that end C becomes a N-pole while end D becomes a S-pole. Th double stroke method is also called *the divided stroke method*.

Making consequent poles

It is possible to have a magnet with like poles on both ends. These are calle consequent poles.

Experiment 7.3 : To make a magnet with consequent poles

Apparatus:

- 2 bar magnets
- steel needle

Procedure:

- Repeat Experiment 7.2 above as shown in Fig. 7.3 using similar poles in stroking.

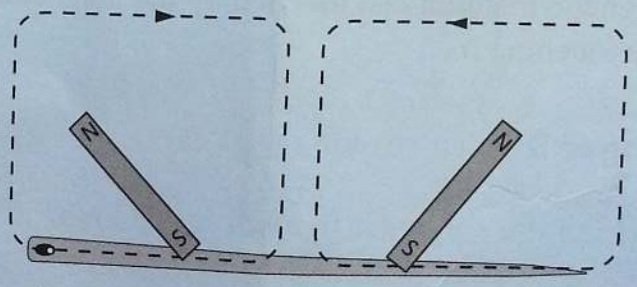


Fig. 7.3: Making a consequent poles on the magnet

- Test for the polarities of the magnet made.

Observation

Similar poles appear at each end of the steel needle. The middle of the needle becomes a south pole (Fig. 7.4).

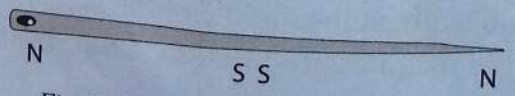


Fig. 7.4: Magnet with consequent poles.

(b) Electrical method

Experiment 7.4: Making a magnet by electrical method

Apparatus:

- cells in a cell holder
- a hollow non-metal tube (eg. manila paper)
- steel needle
- connecting wires
- an ammeter
- a copper wire
- switch

Procedure:

1. Using a wire, wind a number of turns around a hollow tube. This is called a *solenoid*.
2. Place a steel knitting needle and pass a direct current (*DC*) through the turns of the solenoid as shown in Fig. 7.5.

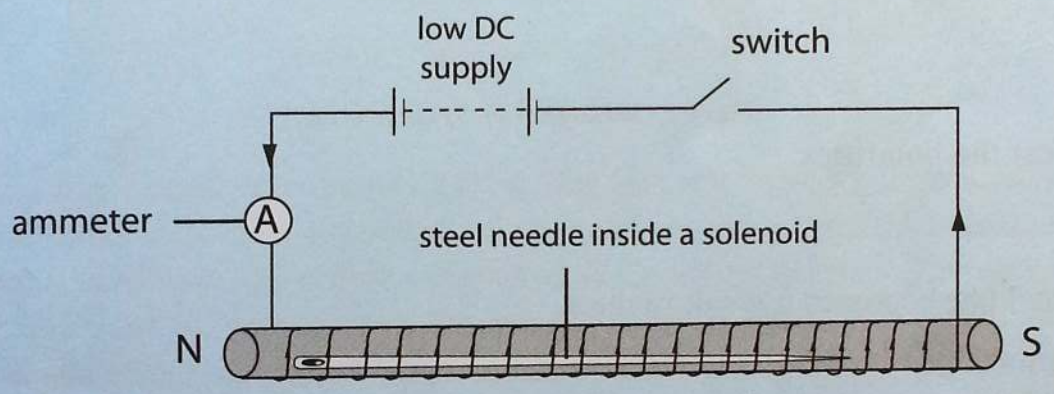


Fig. 7.5: Making a magnet by electrical method.

3. Switch off the current and remove the needle.
4. Test for polarity of the needle.
5. Repeat the experiment but with the electric current direction reversed.
6. Use another magnet of known polarity to test for polarity of the needle.

Observation

The polarity of the magnet produced depends on the direction of the electric current.

Conclusion

The current flowing in a coil has a magnetic effect. It induces magnetism to the iron needle. Such a magnet is known as *an electromagnet*. We will learn more about electromagnets.

(c) Hammering

Experiment 7.5: To make a magnet by hammering

Apparatus:

- steel bar
- hammer

Procedure:

1. Hammer one end of a steel bar fixed in north-south direction several times (Fig. 7.6).

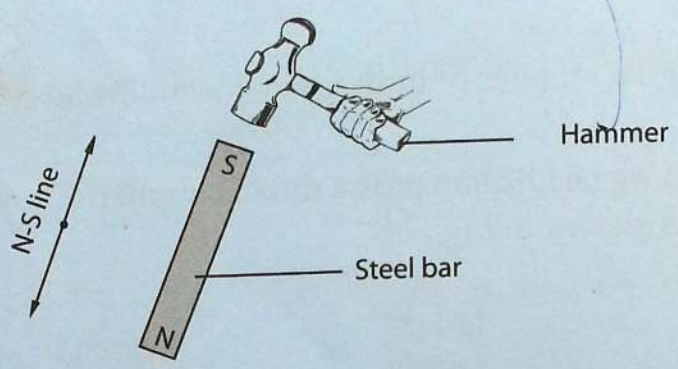


Fig. 7.6: Magnetisation by hammering.

2. Test the polarities.

Observation

The steel bar becomes a weak magnet.

Discussion

The lower end becomes a weak north pole. In this method the influence of earth's magnetic field is used to magnetise the steel bar being hammered.

(d) Magnetisation by induction

Experiment 7.6 To make a magnet by induction

Apparatus

- Office pins
- two bar magnets

Procedure:

1. Place a magnet near an unmagnetised steel pin and note what happens.
2. The pin is attracted by the bar magnet. Bring another pin next to the first pin and note what happens.
3. Separate the first pin from the magnet and note what happens to the second pin.

4. Repeat the experiment using two pins placed side by side.
5. Introduce a north pole between the two pins and observe what happens.

Observation

The second pin is attracted to the first pin (Fig. 7.7 (a)).

The two pins separate further when a north pole is placed in between them (Fig. 7.7 (b)).

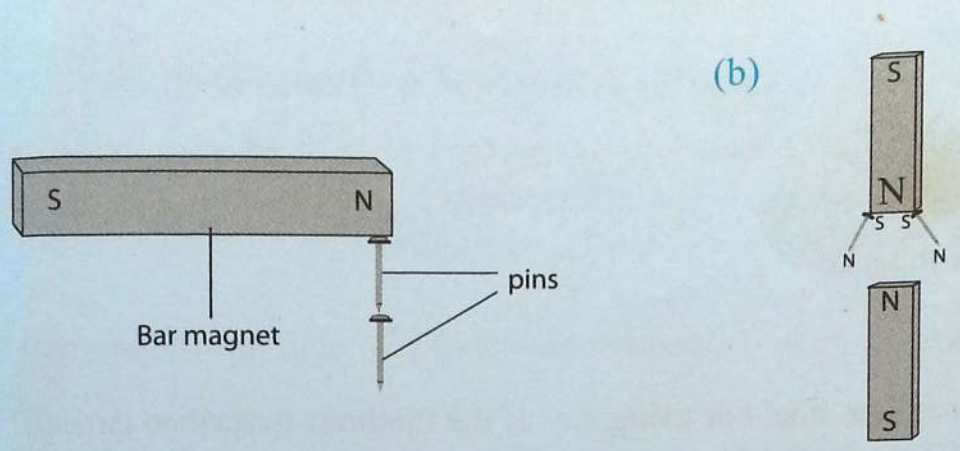


Fig. 7.7: Magnetisation by induction.

Conclusion

The first pin becomes magnetised by the magnet through a process called *induction* and then gets attracted to the magnet. The induced pole nearest to the magnet is of opposite polarity to that of the inducing magnet. The second pin gets magnetised by the first pin through the same process. This shows that it is the presence of the bar magnet that sustains the magnetism between the first and second pin.

7.2 Demagnetisation

Demagnetisation is the process through which magnets lose their magnetism. The process may be achieved through a number of methods. Some of the methods are discussed as follows.

(a) Hammering

Hammering a magnetised material placed in the East-West direction or dropping it violently on a hard floor several times makes disorganises the alignment of dipoles hence loses most of its magnetism.

(b) Heating

Heating a magnetised material until red hot and cooling it suddenly when resting in East-West direction makes it lose its magnetism by disorganising the alignment of dipoles.

(c) Electrical method

Placing a magnet in a coil placed in East-West direction and passing an alternating current (A.C) demagnetises the needle.

7.3 Domain theory of magnetism

The domain theory of magnetism was developed by a scientist called *Wilhelm Weber* and helps us to explain the phenomenon of magnetism.

Experiment 7.7: To show the existence of molecular magnets

Apparatus

- A steel bar
- A bar magnet

Procedure

1. Magnetise a steel bar using any of the methods described earlier.
2. Cut the magnetised bar into two halves. Test the polarities of the ends of each half.
3. Cut one of the halves into two halves and again test the polarities.
4. Continue cutting one piece until you are not able to cut it any more. Each time test the polarity of the halves (Fig. 7.8).

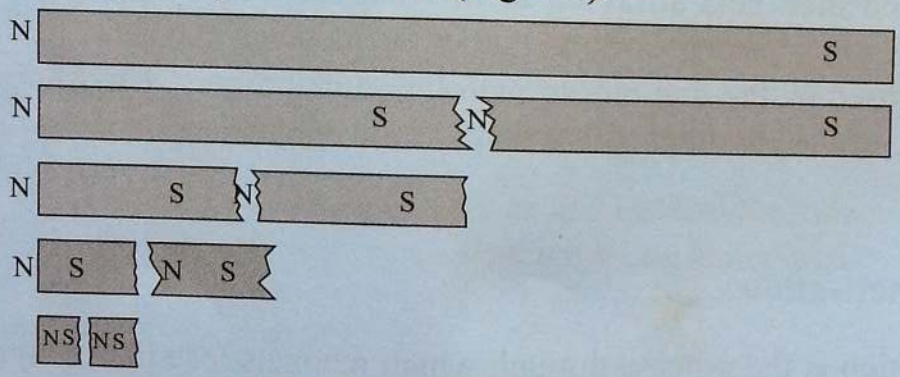


Fig. 7.8: Effects of cutting a bar magnet

Observation

The polarity test for the first halves shows that each piece is a magnet in its own right. Further cutting of the pieces still yields a smaller magnet.

Discussion

The smallest portion of any matter is a molecule. Thus, if we were able to cut the magnet further we would see that the *smallest magnet would be a molecule*. In ferromagnetic materials these *molecular magnets* or *dipoles* (with two poles) occupy tiny regions called *domains*. The magnetism of each domain is aligned. However, the domain points in different and random directions (Fig. 7.8).

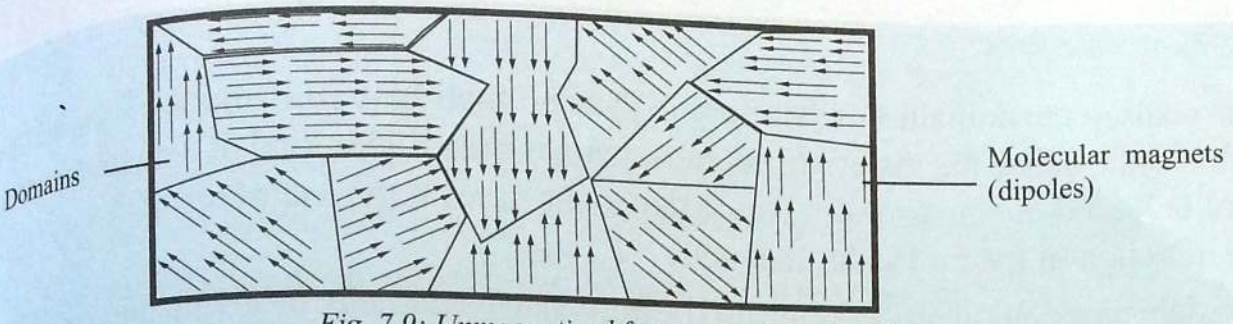


Fig. 7.9: Unmagnetised ferromagnetic material.

Domain theory in magnetisation and demagnetisation

The domain theory may be used to explain the processes of magnetisation and demagnetisation. The domain theory states *that inside a magnet there are small regions in which the magnetic direction of all dipoles are aligned in the same directions*.

A dipole is the smallest particle of a magnetic material. It is equal to an atom in electric conductor.

Magnetisation

Magnetization is the process of making a magnet from a magnetic material.

- Since the domains are aligned in all possible directions in an unmagnetised material (Fig. 7.9), the net magnetism in the material is zero.
- In a partially magnetised material the domains align themselves as shown in Fig. 7.10(a). Notice that the *domains* in Fig. 7.9 and 7.10(a) are not all aligned in the same direction.
- When the material is fully magnetised ,the domain walls move and the molecular magnets align themselves in one particular direction as shown in Fig. 7.10 (b).

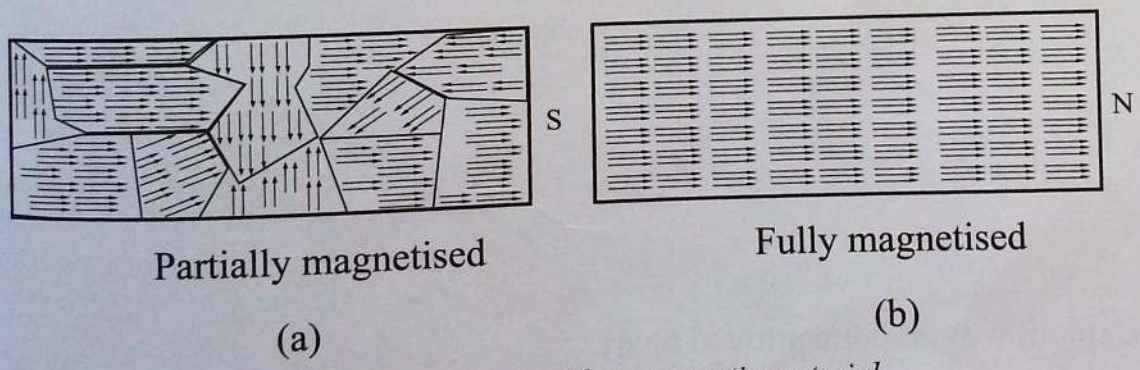


Fig. 7.10: Magnetised ferromagnetic material.

A ferromagnetic material is said to be *magnetically saturated* when the walls are swept out and the molecular magnets point in the same direction.

A resultant north pole is produced at one end and a south pole at the other end as shown in Fig. 7.10(b).

Demagnetisation

The walls of the domain slowly return to their original state with time as this is a more stable state; hence the material becomes demagnetised. This kind of demagnetisation is called *self-demagnetisation*. This is due to the poles at the end which tend to reverse the direction of the molecular magnets.

The demagnetisation process can also be influenced externally by giving the molecular magnets enough energy to overcome the forces holding them in a particular direction. The energy may be provided by heating, hammering or dropping on a hard surface or by using an alternating current.

Unit summary

- Magnets can be made by stroking, electrical or hammering methods.
- The domain theory helps us to explain magnetism and demagnetism.
- Magnetisation is the process of making a magnet from a magnetic material.
- Demagnetisation is the process through which a magnet loses its magnetism.

Unit Test 7

1. Using domain theory of magnetism, explain magnetisation using electrical method.
2. Two steel pins were attracted by a magnet. When a south pole was brought in between the two pins, the pins moved further away, as shown in Fig. 7.11.

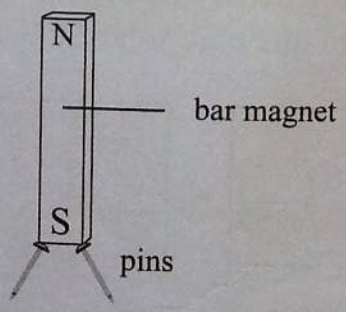


Fig. 7.11

Explain why the pins moved apart.

3. With the aid of a diagram, explain how bar magnets are stored so as to minimise self-demagnetisation.
4. (a) With the aid of a diagram describe how an electromagnet is made.
   (b) Describe an experiment to show how you would investigate the variation of the lifting strength of the electromagnet and the current

in the electromagnet indicating clearly the measurements you would make.

(c) State three applications of an electromagnet.

5. Describe a simple experiment to show the existence of magnetic poles.
6. What is the name to the smallest particles of a magnetism.
7. Explain how one can make a magnet using induction.
8. Fig. 7.12 is amethod of making a magnet

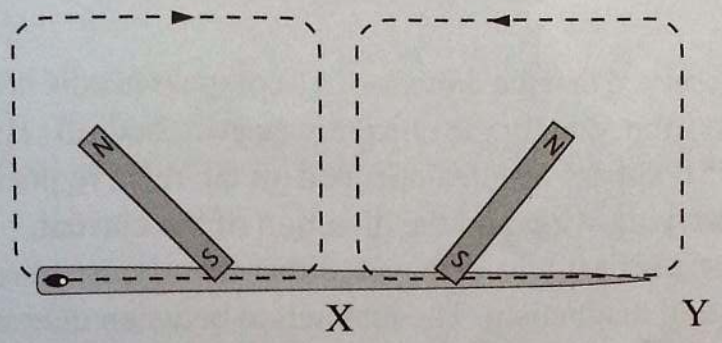


Fig. 7.12: Magnetisation

(a) Name the method of magnetisation shown in Fig. 7.12.

(b) identifypolarity of pole x and y.

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UNIT

8 Electromagnetism

Success criteria

By the end of this unit, you must be able to:

- Describe electromagnetism
- Explain the applications of electromagnetism.

Introduction

In 1819, Oersted observed that the direction of a compass needle near a current-carrying conductor changed immediately the current was switched off. He also observed that the direction on the compass needle depended on the relative position of the compass from the current-carrying wire, and the direction of the current.

From Oesterd experiment it was discovered that there exists a relationship between an electric current and magnetism. The interaction between the two fields is known as electromagnetism. In this unit, we will study the magnetic effect of current and some of its applications in technological development.

8.1 Magnetic field due to a straight current-carrying conductor

Experiment 8.1: To show the magnetic field pattern due to a straight current-carrying conductor.

Apparatus

- A long straight stiff wire
- Iron fillings
- d.c source
- Stand and Clamp
- Cardboard
- Rheostat
- Switch

Procedure

1. Set up the apparatus as shown in Fig. 8.1.

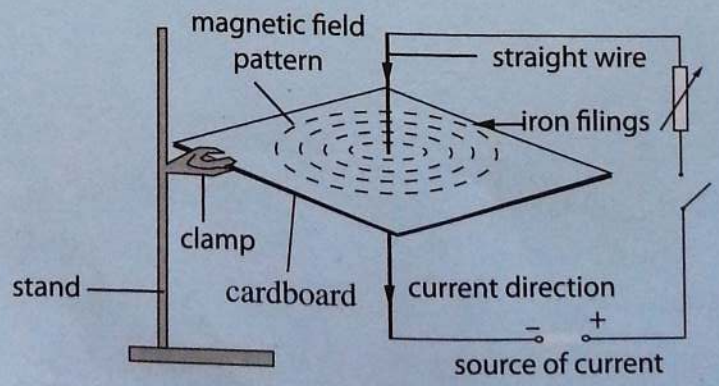


Fig. 8.1: Magnetic field pattern due to a straight current carrying conductor

2. Sprinkle iron filings on the card and close the switch. Tap the card gently and observe the pattern formed by the iron fillings. You may use the variable resistor to vary the current, I.

Observation

When the card is tapped, the iron filings settle in concentric circles round the wire. When we were studying magnetic field around magnets in Form 1, we found that iron filings settle in a particular pattern depending on the magnetic field present. In the same way, the observation in this experiment suggest that there is a magnetic field around the wire.

Conclusion

We can conclude that the current in the conductor has produced a magnetic field around it.

Magnetic field around a straight current-carrying conductor is a pattern of concentric circles around the conductor.

The field has three features:

(i) The magnetic field lines are circular.
(ii) The field is strongest close to the wire.
(iii) Increasing the current increases the strength of the field.

8.2 The direction of a magnetic field around a current-carrying conductor

Experiment 8.2: To determine the direction of magnetic field for current-carrying conductors

Apparatus

- A long straight stiff wire
- 7 plotting compasses
- stand and clamp
- cardboard
- rheostat
- d.c source

Procedure

1. Repeat Experiment 8.1 using 6 or 7 plotting compasses instead of iron filings as shown in Fig. 8.2.
2. Describe what you observed.
3. Reverse the direction of the current in the wire and observe the direction of the plotting compasses.

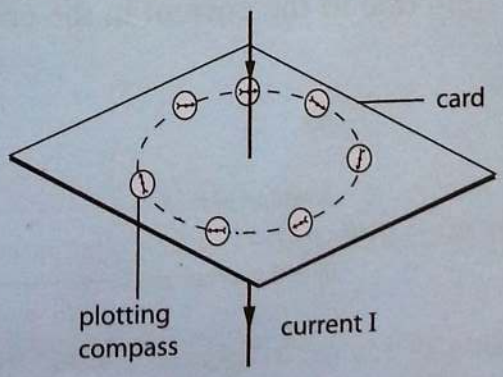


Fig.8.2: Plotting compasses around a wire.

Observation

The pattern is the same as in Experiment 8.1, with the added information on the direction of the field (Fig. 8.3).

When the current direction is reversed the compass needles point in the opposite direction.

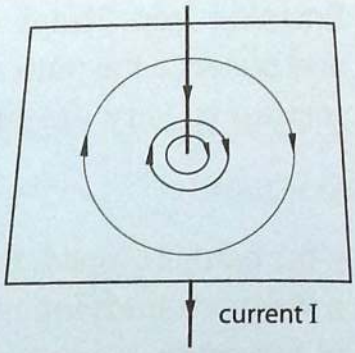


Fig. 8.3: Direction of magnetic field

Conclusion

The direction of the magnetic field is around a current carrying conductor. 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. 8.4. The other fingers will point in the direction of the magnetic field due to the current in the wire.

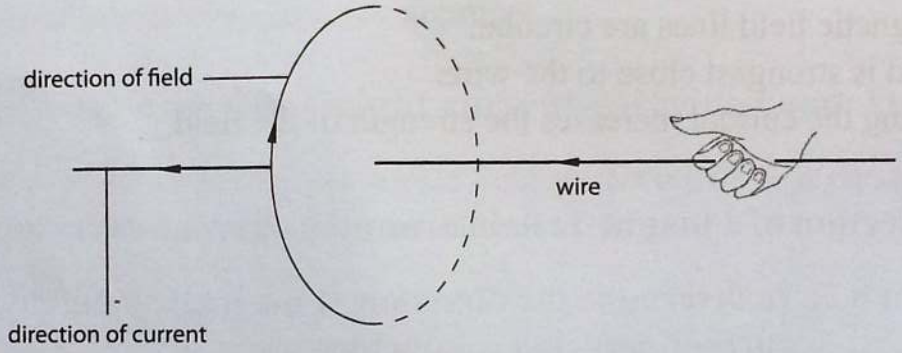


Fig. 8.4: Right hand grip rule

(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. 8.5.

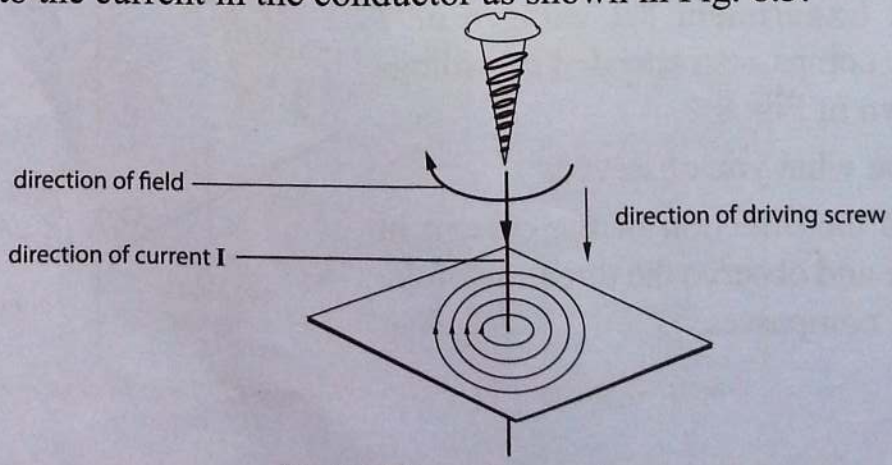


Fig. 8.5: The corkscrew rule

8.3 Magnetic field due to a current-carrying solenoid

A solenoid is a long cylindrical coil made up of a number of turns of a closely packed wire.

Experiment 8.3: To show the magnetic field pattern due to a current carrying solenoid

Apparatus

- A solenoid
- Iron fillings
- Cardboards

Procedure

1. Mount a solenoid on a rectangular piece of cardboard as shown in Fig. 8.6(a). Sprinkle some iron filings on the cardboard.

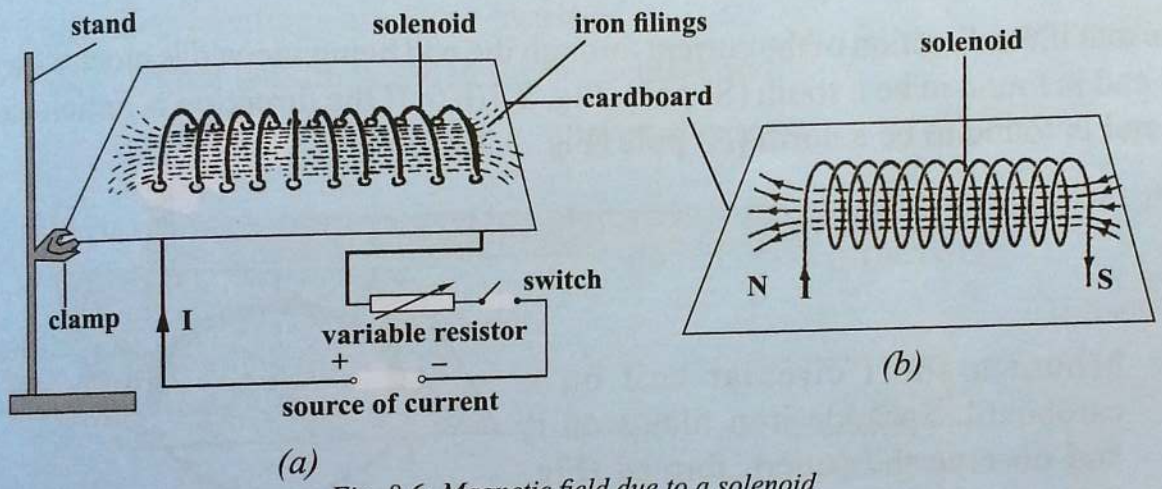


Fig. 8.6: Magnetic field due to a solenoid

2. Close the switch and tap the cardboard gently. Observe and draw the field pattern shown by the spread of the iron filings (Fig. 8.6(a)). Repeat the experiment by placing a number of magnetic plotting compasses both inside and outside the solenoid.

Observation

The iron filings arrange themselves as shown in Fig. 8.6(b).

The plotting compasses show a similar pattern as iron filings, but this time the direction of field pattern is also indicated.

The experiment shows that the solenoid behaves like a magnet with the N and S poles as indicated in Fig. 8.6(b).

The polarity of a coil (solenoid) carrying an electric current

Activity 8.1: To determine polarity in solenoid.

- View the coil from both ends each at a time (Fig. 8.6(b)).
- Sketch how the current is flowing through the turns in each case.

You should obtain the sketches in Fig. 8.7 for current as seen from the ends in Activity 8.1.

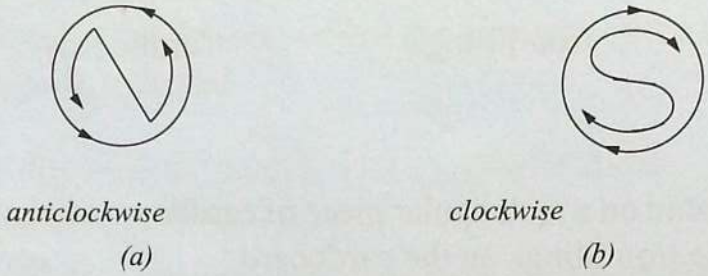


Fig. 8.7: Polarity of a solenoid

Note that if the direction of the current through the end being viewed is clockwise, then that end is found to be a south (S) pole (Fig. 8.7(b)). If the direction is anticlockwise the end is found to be a north (N) pole (Fig. 8.7(a)).

Activity 8.2: To show the magnetic field pattern around a short circular current -carrying coil

Procedure

1. Mount a short circular coil on a cardboard. Sprinkle iron filings on it and observe the pattern formed (Fig. 8.8.
2. Use plotting compasses to plot the field pattern due to the electric current flowing in the coil.
3. The field pattern obtained is as shown in Fig. 8.9.

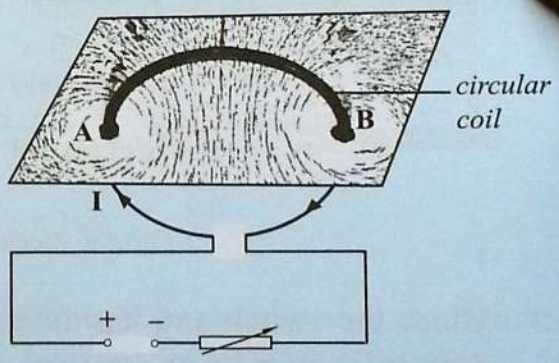


Fig. 8.8: Current through a coil

Observation and Conclusion

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. 8.8. We use the symbol ⊙ to represent current coming out of paper and ⊗ to represent current going into the paper (Fig. 8.9). Applying the right hand screw rule or the right hand grip rule at points A and B, the direction of the field in Fig. 8.9 can also be determined.

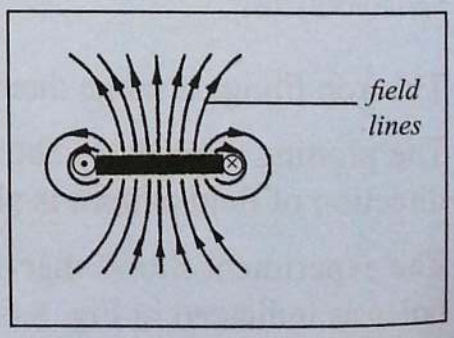


Fig.8.9: Magnetic field due to a short coil.

8.4 Simple electromagnets

An electromagnet is a device made by coils of an insulated wire wound on a magnetic material and then current passed through the coils (see Fig 8.10).

Experiment 8.4 To determine the strength of an electromagnet

Apparatus

- Insulated copper wire
- switch
- connecting wires
- soft iron nail
- a variable resistor
- steel pins
- a cell in a cell holder
- ammeter

Procedure

1. Wind the insulated copper wire round the long iron nail and connect it in a circuit as shown in Fig. 8.10. Care should be taken to ensure that:
   (i) All the windings are in a single layer (i.e.) all are touching the nail.
   (ii) The windings are close together.
   (iii) All the windings are in the same direction.

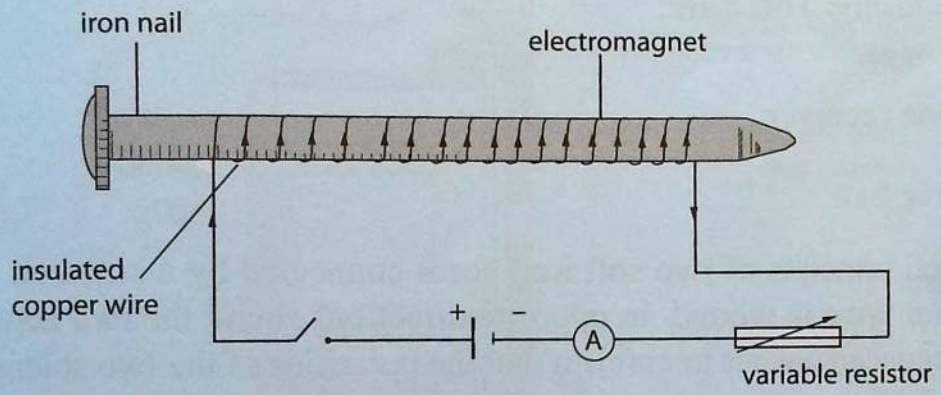


Fig. 8.10: Simple electromagnet

2. Close the switch and adjust the variable resistor so that a suitable current flows in the circuit.
3. Place steel drawing pins at the base of the nail, one after the other and note the maximum number of pins the electromagnet can keep attracted to it.
4. Repeat the experiment by varying the current and noting the new maximum number of pins.
5. Enter your results in a table as shown in Table 8.1.

Table 8.1

Current (A)									
Number of pins									

6. Switch off the current and note what happens to the pins.

7. Repeat the experiment with a constant value of current but with a double and triple layer of windings round the nail wound in the same direction.
8. Record your results.
9. Analyse your results to establish how the strength of the magnet varies with:
   (i) The current when the number of windings is constant.
   (ii) The number of turns (windings) when the current is kept constant.

Observation and Conclusion

The above experiment shows that the *strength of the electromagnet increases with:*

1. *Increasing current* when the number of windings per unit length is constant.
2. The *number of turns per unit length* when the current is kept constant.

It should be noted that the strength of an electromagnet also depends on the material the nail is made of. Soft magnetic alloys will make stronger electromagnets.

Applications of electromagnets

There are many devices that make use of electromagnets. Let us study two such devices more closely. These are:

1. The electric bell
2. The telephone receiver

(a) The electric bell

The electric bell consists of two soft iron cores connected by a soft iron core. An insulated copper wire is wound in opposite directions round the two cores. Apply the method discussed earlier to confirm that the polarities of the two solenoids is as shown in Fig. 8.11.

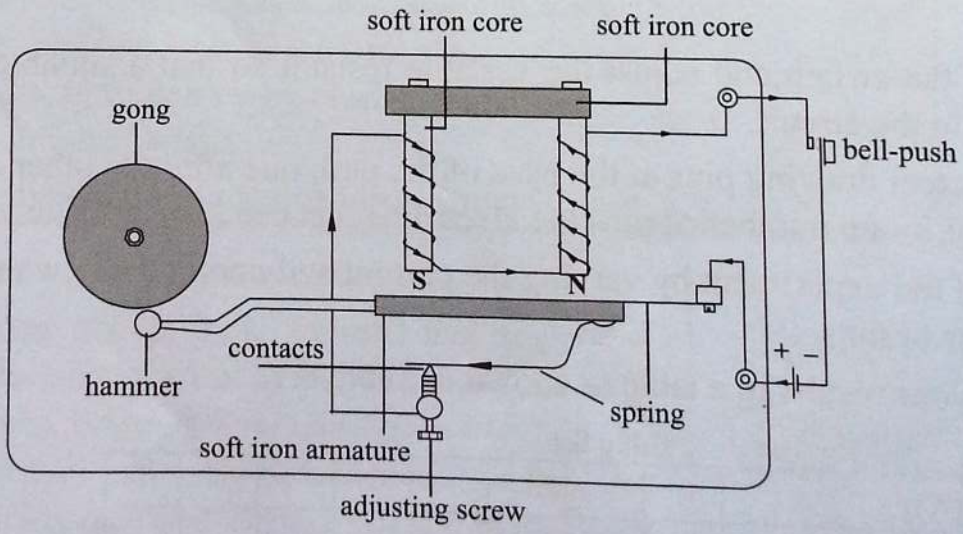


Fig. 8.11: Electric bell

When the switch is closed (by pushing a button switch) a current flows through the circuit and the cores become magnetised. The cores then attract the soft iron *armature*

which creates a gap between the contacts thus breaking the circuit and stopping the flow of the current.

As a result the cores lose their magnetism and the *armature* returns to its original position. This results in contacts closing so that a current flows. The cycle is repeated as long as the switch is closed. A hammer which is attached to the end of the armature keeps on hitting the gong every time contact is made resulting in the familiar continuous sound of a ringing bell. When the push switch is released the current flow stops and the bell stops ringing.

(b) The telephone receiver

The telephone receiver, also commonly referred to as the *earpiece* (Fig. 8.12) works on the same principle as the electric bell. When a person speaks into the *microphone* on the other end of the line an electric current is set up in the earpiece receiver having the same frequency as that of the sound waves in the microphone.

As the current in the earpiece is varying the *diaphragm* made of springs of magnetic alloy vibrates accordingly. A similar sound to the one in the microphone is reproduced in the receiver (earpiece).

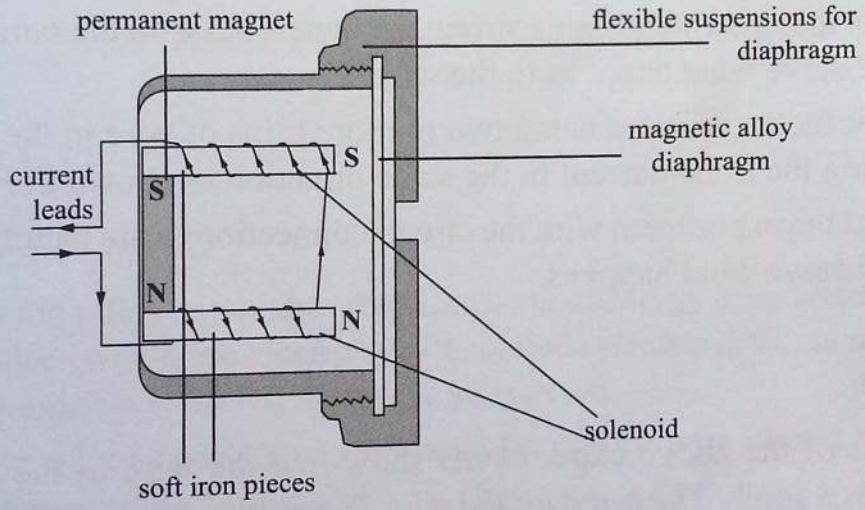


Fig. 8.12: The telephone receiver

8.5 Force on a current-carrying conductor in a magnetic field (Motor effect)

Experiment 8.5: To demonstrate the force on a current-carrying conductor (motor effect)

Apparatus

- Two strong magnets
- Current carrying conductor
- Tripod stands

Procedure

1. Arrange the apparatus as shown in Fig. 8.13(a). AB is a flexible wire loosely held between the poles of strong magnets.

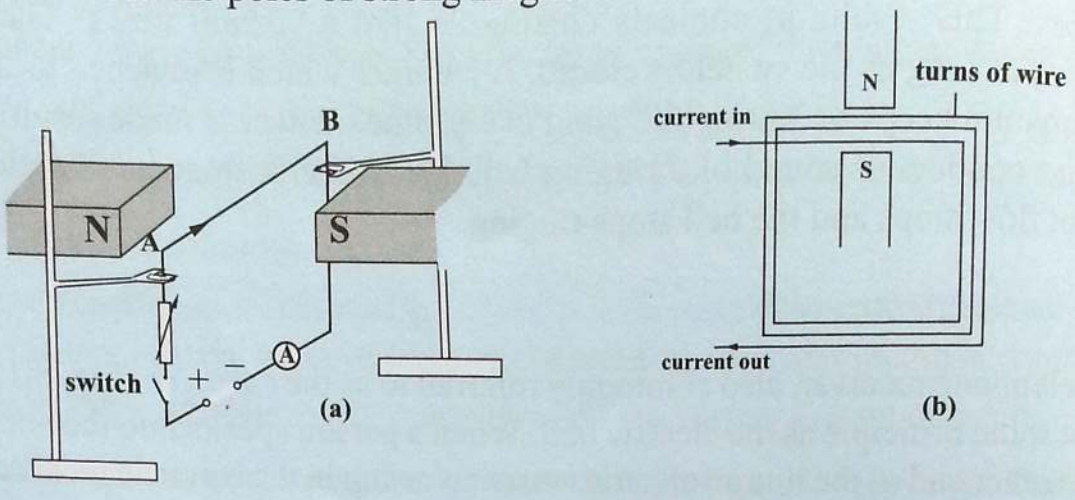


Fig. 8.13: Electric motor effect

2. Close the switch and observe what happens to the wire. Repeat the experiment with a larger current and observe what happens to the wire.
3. Repeat the experiment using stronger magnets but with the same initial current and observe what happens to the wire.
4. Repeat the experiment using two or more turns of wire in the magnetic field carrying the same current in the same direction as shown in Fig. 8.13(b).
5. Repeat the experiment with the circuit connection to the battery interchanged and observe what happens.

Discussion

The results of the above experiments show that the wire in the magnetic field experiences a force. *The force on the wire increases when:*

1. the *current* is *increased.*
2. *stronger magnets* are used.
3. the *number of turns* of the *wire in the magnetic field* was *increased.*

The wire moves in the opposite direction. When the experiment is repeated with the flexible wire and AB kept at an angle less than 90° to the magnetic field, the force on the conductor is found to decrease.

Conclusion

From the above experiment we can conclude that a current carrying conductor placed in a magnetic field experiences a force. This is called the motor effect.

Fleming's left hand rule

The method 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. 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. 8.14).

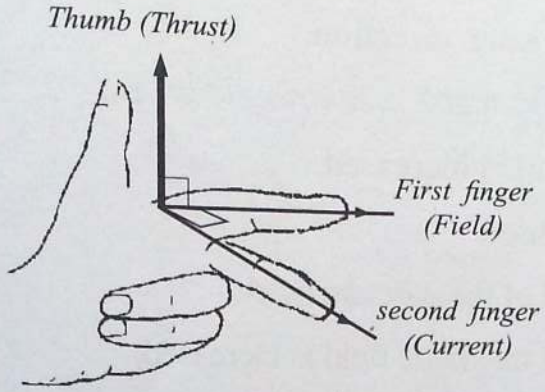


Fig 8.14: Fleming's left hand rule

8.6 Applications of electric motor effect

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. 8.15.

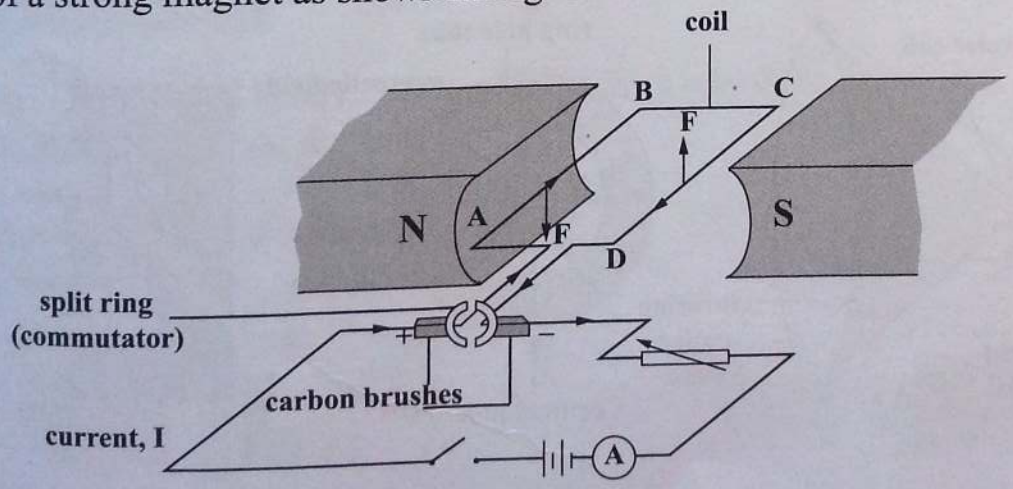


Fig. 8.15: Simple d.c motor.

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 and strongly* 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. 8.16 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.

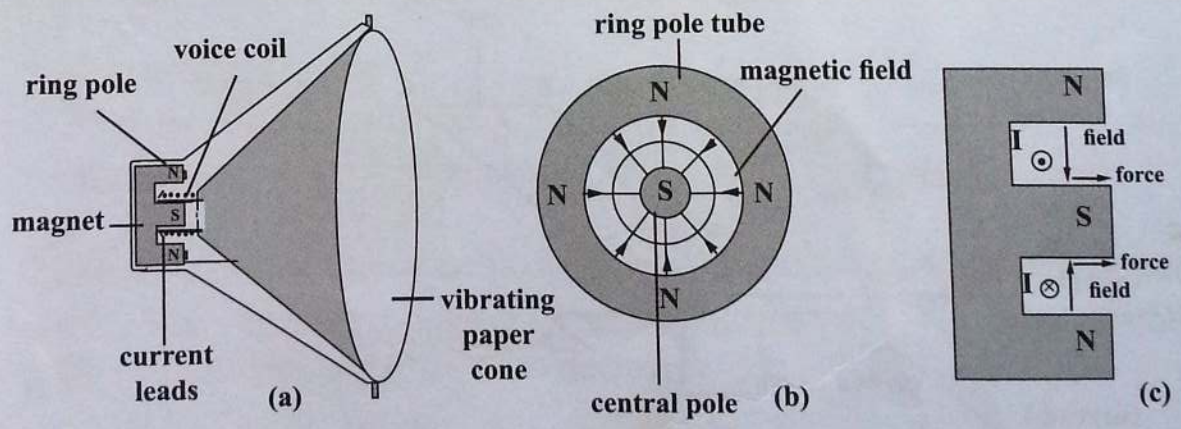


Fig. 8.16: The moving coil loudspeaker

Example 8.1

Fig. 8.17 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.

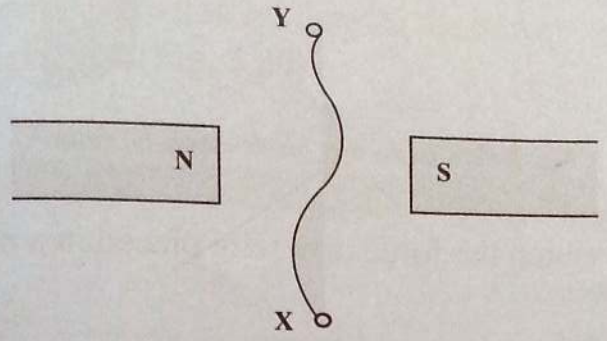


Fig. 8.17

Solution

Connect a source of electric current to the wire as shown in Fig. 8.18. When the switch is closed, the wire XY experiences a force upward and becomes taut.

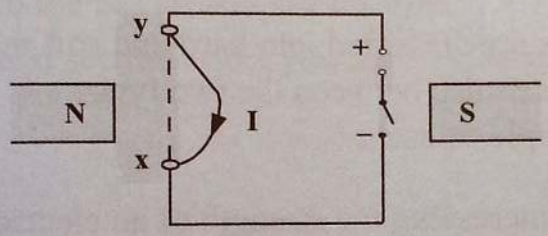


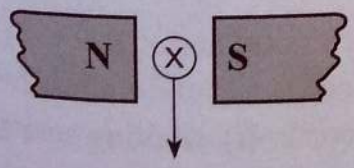
Fig. 8.18

Exercise 8.1

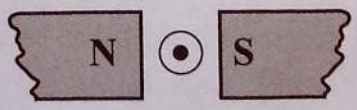
1. Use Fleming's left hand rule to work out which way the wire in Fig. 8.19 moves. The first one is done for you.

Remember ⊗ = current into paper.
⊙ = current out of paper.

(a)



(b)



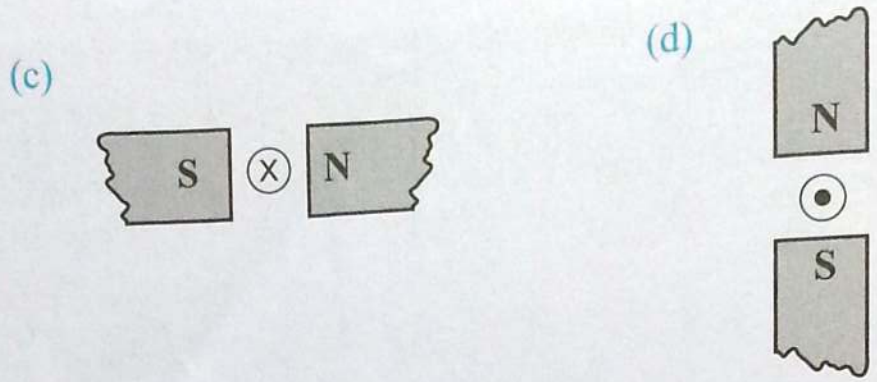


Fig. 8.19: Conductors inside magnetic fields

2. Give four ways in which the force on a wire placed in a magnetic field can be increased.

3. Complete Fig. 8.19 (a) and (b) by indicating the shape and direction of the field around a current carrying conductor.

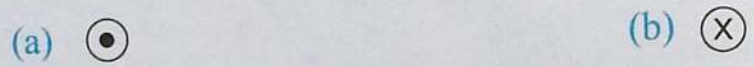


Fig. 8.19: Straight current carrying conductors

4. Magnetic materials are classified into hard and soft materials.
   (a) What is the difference between the two types.
   (b) Give one example of each.

5. State two ways of increasing the strength of an electro magnet.

Project: Construction of:

1. An electromagnet

Suggested materials:

An iron nail or bolt about 6-7 cm long; about 100 cm insulated copper wire (S.W.G 26-28) or any suitable gauge wire to withstand a current of 1-2 A, sellotape, cutting pliers or razor blade, power supply (2-3 dry cells), switch, variable resistor (0-20 Ω), Ammeter (0-2 A), few iron nails (or thumb tacks or paper clips or staple pins), connecting wires.

Assembly

- Wind a layer of the insulated wire on the nail (or bolt), making sure to leave about 10 cm of wire sticking out where the winding started. Wind several layers

of turns, making sure that the windings are in the same direction. At the end leave about 10 cm of wire sticking out. At the end of the nail, stick sellotape so that the turns of wire do not unwind themselves.

- Remove the insulation from the two free ends of wire. You have now made your electromagnet.
- Connect your electromagnet in series with the power supply, switch, ammeter and the variable resistor (Fig. 8.20).

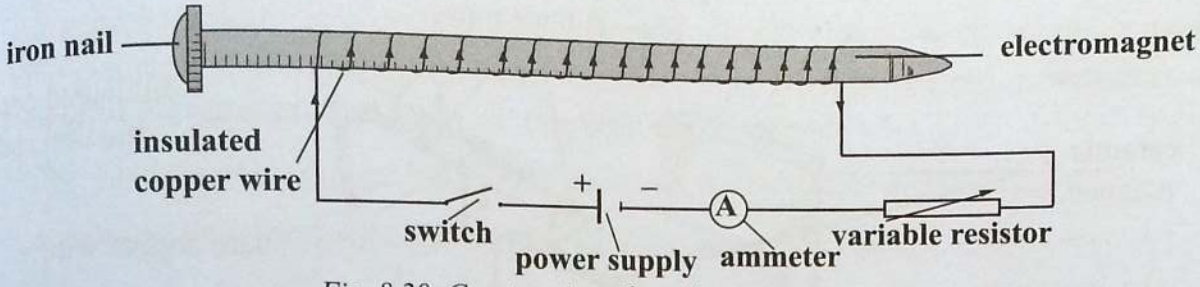


Fig. 8.20: Construction of an electromagnet.

- Close the switch and adjust the variable resistor to pass a suitable current through the coil wound on the nail (bolt), i.e. your electromagnet.
- Keep some iron nails or staple pins closer to the base of the nail and observe what happens. Open the circuit and see the effect.
- Pass more current and see the effect you have made on the electromagnet.

2. 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.8.20) 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. 8.21).
- 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.

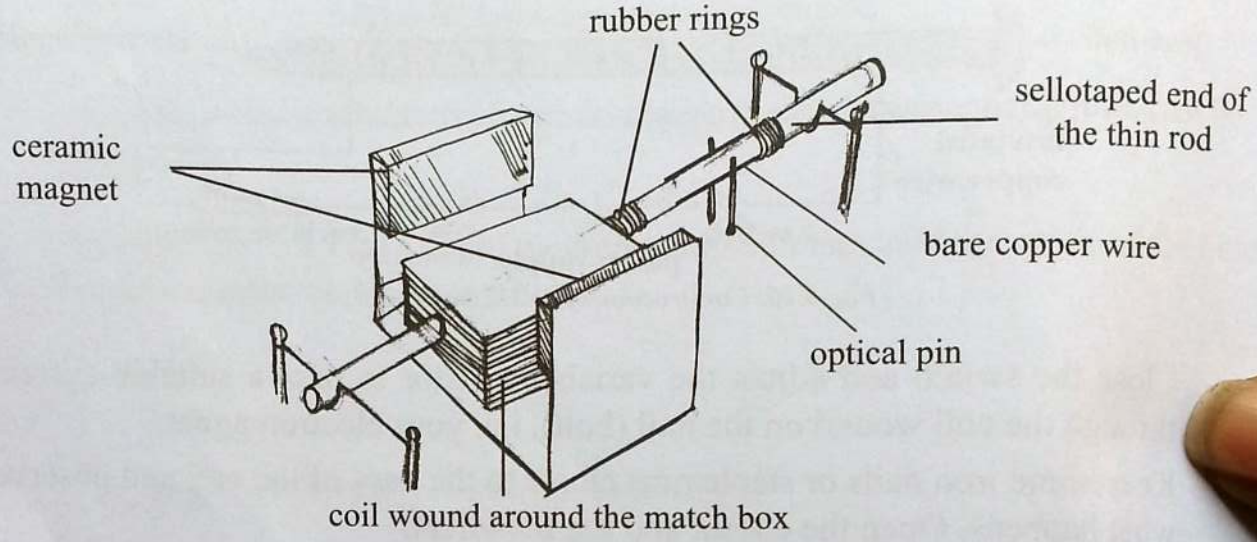


Fig. 8.21: Construction of an electric motor.

Unit 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.

Unit Test 8

1. Draw the magnetic field pattern due to two isolated straight conductors carrying a current as shown in Fig. 8.22(a) and (b).

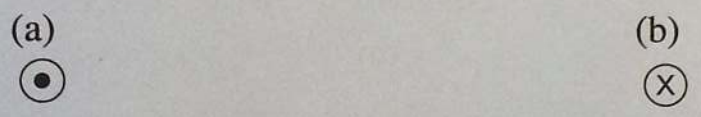


Fig. 8.22: Straight current carrying wire

2. Fig. 8.23 below shows a current-carrying conductor passing between two cardboards. Show the direction of the deflection of each compass on the cardboard.

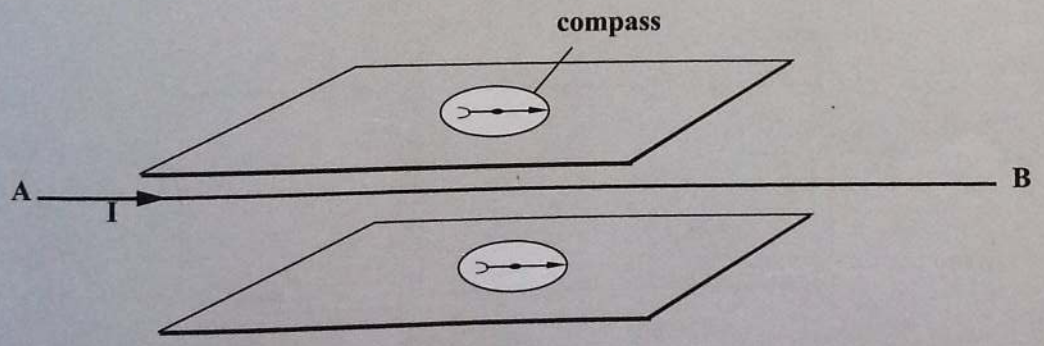


Fig. 8.23.

3. Magnetic field lines have the properties that they experience lateral repulsion and longitudinal tension. This means that rather than cross each other magnetic field lines will either repel each other or reinforce each other creating areas of strong magnetic field and very weak field (neutral points).

Use this information and any other information to draw the magnetic field pattern in Fig. 8.24(a), (b) and (c).

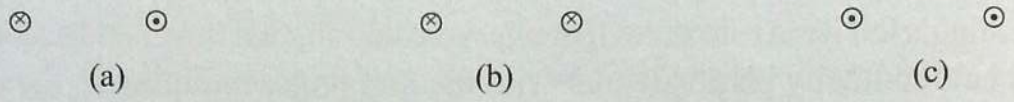


Fig. 8.24.

(a) Two current-carrying conductors close to each other and carrying equal currents in different directions.

(b) Two current-carrying conductors close to each other and carrying equal currents in the same (into the paper) direction.

(c) Two current-carrying conductors close to each other and carrying their currents in the same (out of paper) direction.

4. The three diagrams of Fig. 8.25 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.

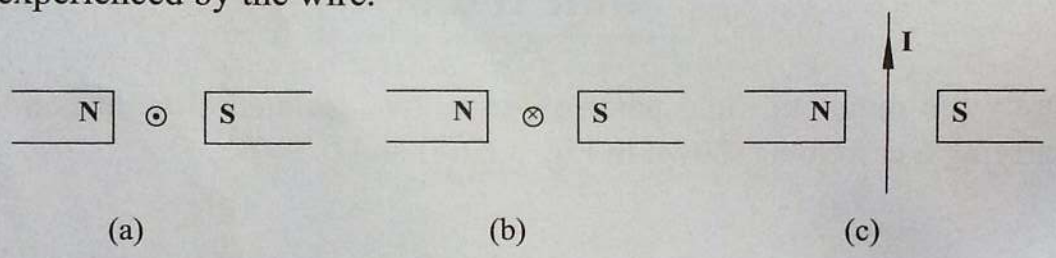


Fig. 8.25.

5. Mercury is a good conductor of electricity. Fig. 8.26 shows a wire freely pivoted at point P and just touching the mercury in the bowl. Study the diagram and answer the questions that follows.

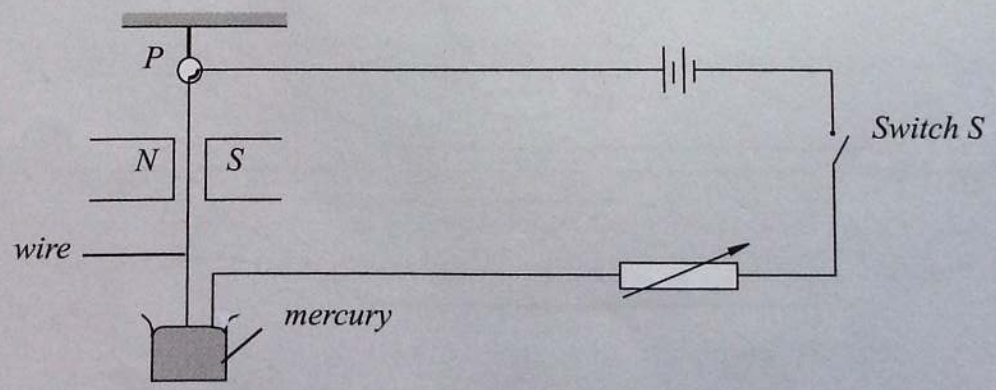


Fig. 8.26.

(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?

6. (a) With the aid of a diagram describe how an electromagnet works.

(b) Describe an experiment to show how you would investigate the variation of the lifting strength of the electromagnet and the current in the electromagnet indicating clearly the measurements you would make.

(c) State three applications of an electromagnet.

7. 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.

8. With the aid of a diagram describe and explain the working of a simple electric bell. Show how you would connect the bell so that it can be rung from two different points.

9. 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?

10. Fig. 8.27 represents a simple electric motor. Study the diagram then answer the questions that follow.

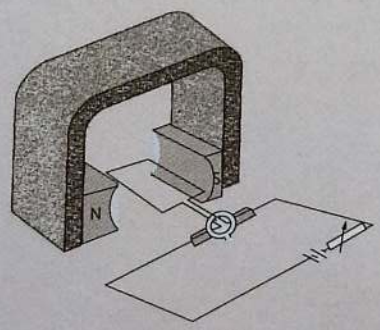


Fig. 8.27.

(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. 8.28 below. Copy the diagram and draw the magnetic field pattern between the two poles of the magnet.

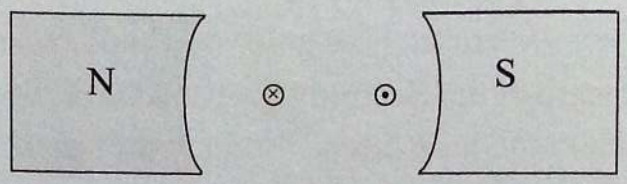


Fig. 8.28

UNIT 9

Electromagnetic Induction

Success Criteria

By the end of this unit, you must be able to:

- Describe electromagnetic induction.
- Explain 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 electric current can be generated. This method of generating electricity is called *electromagnetic induction*. In this unit, we will discuss this concept and apply it in making some devices.

9.1 Demonstration of electromagnetic induction

The following experiments will help us to understand electromagnetic induction.

Experiment 9.1: To induce an electromotive force in a conductor (wire)

Apparatus

- U-shaped magnet
- galvanometer,
- copper wire

Procedure

1. Connect a copper wire XY to a sensitive centre zero galvanometer. (Fig. 9.1)

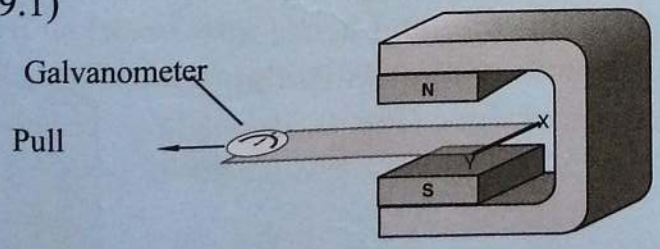


Fig. 9.1: A conductor in between the poles of a U-shaped magnet

2. Place the wire in between the poles of a magnet as shown in Fig. 9.1 and observe the galvanometer reading.

3. Quickly pull the wire horizontally away from the poles and stop.
4. Quickly re-introduce the wire in between the poles of the magnet and stop.
5. Repeat the experiment, keeping the wire stationary and moving the magnet.
6. Repeat the experiment by first moving the wire vertically up and down and then repeat by moving the magnet.

What happens to the galvanometer pointer in each case?

Observation

When the wire XY is stationary, the pointer does not move. When the wire is moved out, the pointer shows a deflection in one side (Fig. 9.2 (a)), but returns to the zero position once the wire stops (Fig. 9.2 (b)).

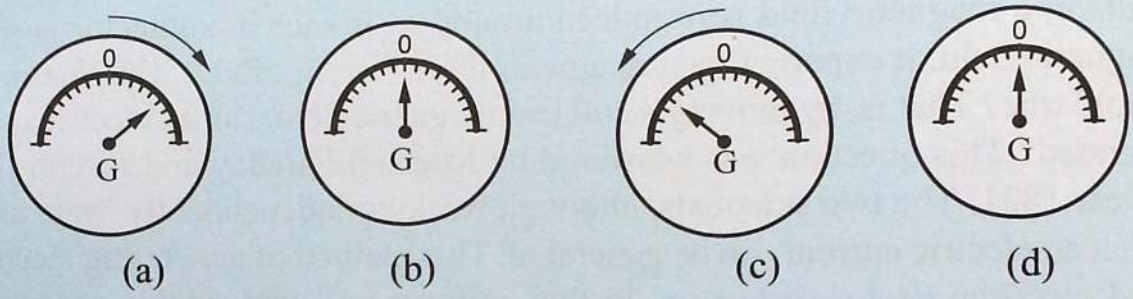


Fig. 9.2: Deflection on a glavanometer

When the wire is re-introduced in between the poles, the pointer deflects but in the opposite direction (Fig. 9.2 (c)). However, when the wire stops, the pointer once again returns to the zero position (Fig. 9.2 (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.

Conclusion

For a current to flow in a circuit, there must be a driving force called *electromotive force (e.m.f.)*. From this experiment, we can conclude that whenever there is relative motion between a wire and a magnet, an electromotive force is induced in the wire and hence a current flows in the circuit. This motion is such that the wire 'cuts' the magnetic field lines of force (Fig. 9.3).

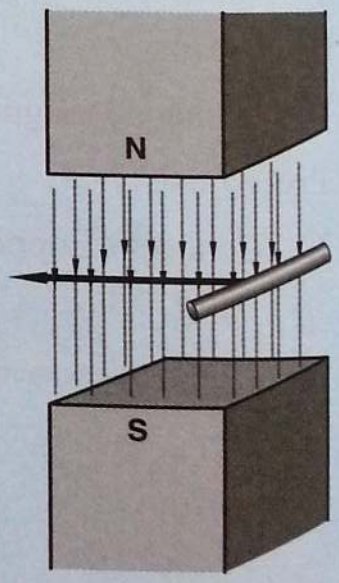


Fig. 9.3: A conductor cutting magnetic field lines of force

Experiment 9.2 To induce an electromotive force in a coil using a magnet

Apparatus:

- Insulated copper wire
- Bar magnet
- Galvanometer
- Connecting wires

Procedure:

1. Make a coil using the insulated copper wire.
2. Connect the ends of the coil to a sensitive centre zero galvanometer.
3. Quickly introduce a bar magnet into the coil and stop (Fig. 9.4).

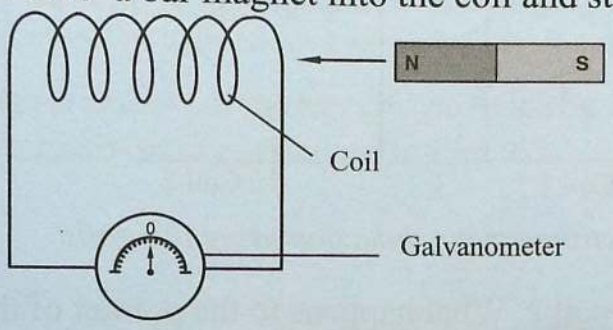


Fig. 9.4: Moving a magnet into a coil

4. Withdraw the magnet quickly from the coil and stop.
5. Repeat the experiment by moving the coil and keeping the magnet stationary. Observe 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. What happens to the pointer of the galvanometer?

Observation

- 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.

Conclusion

From this experiment, 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.

Experiment 9.3 To induce an electromotive force in a coil using another coil

Apparatus:

- Insulated copper wire
- Connecting wires
- Galvanometer
- Source of current

Procedure:

1. Make two coils using the insulated copper wire. Connect the coils as shown in Fig. 9.5. Keep the coils close together.

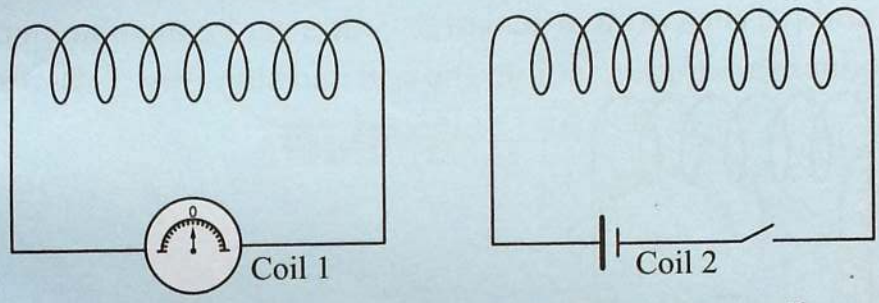


Fig. 9.5: Electromagnetic induction using two coils

2. Close the switch in coil 2. What happens to the pointer of the galvanometer?
3. Open the switch. Observe what happens to the galvanometer pointer.

Observation

When the switch is closed, the pointer of the galvamometer momentarilly deflects to one side but returns to the zero position when the switch is left closed. When the switch is opened, the pointer momentarilly deflects but in the opposite direction. However, when the switch is left open, the pointer once again returns to the zero position.

Conclusion

From this experiment, we can conclude that an e.m.f is induced in coil 1 the moment the switch in coil 2 is closed or opened.

Explaining electromagnetic induction

Electromagnetic induction is as a result of one of those actions at a distance effects. 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 when there is a change in the number of magnetic field lines linking (passing through) it or when the conductor 'cuts' the field lines.

Consider a coil moving away from a magnet as shown in Fig. 9.6.

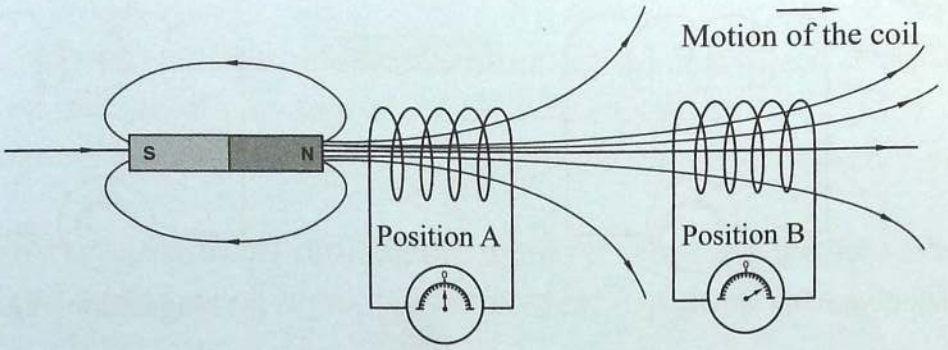


Fig. 9.6: Electromagnetic induction using two coils

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. 9.7.

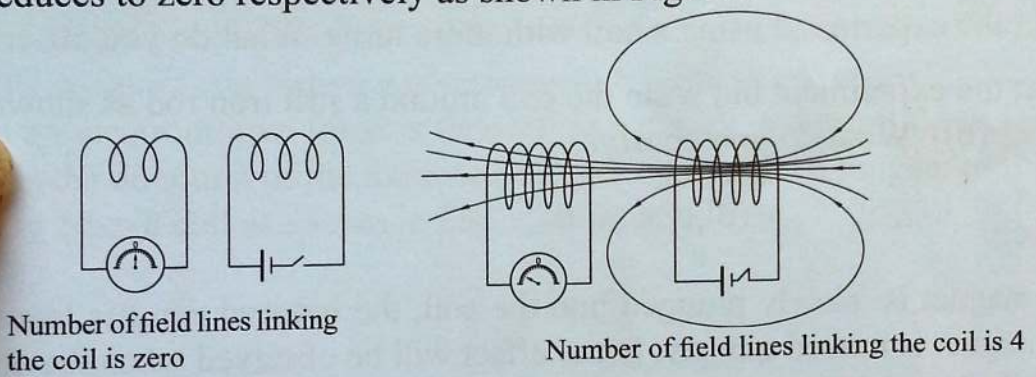


Fig. 9.7: Building the magnetic field

9.2 Factors affecting the magnitude of the induced electromotive force

The magnitude of the induced electromotive force depends on a number of factors. The following experiments will help us to investigate what the magnitude of the induced e.m.f depends on.

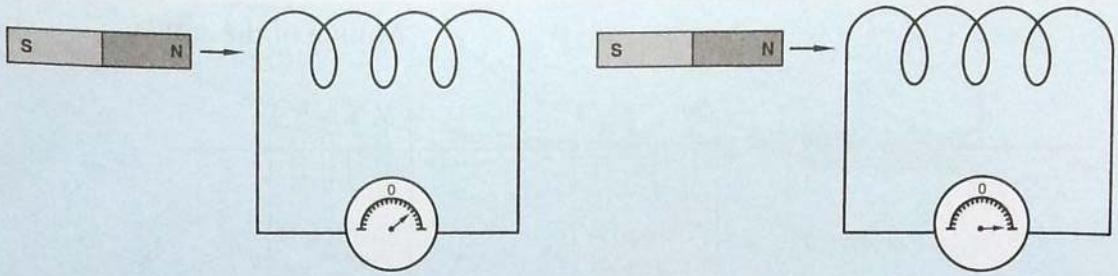
Experiment 9.4: To investigate the magnitude of the induced e.m.f.

Apparatus:

- Insulated copper wire
- Galvanometer
- Bar magnet
- Connecting wires.

Procedure:

1. Make a coil of a few turns using the insulated copper wire. Connect the circuit as shown in Fig. 9.8.



(a) Magnet moving slowly (b) Magnet moving fast

Fig. 9.8: Moving a magnet into a coil at different speed

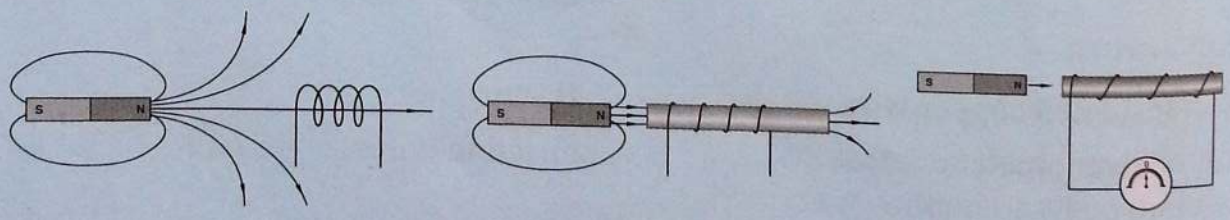
2. Slowly plunge the magnet into the coil.
3. Repeat the experiment by quickly plunging the magnet into the coil. Note what happens to the pointer of the galvanometer.
4. Repeat the experiment but use a stronger magnet e.g. ceramic magnets. What do you observe?
5. Repeat the experiment using a coil with more turns. What do you observe?
6. Repeat the experiment but wind the coil around a soft iron rod as shown on (Fig. 9.9(b)). What do you observe.

Observation

When the magnet is slowly plunged into the coil, the induced e.m.f 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.

Discussion

When a stronger magnet is used the induced electromotive force increases. When a coil with more turns is used the induced e.m.f is found to increase.
The induced electromotive force is found to increase when a soft iron core is used. Fig. 9.9 (b) shows one line of force linking the coils while in (c) 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. 9.9: Inducing an e.m.f using a coil wound on a soft iron core

Conclusion

We can conclude that, the magnitude of the induced e.m.f is directly proportional to:

- *the rate of change of the magnetic flux linked to the coil.*
- *the strength of magnetic field i.e the stronger the magnet the higher the induced e.m.f.*
- *the number of turns in the coil* i.e. *the more turns the higher the induced e.m.f.*
- *the induced emf is much higher in the presence of a soft iron cover.*

9.3 Laws of electromagnetic induction

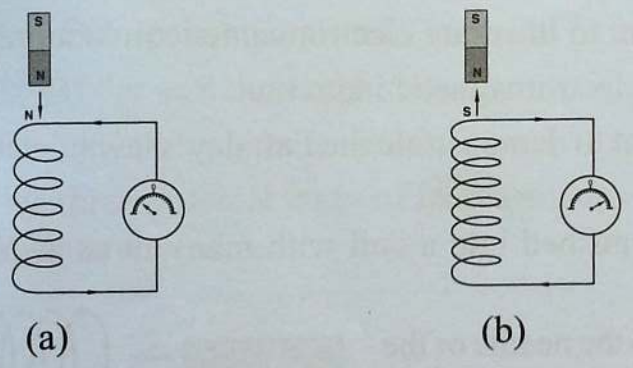
Faraday's law of electromagnetic induction

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 of change of the magnetic flux linked to the conductor.*

The direction of the induced electromotive force (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. 9.10 (a) and (b).



(a) (b)

Fig. 9.10: 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.*

Fleming's right hand rule

In case of straight conductors moving in a magnetic field, Fleming's left 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 **F**irst finger points in the direction of the **F**ield and the thu**M**b in the direction of **M**otion of the conductor, then the se**C**ond finger points in the direction of the induced **C**urrent* as shown on Fig. 9.11.

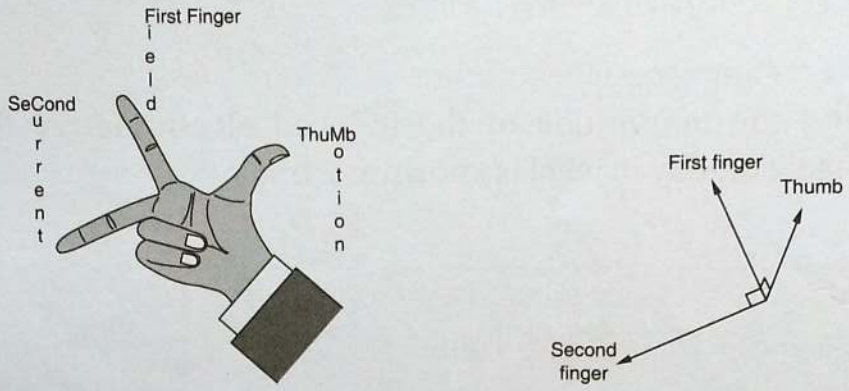


Fig. 9.11: Fleming's right hand rule

Exercise 9.1

1. Describe an experiment to illustrate electromagnetic induction.
2. State the two laws of electromagnetic induction.
3. Describe an experiment to demonstrate the Faraday's law of electromagnetic induction.
4. A long bar magnet is pushed into a coil with many turns as shown in Fig. 9.12.
   - (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.

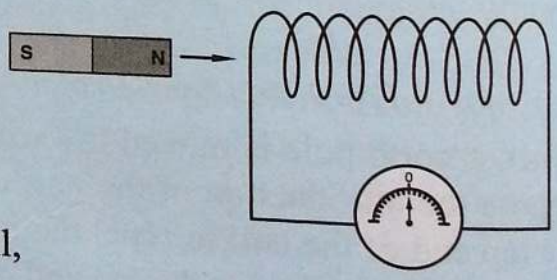


Fig.9.12

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. 9.13.

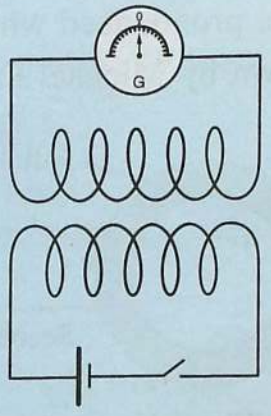


Fig. 9.13

   (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.

9.4 Mutual induction

In Experiment 9.3, we 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. 9.14 (a). Fig. 9.14 (b) shows how the induced current varies with time.

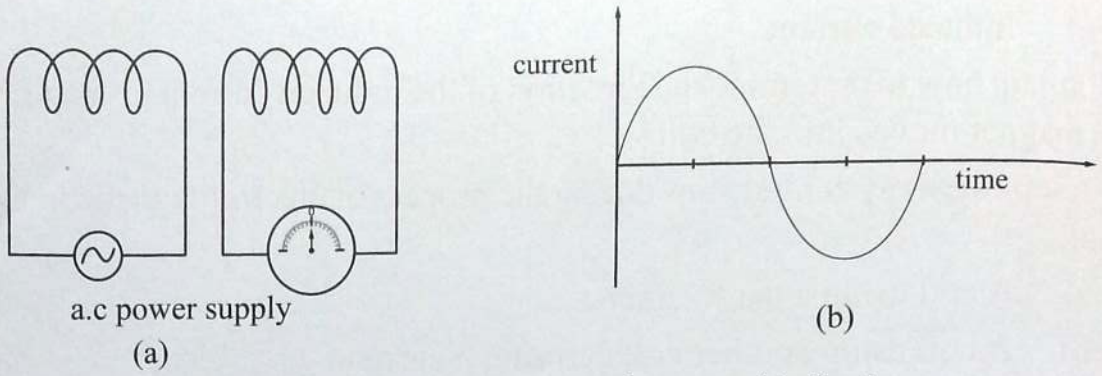


Fig. 9.14: Inducing a current by mutual induction

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. 9.15.

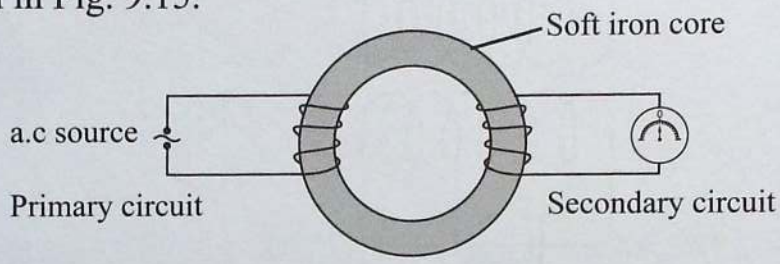


Fig. 9.15: Faraday's ring

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 coin in a way that this current tend 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. 9.16 (a). Thus, the change in the number of magnetic field lines threading the secondary circuit induces an electromotive force in the secondary circuit in an opposite direction in accordance with Lenz's law as shown on Fig. 9.16 (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. 9.16 (b)). The induced electromotive force in the secondary circuit has the same frequency as the electromotive force in the primary circuit.

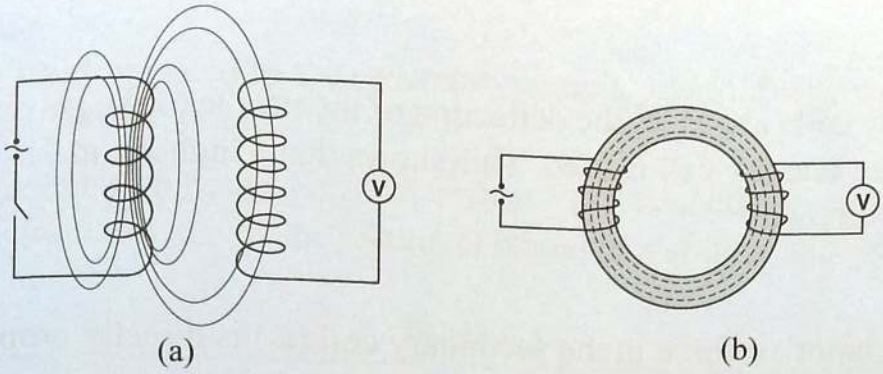


Fig. 9.16: Effects of soft iron core on the number of field lines threading the secondary coil

Factors affecting the magnitude of the induced electromotive force in the secondary circuit

Experiment 9.5: To investigate how the electromotive force of the primary circuit affects the electromotive force of the secondary circuit

Apparatus:

- Insulated copper wire
- 2 coils of wire
- three dry cells
- soft iron rod
- galvanometer

Procedure

1. Make two coils of 4 turns each using an insulated copper wire.
2. Connect the dry cell and the switch to the ends of one coil called the *primary coil*. To the ends of the other coil, i. e the *secondary coil*, connect the sensitive centre-zero galvanometer.
3. Introduce the soft iron rod inside the two coils as shown on Fig. 9.17.

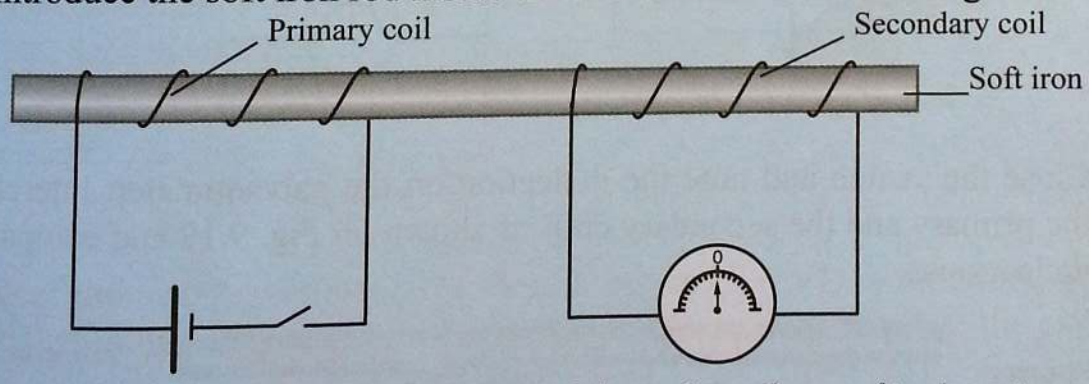


Fig. 9.17: Induced e.m.f in the secondary coil depends on the e.m.f in the primary coil

4. Close the switch and note the deflection of the needle of the galvanometer.
5. Repeat the experiment but use three dry cells instead of one. Compare the deflections.

Observation

When three dry cells are used, the deflection of the needle of the galvanometer is more than when one dry cell is used. This shows that a higher e.m.f is induced in the secondary circuit.

Conclusion

Induced electromotive force in the secondary coil (ε_s) is directly proportional to the electromotive force in the primary coil (ε_p)

i.e $\varepsilon_s \propto \varepsilon_p$

Experiment 9.6: To investigate the effect of the number of turns in primary and secondary circuit on induced electromotive force.

Apparatus:

- A long soft iron rod
- galvanometer
- a dry cell
- two coils
- one with more turns than the other

Procedure:

1. Set the apparatus as in Experiment 9.5 but use 8 turns of secondary coil as shown in Fig. 9.18.

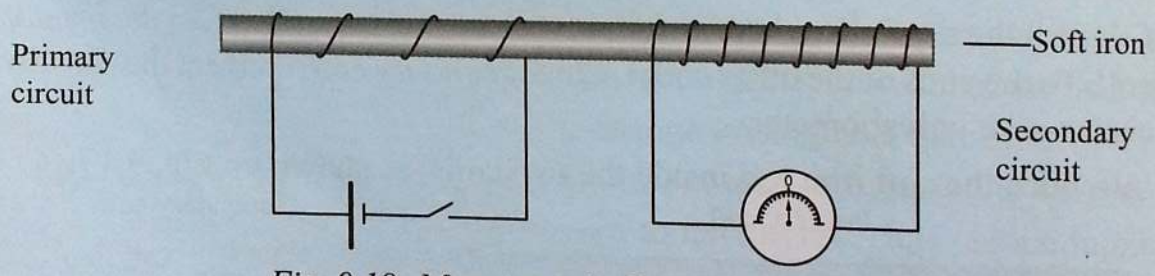


Fig. 9.18: More turns in the secondary circuit

2. Close the switch and note the deflection on the galvanometer. Interchange the primary and the secondary coils as shown on Fig. 9.19 and compare the deflections.

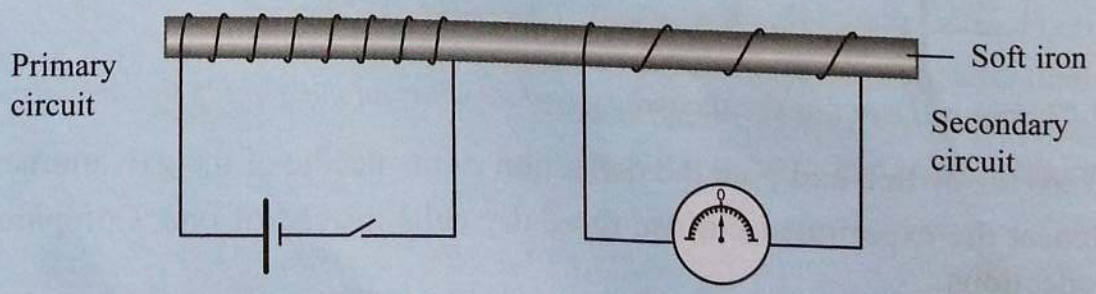


Fig. 9.19: Less turns on the secondary circuit

Observations

When more turns are used in the secondary circuit, a higher electromotive force is induced in the secondary circuit.

Alter the number of turns in both the primary and secondary coils and repeat the experiment. Table 9.1 shows the results obtained in a similar experiment.

Table 9.1

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	Smallest
1.5	10	10	1.0	High
1.5	10	20	2.0	Higher
1.5	10	30	3.0	Highest

Conclusion

From this experiment, we can conclude that the magnitude of the induced electromotive force in the secondary circuit depends on the ratio of the number of turns of coils used.

$$\text{Electromotive force induced in the secondary circuit } (\varepsilon_s) \propto \frac{\text{Number of turns in secondary coil, } N_S}{\text{Number of turns in primary coil, } N_p}$$

$$\text{i.e } \varepsilon_s \propto \frac{N_s}{N_p}$$

When the experiment is done using an a.c power supply, it can be shown that

$$\frac{\text{Secondary e.m.f, } V_s}{\text{Primary e.m.f, } V_p} = \frac{\text{Number of turns in secondary coil, } N_S}{\text{Number of turns in primary coil, } N_p}$$

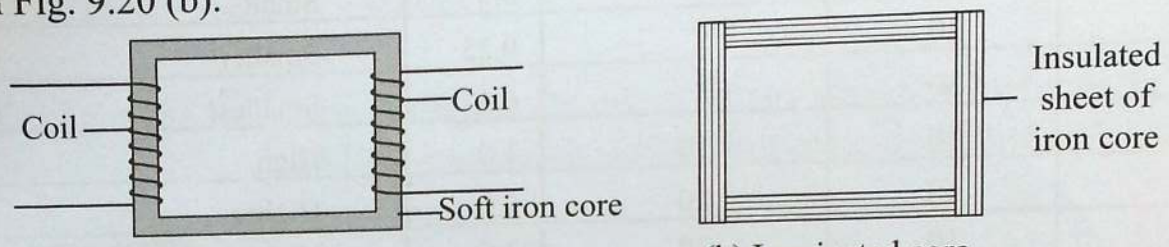
$$\frac{V_s}{V_p} = \frac{N_s}{N_p}$$

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, $\frac{I_s}{I_p} = \frac{N_p}{N_s}$

It should be 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.

9.5 Transformers

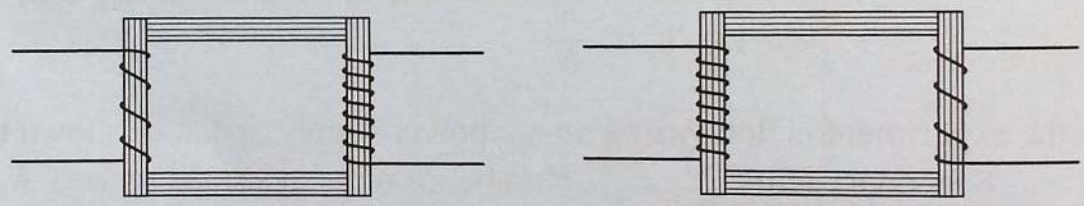
A transformer is an electrical device that transfers electrical energy from one circuit to another by electromagnetic induction. In transferring this energy, a transformer changes voltage or electromotive force to a higher or lower value. A transformer consists of two coils. One of the coils is called *the primary coil* and the other, *secondary coil*. These two coils are not connected to one another in any way but are wound on the same soft iron core as shown in Fig. 9.20 (a). When in operation, the ends of the primary coils are connected to a power supply and the ends of the secondary coils are connected to a load e.g. a resistor, bulb etc. The soft iron core consists of insulated sheets of iron bundled or riveted together. In this way, the core is said to be *laminated* as shown in Fig. 9.20 (b).



(a) A simple transformer (b) Laminated core

Fig. 9.20: Transformer

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. 9.21 (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. 9.21 (b)). Fig. 9.21 (c) shows a commercial step-down transformer.



(a) Step-up transformer (b) Step-down transformer

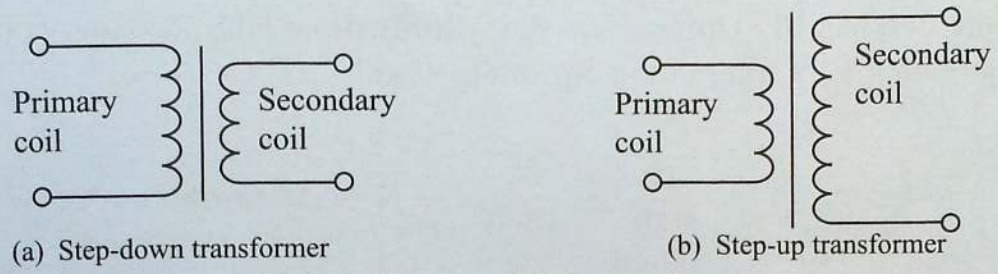
(c) A commercial step-down transformer

Fig. 9.21: 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.

and $\frac{I_s}{I_p} = \frac{N_p}{N_s}$ to ideal transformer only (asumed to have no power loss).

As seen in Experiment 9.6, the equation, $\frac{V_s}{V_p} = \frac{N_s}{N_p}$ also applies to all transformers.



(a) Step-down transformer (b) Step-up transformer

Fig. 9.22: Circuit symbols for transformers

Fig. 9.22 shows the circuit symbols for the set down and set up of transformers. A transformer may have more than one secondary coil. Fig. 9.23 shows a transformer with two coils in the secondary circuit. Such transformers can step-up and step-down voltages simultaneously.

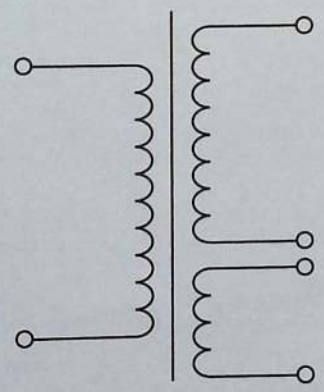


Fig. 9.23: A transformer with two coils in the secondary circuit

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.

$$\text{Efficiency} = \frac{\text{power output}}{\text{power input}} \times 100\%$$

Well designed practical transformers often have efficiency as high as 98%.

For an ideal transformer power output = power input (efficiency 100%)

power input $= V_p I_p$; power output $= V_s I_s$

$$V_p I_p = V_s I_s;$$

$$\therefore \frac{V_s}{V_p} = \frac{I_p}{I_s}$$

Example 9.1

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 9.2

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) $\frac{\text{Power output}}{\text{Power input}} \times 100\% = \text{efficiency}$

$$\frac{I_s \times V_s}{960} \times 100\% = \text{efficiency}$$

$$\frac{0.2 \times 4\,800}{960} \times 100\% = 100\%$$

(b) This is an ideal transformer.

Example 9.3

A transformer has an input coil of 60 turns. When this coil connected to a 240V source, the output voltage is found to be 4800V. The output power is 3 600W.

(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) $N_p = 60$ $V_p = 240v$ and $V_s = 4800$ V, $N_s = ?$

$$\frac{V_s}{V_p} = \frac{N_s}{N_p} \Rightarrow \frac{4800}{240} = \frac{N_s}{60} \qquad N_s = \frac{4800 \times 60}{240}$$

$$= 1\ 200 \text{ turns}$$

(b) **(i)** $P_o = V_s I_s$

$$3\ 600 = 4\ 800\ I_s \Rightarrow I_s = \frac{3\ 600}{4\ 800} = 0.75\ A$$

ii) $$\text{Efficiency(E)} = \frac{P_i}{P_0} \times 100\% = \frac{V_s I_s}{V_P I_P} \times 100\%$$

$$80 = \frac{4800 \times 0.75}{240 \times I_p} \times 100\%$$

$$= \frac{360\ 000}{240 I_p} \times 100\%$$

$$Ip = \frac{360\ 000}{240 \times 80} = 18.75\ A$$

Example 9.4

An ideal transformer is used to operate a 16V, 48W 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?

Solution

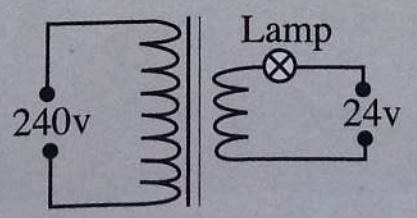


Fig. 9.24 Voltmeter connection to be corrected

(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.

$$I_s = \frac{V_o}{V} = \frac{48W}{16V} = 3A$$

For an ideal transformer, $\frac{N_s}{N_p} = \frac{I_p}{I_s} \Rightarrow \frac{30}{240} = \frac{I_p}{I_s}$. Hence $I_p = \frac{30 \times 3A}{450}$

$$= 0.2A$$

Factors affecting the efficiency of a transformer

The energy supplied in the primary circuit of a transformer is lost in a number of ways. The following factors contribute to the overall efficiency of a transformer.

(a) Resistance of the coils

As the current flows in the coils, the wires heat up and energy is lost in form of heat.

$$\text{Energy} = I^2 \times R$$

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.

(b) 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.

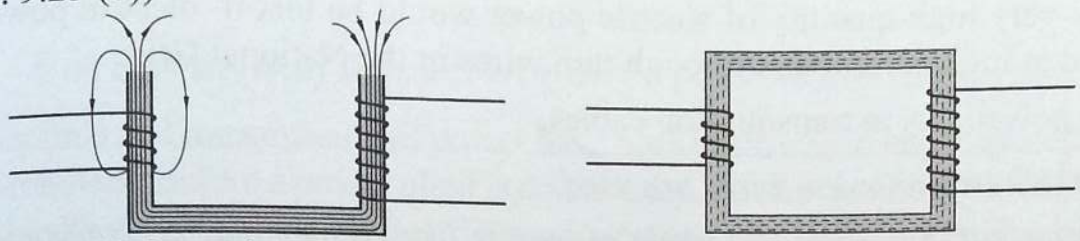
(c) Hysteresis losses

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.

(d) 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. 9.25 (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. 9.25 (b)).



(a) Incomplete core (b) Complete core (loop)

Fig. 9.25: 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.

9.6 Electric Power transmission

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 the *pylons*. Fig. 9.26 shows pylons and cables carrying electricity from a generating station to the consumers.

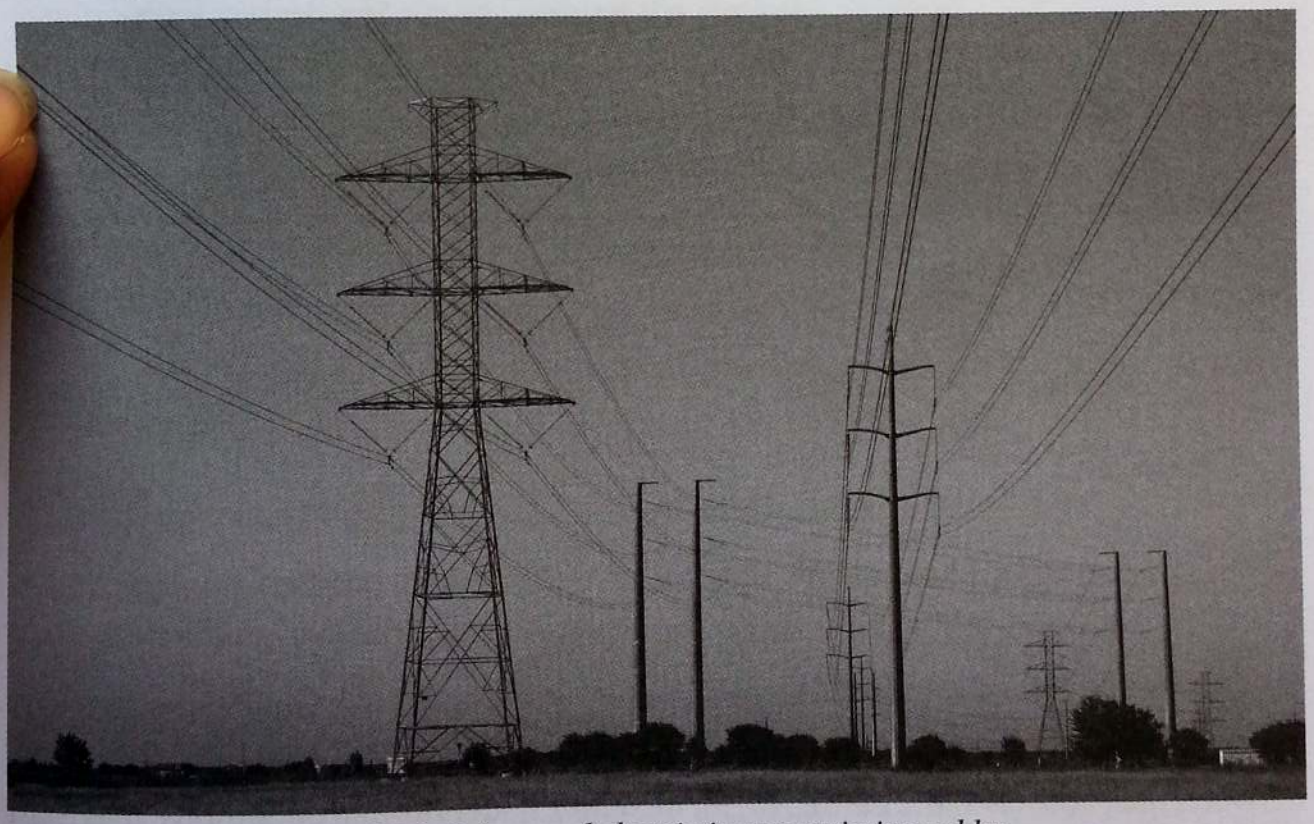


Fig. 9.26: Pylons and electrictity transmission cables

Due to the electrical resistance (R) of the transmitting cables, some electric power

(Given by $P = I^2R$) is lost in form heat in the transmission cables.

Remember, the electrical resistance of a a wire (conductor) is directly proportinal to its length and inversely proportianal to its cross section area (A) i.e. ($R \alpha \rho \frac{l}{A}$). 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,

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.*

For example, if the electric 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 tranformer* 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. 9.27 shows a section of a typical National Grid System from the power generating station to the factories, towns and villages.

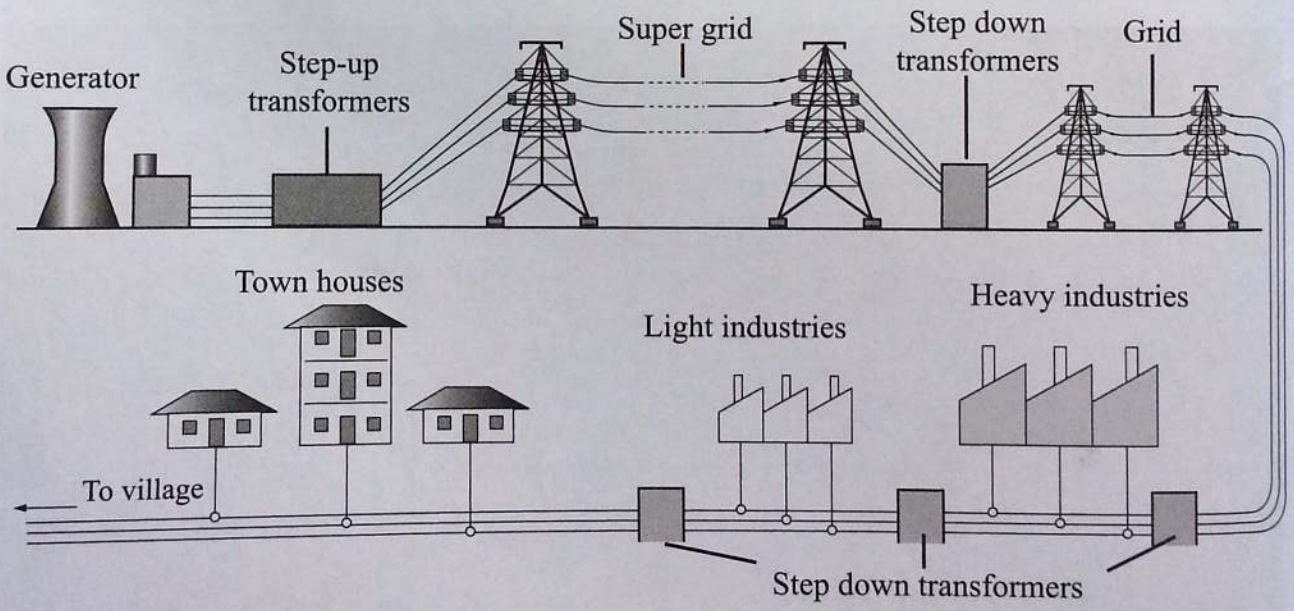


Fig.9.27: The National Grid System

Dangers of the high voltage transmission

Due to the high voltages in the transmission cables, a strong electric field is set up 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

9.7 Environmental impact of power generation and transmission

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. The main causes of *environmental pollution* is the use of *fossil fuels, nuclear* etc. In this section, we shall discuss some of environmental impacts of power generating and transmission.

Power is generated through sources like hydroelectric, nuclear reactions, fossil fuels, solar, geothermal energy and biomass.

Hydroelectric power

Hydroelectric power is the type of power generated from gravitational potential energy of water stored in reservior. This method of power generation is cheaper, has low operating costs, and less extensive compared to other methods of generating electricity like electricity from fossil fuels or nuclear energy. However, there are several negative impact of hydroelectric power generating system to both the environment and people staying around the station.

The negative impacts are:

- Dislocation of people living around 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.

⚠ Malaria is a killer disease. It is can be prevented by keeping mosquitoes away.

While planning to build a dam, for hydroelectric power, one has to make sure that there are minimal negative impacts to the environment.

Nuclear energy (power)

Nuclear energy is commonly used in developed countries. Nuclear power plant produces very high energy. Because of this, the plant requires a lot of water to cool. However, just like hydroelectric power generating plant, it posses environmental problems.

The following are some of the negative impacts of the nuclear power generating:

- Nuclear power plant may reject heat to water bodies e.g. sea. This causes an undesirable increase of the water temperature which affects aquatic life.
- Emission of radioactivity to the environment which posses health problems to people around it.
- Accidental nuclear explosions in nuclear power plants destroy properties and kill many lives. An example is the nuclear explosion of the Japan Fukushim plant on March 11th 2011 that killed over 1000 people.
- Nuclear bombs are used by terrorosts and extremists groups to kill innocent people.

While setting up a nuclear power plant, there are international set standards that are to be observed to minimize these negative environmental impacts.

> Warning!
> Nuclear wastes should be handled by experts and with protective clothing.

Fossil fuels

Another main way of generating electricity today is by burning fossil fuels to producing steam which is then used to drive a steam turbines to produce power in electric generator.

The negative impact of fossil fuels is the emissions of gases like carbon monoxide (CO) and carbon dioxide (CO_2). When carbon dioxide is emitted into the atmosphere, it can cause green house effect and lead to global warming.

Burning of some fossil fuels lead to production and release of gases like sulphur dioxide and nitrogen oxide that contribute to smog and acid rain. They can destroy Ozone layer hence exposing us to dangerous emmissions from the sun, eg ultra-violet rays which can damage our skins.

Biomass

It is important to note that electrical power can be generated by burning anything that can combust. Some electrical power is generated by burning crops which are grown specifically for the purpose.

Burning biomass also produces same emissions as burning fossil fuels. Biomass captures carbon dioxide out of the air so that the net contribution to global atmospheric carbon dioxide levels lowers.

9.8 Other applications of electromagnetic induction

(a) 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. 9.28).

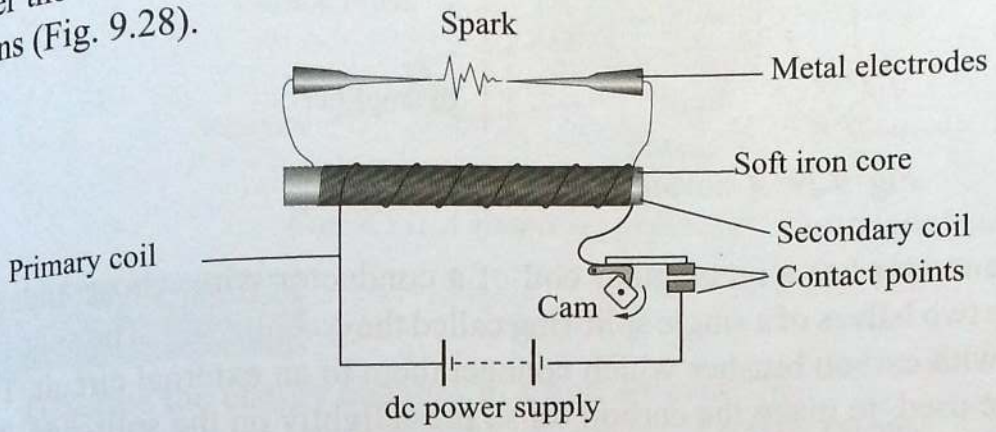


Fig. 9.28: Induction coil

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.

(b) 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. 9.29.

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.

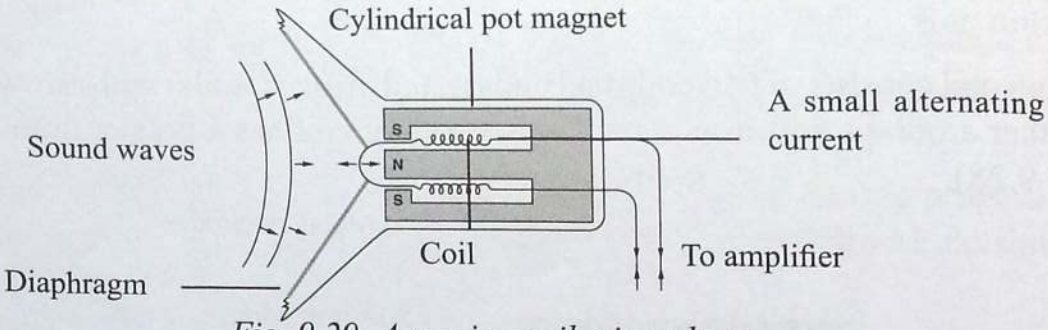


Fig. 9.29: A moving coil microphone

(c) A simple d.c generator

A simple d.c generator has a rectangular coil of a conductor wire whose ends are connected to the two halves of a single split-ring called the *commutator*. The split-ring makes 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 split-ring. 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 to the coil as shown on Fig. 9.30.

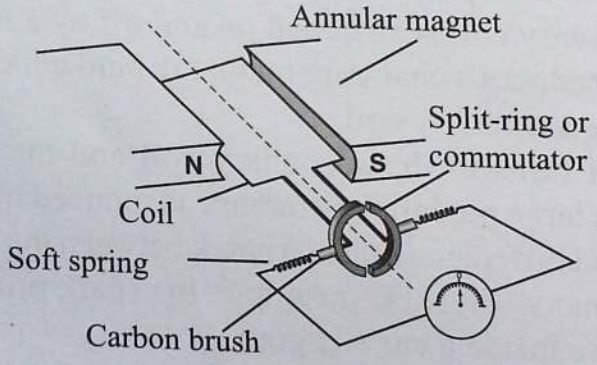


Fig. 9.30: A simple d.c generator

When the coil is rotated about its axis by energy from burning fuel, it 'cuts' across the magnetic field of the permanent magnet, causing current to be induced. This induced current causes a deflection on the galvanometer.

When the coil passes through the vertical position, the two halves of the split-ring change from one brush to another. This change over between the brushes and the two halves split-ring helps to maintain the flow of the current in the same direction

(d) A simple ac generator

This is a modification of the d.c. type. In an a.c generator, the split-rings are replaced by two slip rings, thus the direction of the current in the coil changes after every half rotation. This is because each carbon brushes remain on the same ring when the coil is rotating without interchanging positions as shown in Fig 9.31.

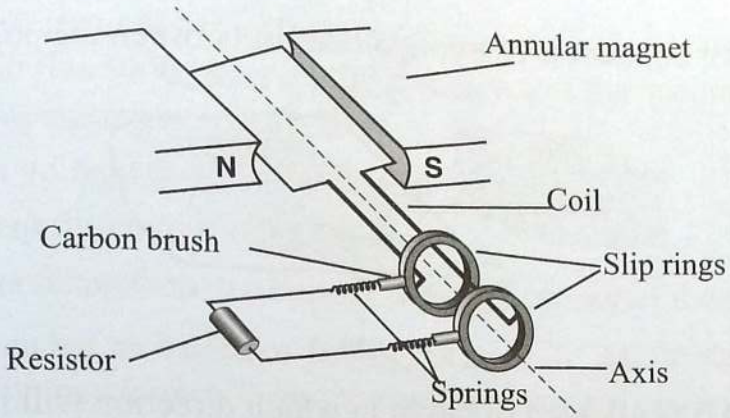


Fig. 9.31: A simple ac generator

Exercise 9.2

1. Describe the energy changes in a transformer.
2. Give two factors that affect the efficiency of a transformer.
3. Fig. 9.32 shows a transformer with 400 turns in the primary coil and 1000 turns in the secondary coil.
   (a) What type of transformer is it?
   (b) Find the potential difference across BC.
   (c) What assumption(s) have you made?

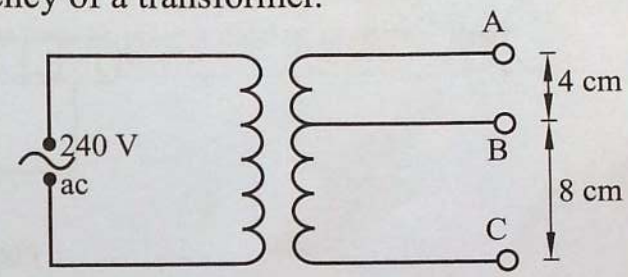


Fig. 9.32

4. A transformer is used to operate a 9 V ac shaving machine (Fig. 9.33).

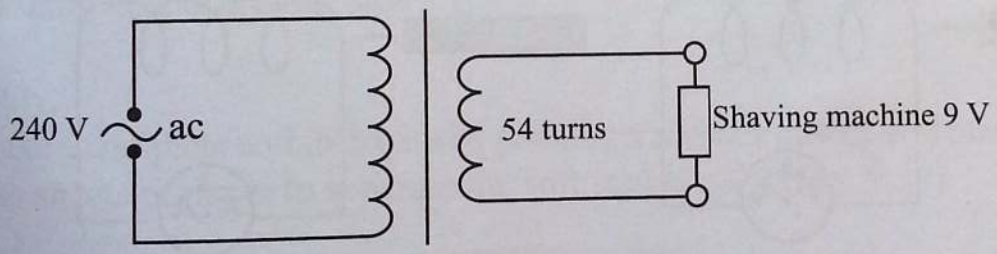


Fig. 9.33

   (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) Why is the soft iron core made of insulated thin sheets of iron instead of being in one piece?
   (d) Explain what would happen to the transformer if a 240 V dc power supply is used instead of 240 V mains.
   (e) What happens to the primary current when the machine is being used?

5. Fig. 9.34 shows a conductor carrying a current between the poles of a magnet.

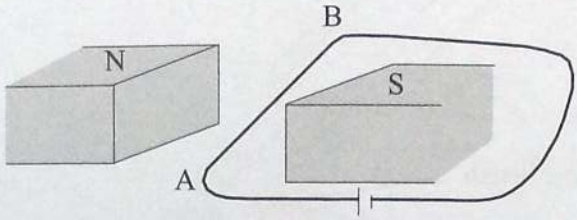


Fig. 9.34

(a) If the wire AB is allowed to move in which direction will it move?
(b) What is the effect of:
  (i) reversing the current?
  (ii) reversing the magnetic field?
  (iii) reversing the field and current at the same time?

6. Fig. 9.35 shows a solenoid with a current flowing through it.

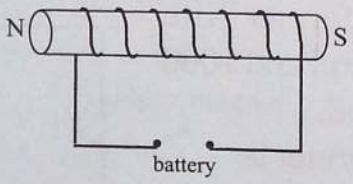
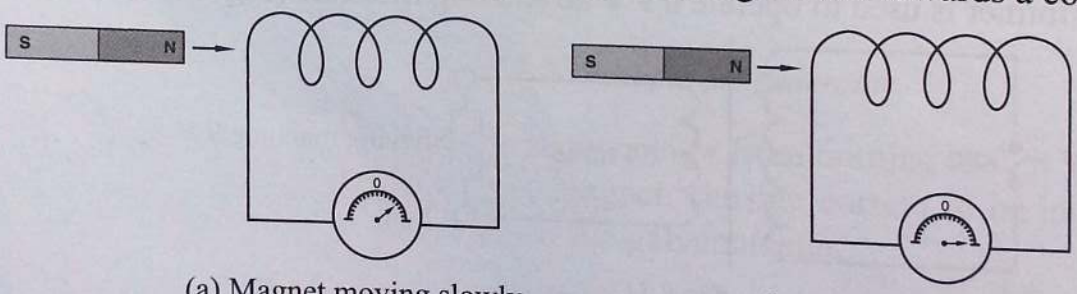


Fig. 9.35

Determine:
(a) The direction flow of the current in the solenoid.
(b) The polarity of the battery.

7. Look at figure 9.36 illustrating a magnet being moved towards a coil



(a) Magnet moving slowly (b) Magnet moving fast

Fig. 9.36: Moving a magnet into a coil at different speed

(a) As the current is induced in the coil, what type of pole is formed at the left end of the coil? Give a reason for your answer.
(b) In which direction does the conventional current flow through the meter?

8. A step-down transformer has a primary coil with 800 turns and secondary coil with100 turns. The primary coil is connected to 240V supply.
(a) Find the voltage output.
(b) If the transformer has a primary current of 0.10A and of secondary 0.72 A, calculate its efficiency.

9. The secondary circuit of a transformer is connected a bulb rated at 12V 40W. 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%.
10. 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 = 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.
11. State three ways power loss in electricity transmission cables is minimised.

Project work:

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. 9.37).

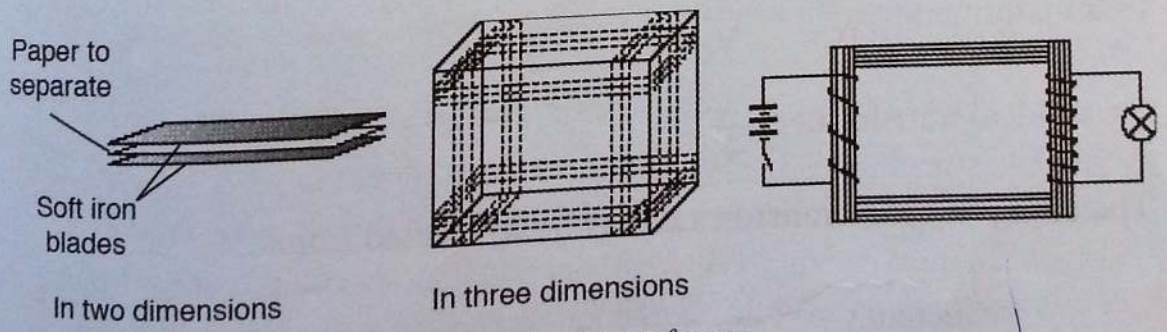


Fig. 9.37: A simple transformer

- Use the masking tape to hold the bundles of soft iron blades together (Fig. 9.34). 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 on and off the circuit rapidly and note what happens to the bulb. *The bulb lights on switching on and goes off when the current is steady. It also lights momentarily when the current is switched off.*

Unit summary

- If a conductor cuts magnetic field lines, an electromotive force is produced. 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 dc generator.
- In both the d.c and a.c generators, the induced electromotive force is maximum when the coil is moving a direction perpendicular to the direction of the field. It is zero when moving parallel to the direction of teh field.
- Mutual induction is the process of producing an electromotive force in the secondary coil from a primary coil.
- 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 a transformer may be calculated from:

$$\text{Efficiency} = \frac{\text{Power output}}{\text{Power input}} \times 100\%$$

- Induction coil and moving coil loudspeaker work on the principle of electromagnetic induction.

Unit Test 9

1. What do you understand by the term 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. 9.40 shows a trolley carrying a magnet moving at a high speed towards the coil. The trolley enters and passes through the coil. (Fig. 9.38).

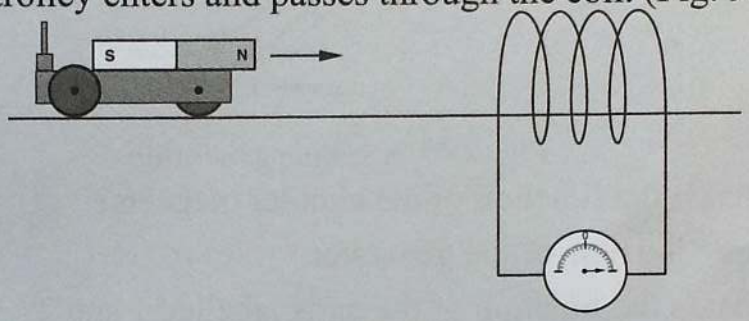


Fig. 9.38

   - **(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. 9.39. 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.

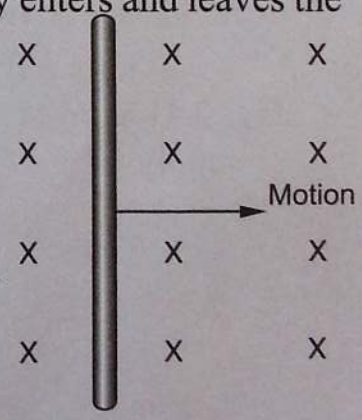


Fig. 9.39

6. (a) Explain the working of a simple d.c generator.

(b) What changes would you make in the d.c generator in order to:

(i) convert it to a simple ac generator?

(ii) produce a larger electromotive force?

7. (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.

8. Fig. 9.40 shows a simple generator.

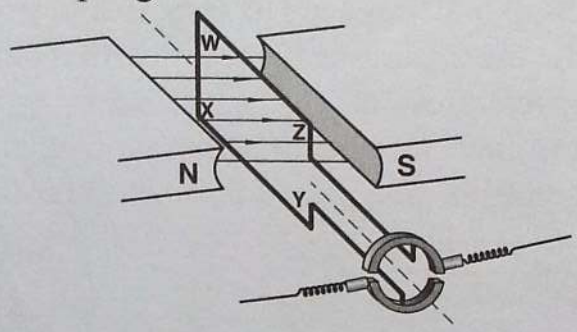


Fig. 9.40: A simple generator

(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.

9. 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.

10. Fig. 9.41 shows a transformer with 1 200 turns in primary circuit to a 240 V ac supply.

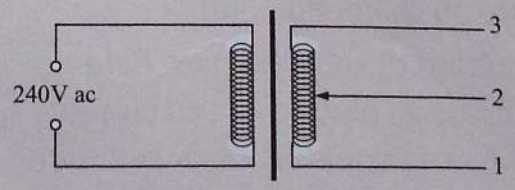


Fig. 9.41

When a 6Ω resistor is connected between terminal 1 and 2, a current of 0.3A flows through the resistor. When a resistor of 12Ω is connected between terminal 2 and 3, a current of 0.6 A flows through the resistor. Assuming the transformer to be 100% efficient, find

(a) Potential difference across 1 and 2.

(b) Potential difference across 2 and 3.

(c) Number of turns between 2 and 3.

(d) The current which would flow in the 6Ω resistor when connected across 1 and 3.

11. Explain two negative impact of generating and transmission of electric power.

UNIT

10 Introduction to Digital Electronics

Success Criteria

By the end of this unit, you must be able to:

(a) Discuss semiconductor devices.

(b) Discuss electronic components and their use.

(c) Describe analogue and digital circuits.

(d) Describe the operation of basic logic gates.

Introduction

Electronics is a branch of Science that is concerned with the development of tiny electrical circuits designed to process, store or transmit information. Concepts learnt in electronics are applied in the design of modern communication devices like televisions, calculators, radios, computers, burglar alarms, (CD) players, digital watches, Automatic Tellers Machines (cash dispenser), mobile phones, etc.

In this unit, we shall learn the basic principles of simple electronic circuits and components like diodes, transistors and their application.

10.1 Conductors, semiconductors and insulators

Materials can be grouped according to their electrical conductivity properties. Materials that allow an electric current to pass through them easily are called *good conductors* e.g. copper, zinc, silver, mercury, etc. Those materials that do not allow the electric current to flow through them at all are known as *insulators* e.g. paper, wood, plastics, etc. *Semiconductors* are those materials whose electrical conductivity lies between that of good conductors and insulators. Such materials include silicon and germanium.

The electrical conductivity of materials may be explained by studying how electrons are held or locked up in the crystal lattice. Many theories have been proposed to explain the electrical behaviour of materials. One such theory is the *band theory*.

Band theory

In this theory, materials are considered to contain two bands in which electrons may be found. These bands are the *valency band* and *conduction band* (Fig. 10.1).

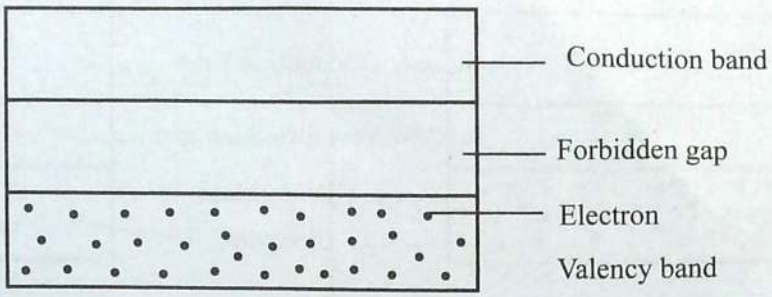


Fig. 10.1: Conduction and valency bands

The two bands are separated by a gap called *forbidden gap* (no electrons are allowed in this gap). For a material to conduct an electric current, electrons should be in conduction band. However, electrons prefer to be in the valency band as this is the lowest energy level. To move the electrons to the conduction band, energy is needed to cross through the forbidden gap. One way of providing the energy to cross the gap is to increase the temperature of the material.

Explanation of electrical conduction in conductors

In conductors, the valency and conduction bands overlap and hence no energy is needed to overcome the forbidden gap (Fig. 10.2).

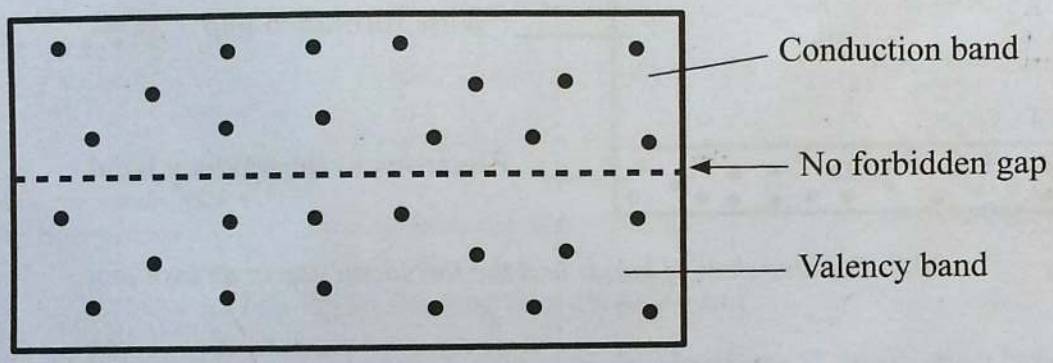
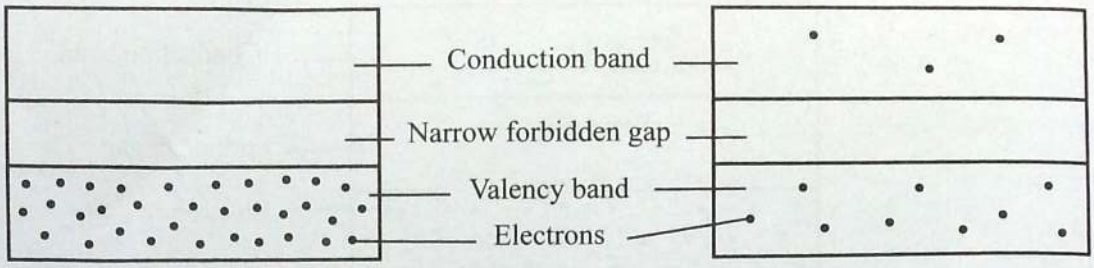


Fig. 10.2: Overlapping of bands in conductors

All the electrons are free and mobile to conduct electric current. If conductors are heated, the internal energy increases and the electrons move in all directions colliding with each other. This explains why metals become poor conductors as temperature increases.

Explanation of electrical conduction in semiconductors

In semiconductors, the forbidden gap is bigger than in conductors (Fig. 10.3). At low temperatures, all the electrons are in the valency band. However, at room temperature some electrons gain thermal energy and cross the forbidden gap to the conduction band. The material then becomes a fair conductor. As the temperature is increased, more electrons move to the conduction band and hence its electrical conductivity is increased. This shows that the resistance of semiconductors decreases with increase in temperature.



(a) At low temperatures electrons are in the valency band

(b) At high temperatures some electrons move to the conduction band

Fig. 10.3.

Explanation of poor electrical conduction in insulators

In insulators, the forbidden gap is so wide (Fig. 10.4) that any attempt, say by heating, to promote the electrons to the conduction band ends up breaking down the material. For example, if the material is paper, it burns off.

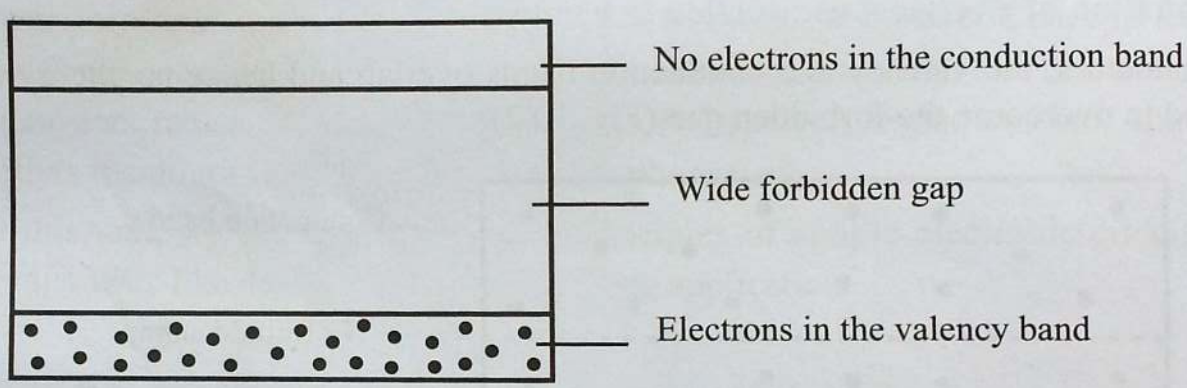


Fig. 10.4: Relative sizes of bands and the forbidden gap in an insulator

10.2 Intrinsic and Extrinsic semi-conductors

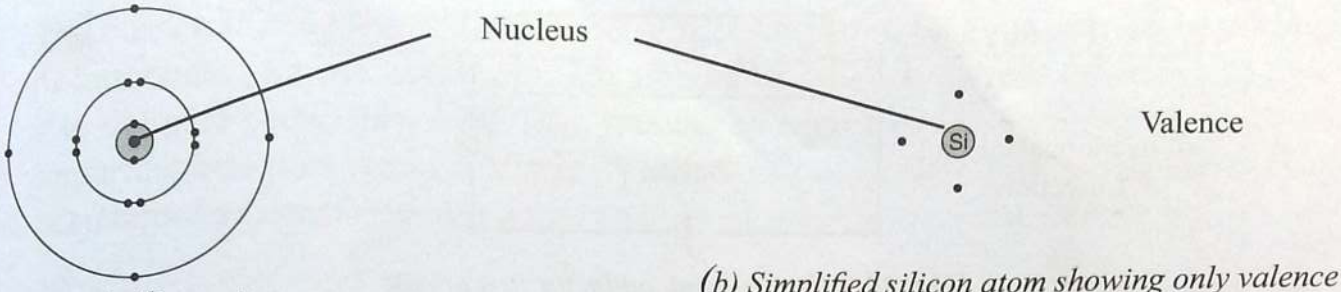
We have already learnt that semi-conductors are those materials whose electrical conductivity lies between those of good conductors and poor conductors. There are two types of semi-conductors:

(a) Instrinsic semi conductors.

(b) Extrinsic semi conductors.

(a) Intrinsic semiconductors

We have seen that a semiconductor can behave as a conductor or an insulator depending on its temperature. Silicon and germanium are the most commonly used semiconductors in electronic equipment. Fig. 10.5 (a) shows the electronic configuration of a silicon atom. It has four electrons in the outermost shell (also called energy level). These electrons are called *bonding or valence electrons* (Fig. 10.5 (b)).

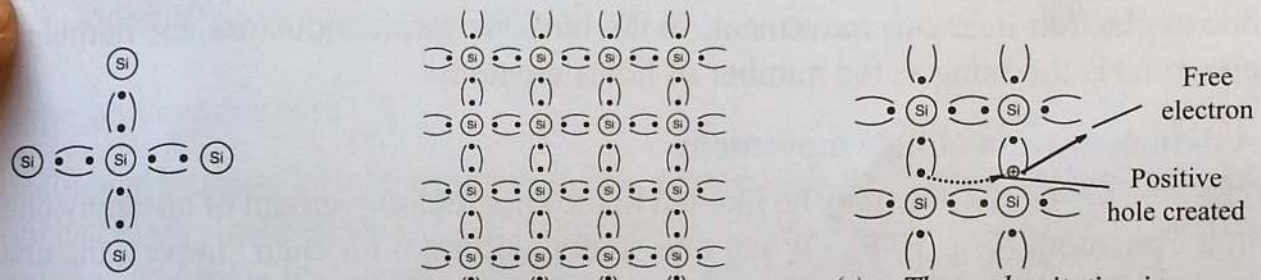


(a) A silicon atom election configuration: 2.8.4

(b) Simplified silicon atom showing only valence electrons

Fig. 10.5: Electronic configuration of a silicon atom

Fig. 10.6 (a) shows a silicon atom bonded with 4 other silicon atoms through covalent bonds. If the bonding is extended in all directions, the silicon lattice structure is formed (Fig. 10.6 (b)).



(a) Silicon atom bonded with 4 other silicon atoms

(b) Crystal lattice of pure silicon

(c) Thermal agitation in a pure semiconductor

Fig. 10.6: Bonding in a silicon crystal

At low temperatures, all the electrons are locked up in the covalent bonds i.e. they are in the valency band. At higher temperatures the electrons may gain thermal energy and move to the conduction band, in so doing, the bond is broken. These free electrons roam within the lattice and are thus available for conduction. These electrons are called *thermal electrons*. A free electron will leave a positive vacancy in the atom it came from. This vacancy is called *a hole* (see Fig. 10.6(c)) above. The atom becomes a positive ion and can attract an electron from the neighbouring atom. When this process is repeated from one atom to another, *a positive hole seems to drift in the lattice*. If the semiconductor is connected in a circuit containing a battery and a milliammeter, a small current is observed to flow (Fig. 10.7).

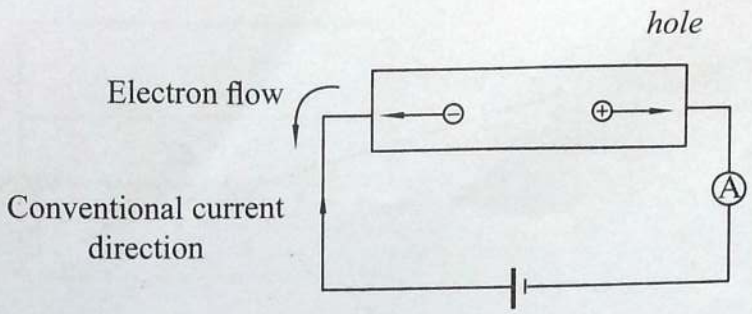


Fig. 10.7: A pure semiconductor in a circuit

Two types of charge seem to contribute to the conduction of the current i.e. the negative charge or electrons and the positive charge or holes. The electrons in the conduction band flow in one direction while the holes in the valence band flow in the opposite direction.

A material which increases its electrical conductivity from within itself (internally) is called *pure* or *intrinsic semiconductor*. Silicon and Germinium are examples of intrinsic semiconductors. Electrical conductivity in intrinsic semiconductors is mainly due to electron-hole pair movement. In the intrinsic semiconductors, the number of electrons is the same as the number of holes created.

A demonstration of hole movement

The *movement* of a hole may be likened to the apparent movement of an empty chair in a classroom (Fig. 10.8). When one student sitting on a chair moves, the chair is left empty (Fig. 10.8 (a)). The student behind can fill in the vacancy created and by so doing creates another vacancy (Fig. 10.8 (b)). This process is repeated until the last student moves (Fig. 10.8 (d)). In this anology, the movement of the student represent the movement of electrons while the movement of the empty chair (vacancy) corresponds to the movement of holes.

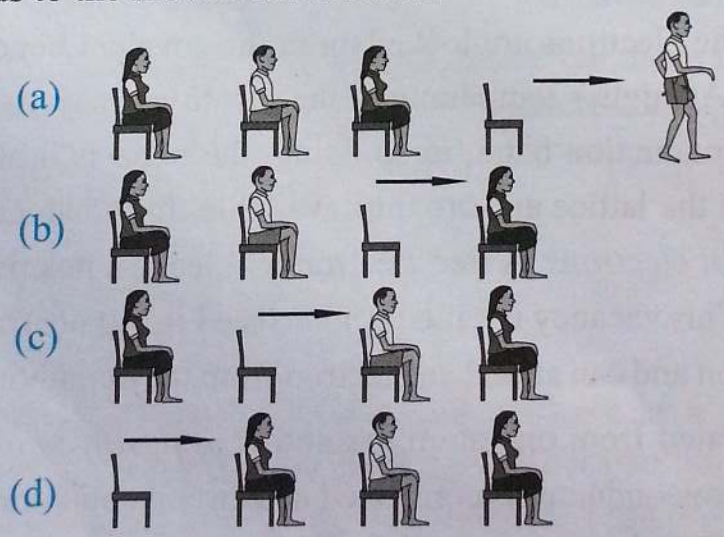


Fig. 10.8: Hole movement

(b) Extrinsic semiconductors

The electrical conductivity of a pure semiconductor may be increased by adding or introducing a small and controlled amount of other materials (called *impurities)* into the pure semiconductors. This process of introducing very small amounts of impurities into pure semiconductors is called *doping*. A pure semiconductor that has been doped externally is called an *extrinsic semiconductor* (Fig. 10.9).

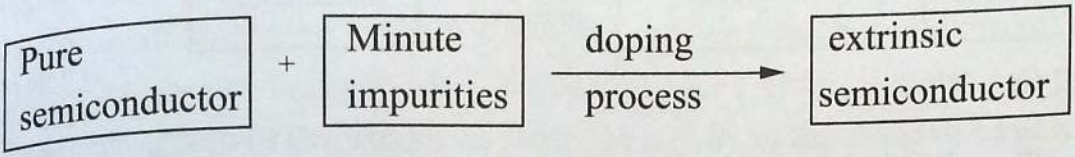


Fig. 10.9: Doping process

The impurities used in the doping process are elements whose atoms have either *three* valence electrons or *five valence electrons*. Examples of elements with *trivalent* atoms include *boron, aluminium, gallium and indium*. Examples of elements with *pentavalent* atoms include *phosphorous, arsenic, antimony* and *bismuth*.

10.3 Doping in semiconductors

n-type semiconductors

Consider an intrinsic silicon semiconductor, doped with arsenic atoms. Each silicon atom has four valence electrons and therefore each atom has four neighbouring atoms bonded to it. Atoms of arsenic will fit into this structure, but they have five valence electrons of which four participate in bonding with neighbouring atoms. The fifth electron is left free to roam within the lattice (Fig. 10.10). This electron is available for conduction. In this case, arsenic is said to be a *donor impurity*. The resulting semiconductor has more electrons and is referred to as the *n-type* semiconductor (n-for negative). In this semiconductor, the *majority charge* carriers are the *electrons*.

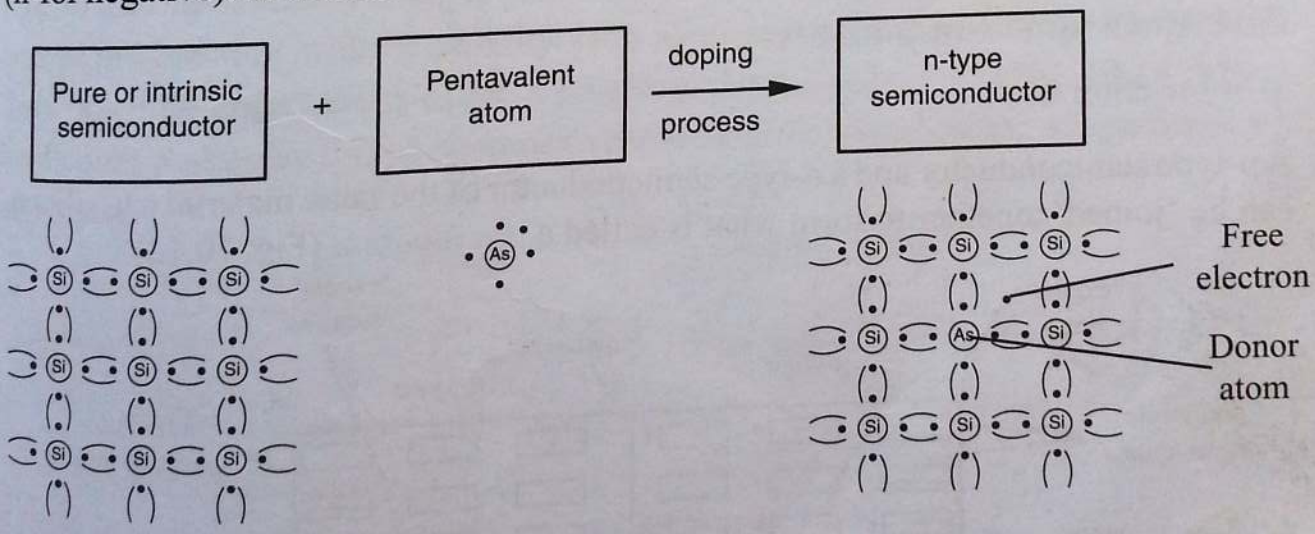


Fig. 10.10: Formation of n-type semiconductor

P-type semiconductors

Consider a crystal of silicon doped with a small amount of trivalent atoms e.g. boron. Boron has three valence electrons which participate in the bonding . This leaves a vacancy in the fourth bond called hole. This vacancy forms what is known as a hole in the fourth bond (Fig. 10.11).

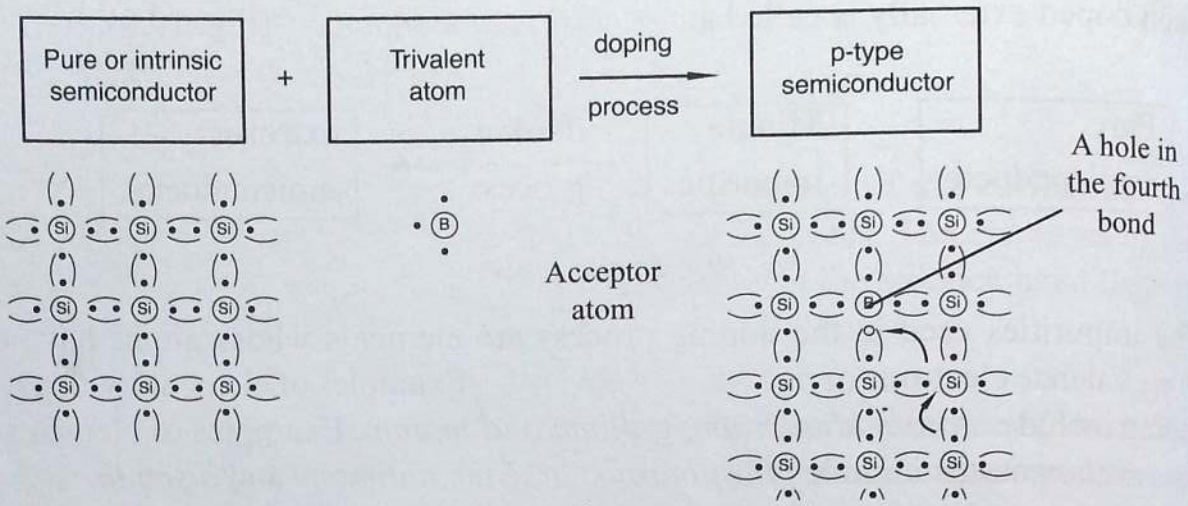


Fig. 10.11: Formation of p-type semiconductor

When a bond is incomplete, it is possible for an electron in the neighbouring silicon atom to leave its electron-bond to fill the hole. The electron moving from the bond to fill a hole leaves a hole in its initial position. Hence, the hole effectively moves in the direction opposite to that of the electron. The hole, in its new position, may again be filled by an electron from another electron-pair bond making the hole move one more step in the direction opposite to the motion of the electron. *We get here a mechanism for the conduction of electricity, that does not involve the free electrons.* The atoms that introduce holes in the pure semiconductors are called *acceptor atoms*. The resulting semiconductor has positive hole as charge carriers and is referred to as the *p-type semiconductor* (p – for positive). In this type of semiconductor, the *majority charge* carriers are the *holes*.

10.4 Electronic components

p-n junction diode

A p-type semiconductor and a n-type semiconductor of the same material e.g. silicon, can be 'joined' together to form what is called a *p-n junction* (Fig. 10.12).

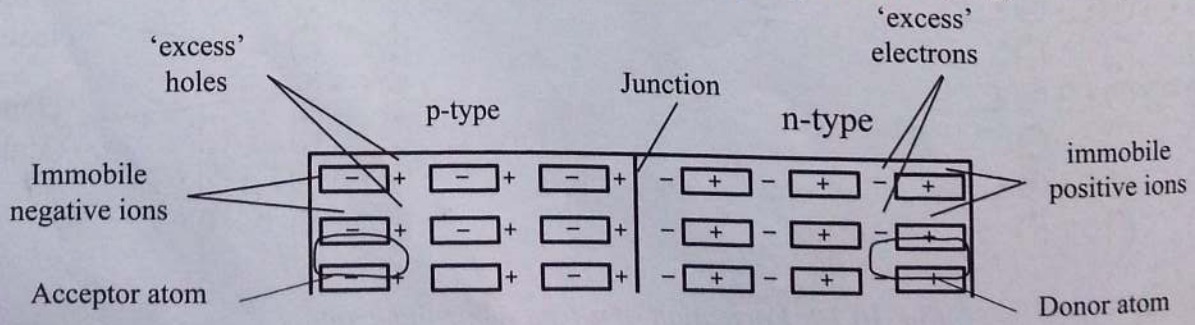


Fig. 10.12: p-n junction

As soon as this junction is formed, a charge movement begins only in the immediate vicinity of the junction until an equilibrium is reached. The charge movement can be likened to the diffusion of gases.

P-type and n-type regions are both electrically neutral. Charge movement results to holes combining with electrons thereby producing a net positive charge to the n-type region and leaving a net negative charge in the p-type region (Fig. 10.13). The net positive charge in the n-type prevents any further movement of the holes from the p-type to n-type. Also the net negative charge in the p-type stops any further movement of the electrons from the n-type to the p-type. A region is created which has lost all its free electrons and holes. This region is called *the depletion layer* (Fig. 10.14 (a)).

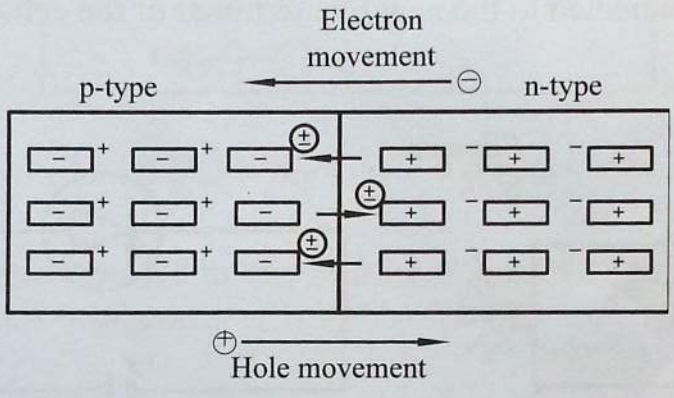
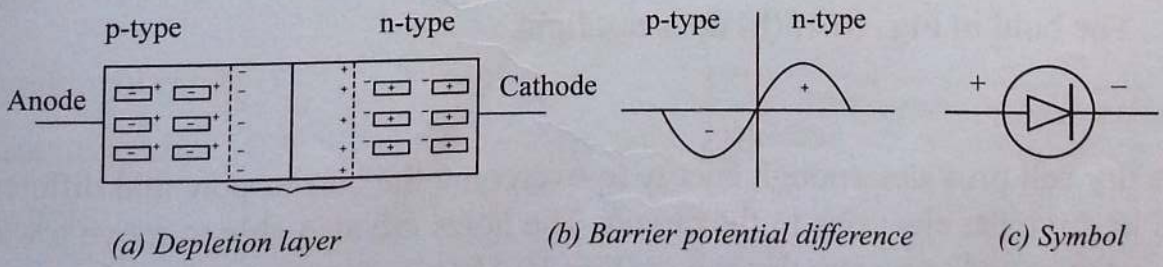


Fig. 10.13: Diffusion of holes and electrons

When the equilibrium has been achieved, the resulting device is known as *p-n junction diode*. Fig. 10.14 (c) shows the symbol of a junction diode.

Due to the movement of charges across the junction, a potential difference develops across the junction with its polarity such as to prevent further charge movement. This potential difference is called a *barrier potential difference* (Fig. 10.14 (b)). A lead connected to the n-type becomes a cathode while a lead on the p-type becomes an anode.



(a) Depletion layer *(b) Barrier potential difference* *(c) Symbol*

Fig. 10.14: A p-n junction diode

Working of a p-n junction diode

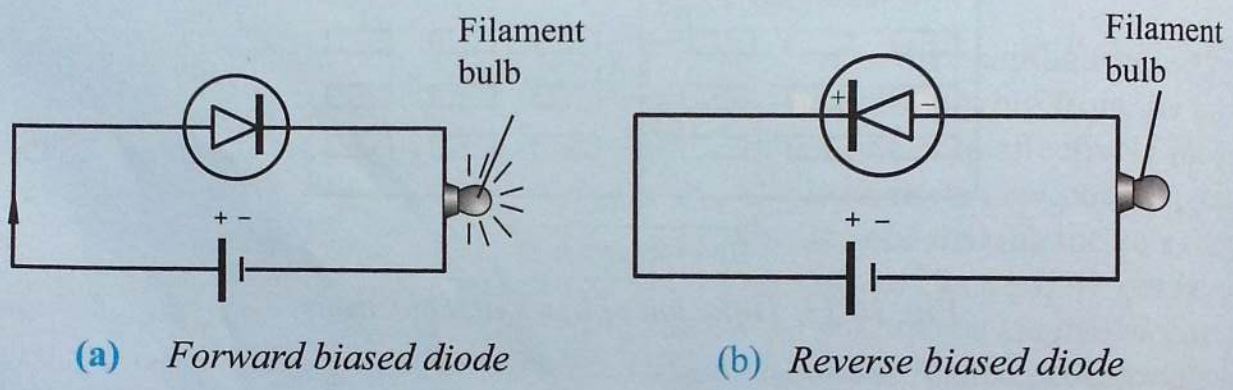
Experiment 10.1: To show that a p-n junction diode conducts only in one direction

Apparatus

- Diode
- Dry cell
- Bulb
- Connecting wires

Procedure

1. Connect a p-n junction diode as shown in Fig. 10.15 (a) with the negative end (n-type) connected to the negative terminal of the cell. What happens to the bulb?



(a) *Forward biased diode* (b) *Reverse biased diode*

Fig. 10.15: Working of P-n junction diode

2. Reverse the connection of the diode and repeat the experiment (Fig. 10.15 (b)). What happens to the bulb.

Observation

- The bulb in Fig. 10.15(a) lights. This means that the current flows through the circuit.
- The buld in Fig. 10.15(b) does not light.

Discussion

The dry cell provides enough energy to overcome the barrier potential difference and to drive the electrons in the circuit. The holes are also able to move towards the junction and complete the circuit (Fig. 10.15 (b)).

When the diode is connected in this way, it is said to be *forward biased*.

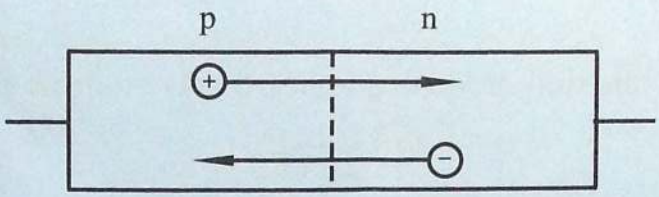


Fig. 10.16: Forward biased diode

The electrons and the holes are attracted to the opposite ends of the cell. This increases the width of the depletion layer (Fig. 10.17) and hence increases barrier potential difference. No current can now flow through the diode.

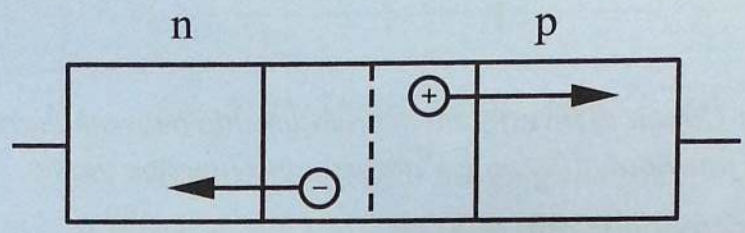


Fig. 10.17: Increased width of depletion layer

When the diode is connected in this manner, it is said to be *reverse biased*. The diode behaves as an insulator.

Conclusion

The results of this experiment shows that a p-n junction diode is a device that conducts current in only one direction.

The characteristics of a p-n junction diode

Experiment 10.2 To investigate the relationship between the current through and the voltage across a p-n junction diode

Apparatus

- Diode, voltmeter
- Crocodile clip
- Switch
- Connecting wires
- Ammeter
- Resistance wire
- Cells

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Procedure

1. Connect the p-n junction diode in a forward bias mode as shown in Fig. 10.18.

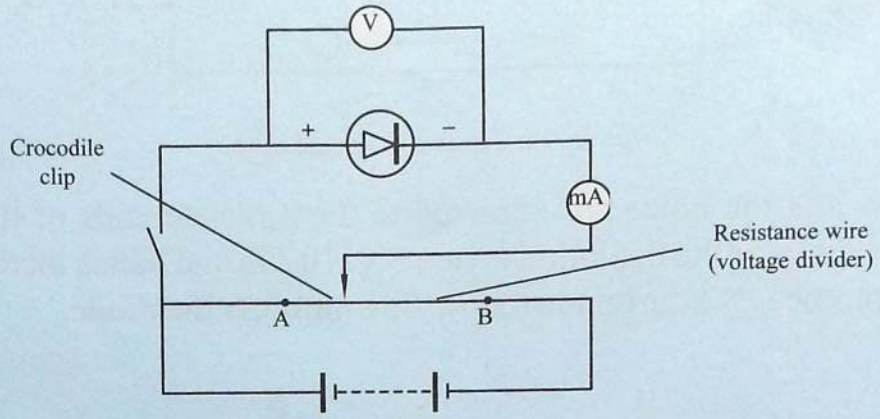


Fig. 10.18: Circuit to investigate the relationship between current I and potential difference V across a p-n junction diode

2. Connect the crocodile clip at A.
3. Close the switch and record the potential difference across the diode and the current through it.
4. Repeat the experiment with crocodile clip at other positions along AB.
5. Record, in each case, the values of potential difference and the current.
6. Reverse the connection of the diode and repeat the experiment.
7. Tabulate the results (Table 10.1).

Table 10.1

Potential difference (V)	Current (mA)

8. Plot a graph of current against the potential difference.

Discussion

On plotting the values of current against voltage, we get a graph similar to the one in Fig. 10.19.

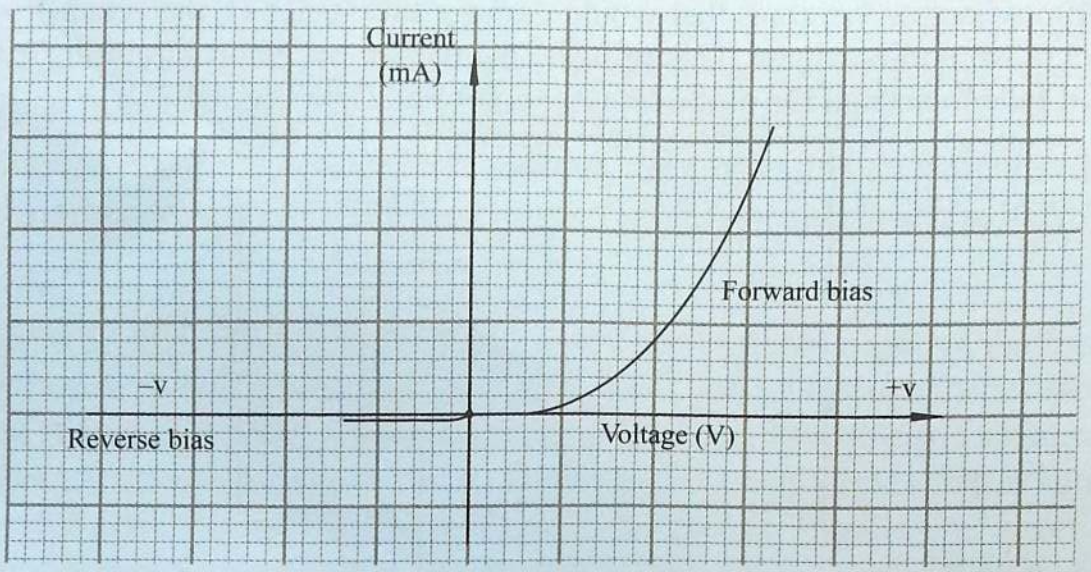


Fig. 10.19: Diode characteristics

The graph is called *characteristics of a p-n junction diode*. The small current in the reverse bias is due to the intrinsic conduction in the p-n junction diode.

Conclusion

The result shows that a p-n junction diode is a device that produces non-linear characteristics i.e. it *does not obey Ohm's law.* Such devices are called *non-ohmic conductors*.

Applications of p-n junction diodes

1. Protecting electrical devices in a circuit

Some devices that operating on direct current (d.c), break down when large voltages are connected in reverse / opposite order to the supply terminals of the devices.

To protect such devices, a diode is usually connected in series with them and in reverse bias as in Fig. 10.20. It ensures that the device is protected by offering very high (almost infinite) resistance to the flow of the current in the reverse diretion when the terminals are interchanged.

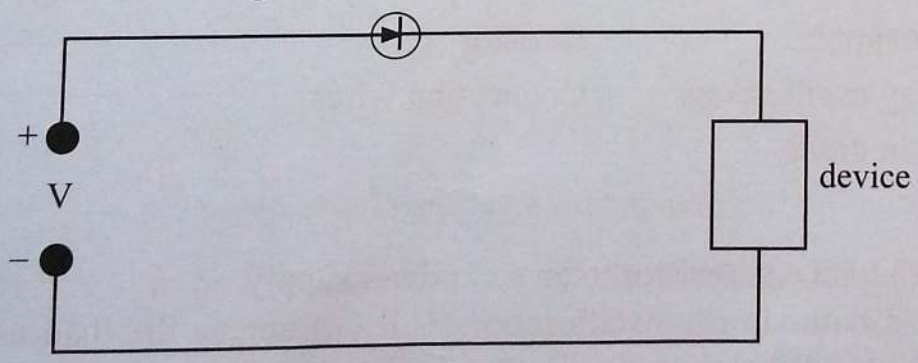


Fig. 10.20: Using a diode to protect a device.

2. Zener diodes

Some special types of diodes called *Zener diodes* are used to protect d.c devices by regulating the voltages applied across the devices. When the p.d (V) increases

or abruptly surges to values that would damage the device C, the zener diode (D_Z) breaks down and conducts. This protects the device by "short circuiting" it. When the p.d falls to normal the diode returns to normal. (See Fig. 10.21)

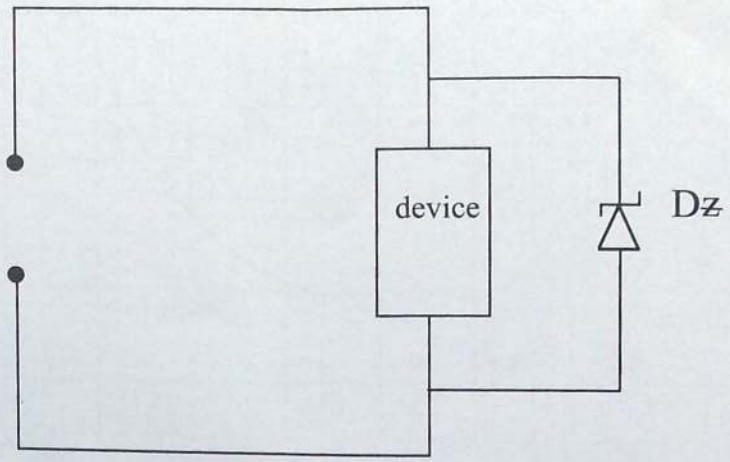


Fig. 10.21: Use of zener diode to protect d.c. devices

Note: Zener diode does not conduct at normal voltages since it is connected in reverse bias mode. It is made to operate in such a way that, if the reverse p.d. connected to it increases beyond a certain value, it breaks down and conducts, offering almost zero resistance.

3. Rectification

Not all electrical devices are operated by alternating current. Some need direct current to operate. It is therefore necessary to convert the alternating current to direct current. A p-n junction diode can be used for this purpose. The process of converting alternating current to direct current is called *rectification*.

Half-wave rectification by a single diode

Experiment 10.3: To convert alternating current to direct current using a single diode

Apparatus

- AC power supply
- Cathode ray oscilloscope
- p-n junction diode
- Resistor
- Connecting wires

Procedure

1. Connect a load e.g. resistor to an a.c power supply.
2. Connect a cathode ray oscilloscope (C.R.O.) across the load as shown in Fig. 10.22 (a). What does the display on the cathode ray oscilloscope show?
3. Now introduce a p-n junction diode as shown in Fig. 10.22 (a).
4. Reverse the connection of the diode and observe the reading of the cathode ray oscilloscope.

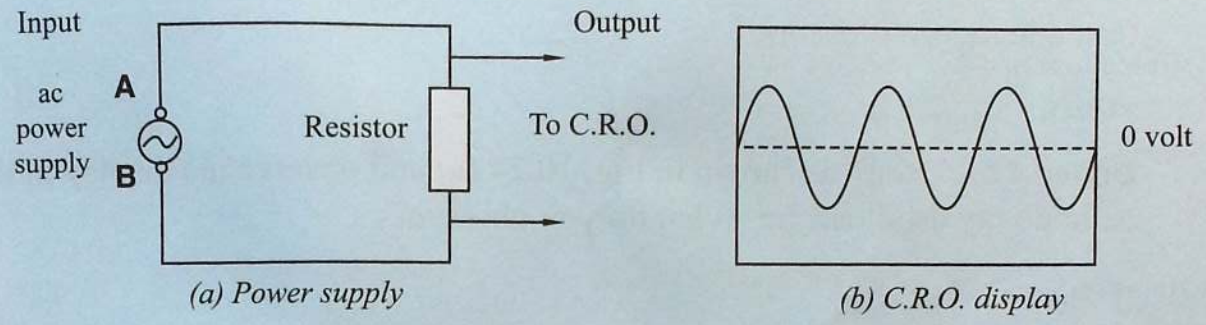
Observation

The cathode ray oscilloscope shows how the voltage across the resistor varies as the current through the resistor changes direction (Fig. 10.22(b).

It is observed that when terminal A is positive, the diode allows a current to flow. However, when A is negative the diode does not allow the current to flow (Fig 10.23 (b)).

Discussion

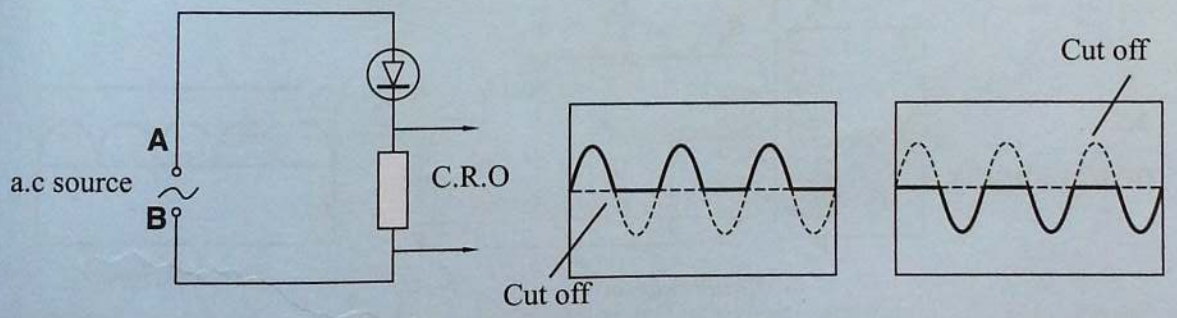
Terminal A is positive during a one half cycle and becomes negative during the next half cycle. When A is positive, a current flows from A through the resistor to terminal B. In the next half cycle, the terminal B becomes positive and the current flows from B through the resistor to A. The display follows a sine wave as shown in Fig. 10.22 (b). During the first half cycle, the current flows in one direction. However, during the next half cycle, the current flows in the opposite directions.



(a) Power supply *(b) C.R.O. display*

Fig. 10.22: Output from an ac power supply

The reading is as shown in Fig. 10.23 (c). Only the positive half cycles appear on screen.



(a) Power supply *(b) C.R.O. screen* *(c) C.R.O. screen*

Fig. 10.23: Half-wave rectification

The current flows in both the circuits in only one direction. Half of the wave has been "cut off". This process of allowing only half of the wave to produce current that flows in one direction is called *half-wave rectification*. Although the alternating current has been converted into direct current, the magnitude varies from zero to a maximum value and from maximum to zero, with some intervals when no current flow at all.

Hence, a varying direct current is obtained across the resistor. In half-wave rectification, half of the input energy is wasted. To avoid this waste, *full-wave rectification* is required.

Full-wave rectification using two diodes and a centre tapped transformer

Experiment 10.4: To convert alternating current to direct current using two p-n junction diodes

Apparatus

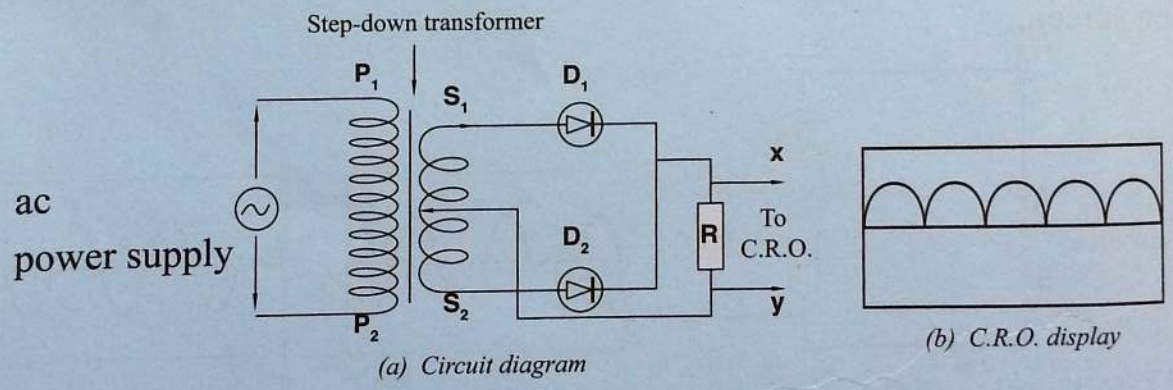
- A.c power supply
- 2 pin-junction diodes
- Cathode ray oscilloscope
- Step-down transformer
- Connecting wires

Procedure

- Connect the circuit as shown in Fig. 10.24 (a) and observe the display in the cathode ray oscilloscope. What do you observe?

Observation

A wave pattern similar to the one shown in Fig. 10.24 (b) is observed in the cathode ray oscilloscope.



(a) Circuit diagram

(b) C.R.O. display

Fig. 10.24: Rectification using 2 diodes

Discussion

During the first half cycle, S_1 is positive and diode D_1 is forward biased. However, during the second half cycle S_2 becomes positive and diode D_2 becomes forward biased with respect to diode D_1 which now will be reverse biased. In this case, irrespective of the polarities of input terminals, the current flows through the resistor continuously.

Conclusion

The alternating current has been *fully rectified* to a varying direct current (Fig. 10.24 (b)).

Transistors

A transistor is a three terminal device formed by merging three pieces of extrinsic (doped). The three terminals of a transistor (c) are known as the *base (b), collector (c)* and *emitter (e)*. Semiconductors in the form n-p-n or p-n-p in. Fig. 10.25 shows the two types of transistors and their symbols.

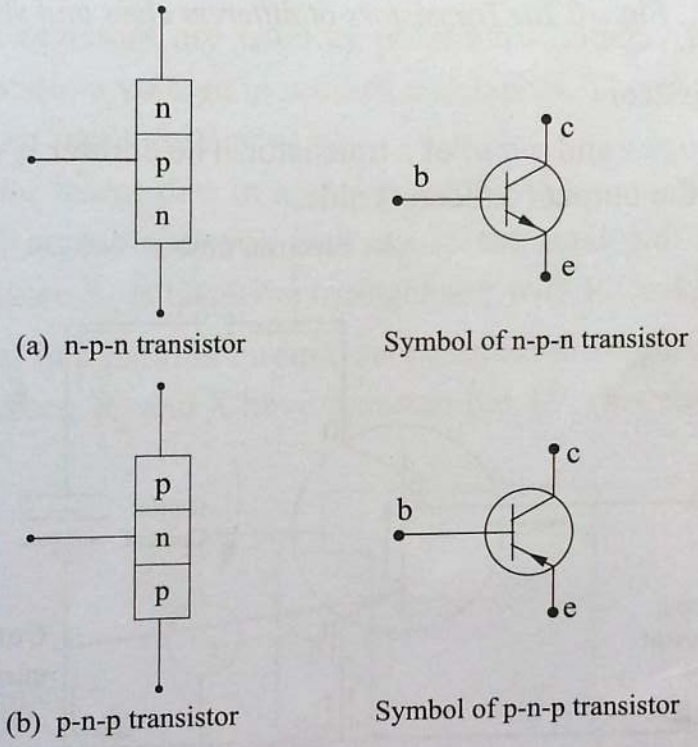


Fig. 10.25: Transistors and their symbols

In the symbols above, the arrows indicate the direction of convectional current flow when the transistor is operating normally. The *emitter (e)* emits electrons which pass through the *base (b)* to the *collector (c)*.

Note

n-p-n transistors are more commonly used than p-n-p because current moves faster in them. Transistors are assembled in different sizes and shapes. In most cases the emitter is marked by tags as shown in Fig. 10.26 (a) and (b).

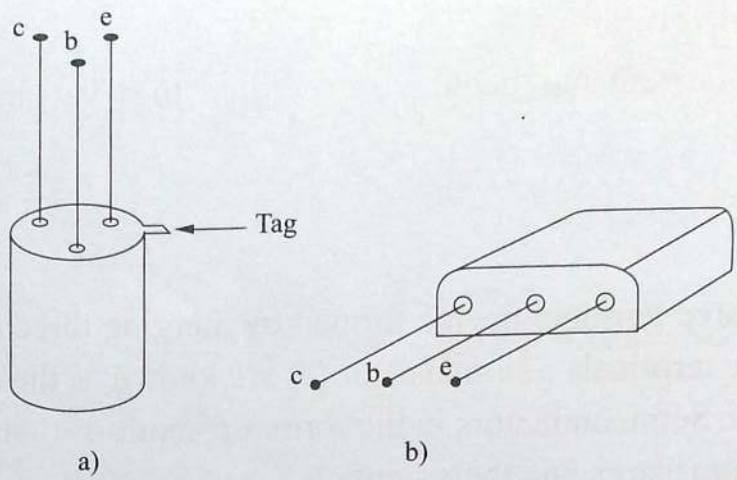


Fig. 10.26: Transistors of different sizes and shapes

Operation of a transistor

Fig 10.27 shows the *input* and *ouput* of a transistor. The emitter is connected to both the input (base) and the output (collector) side.

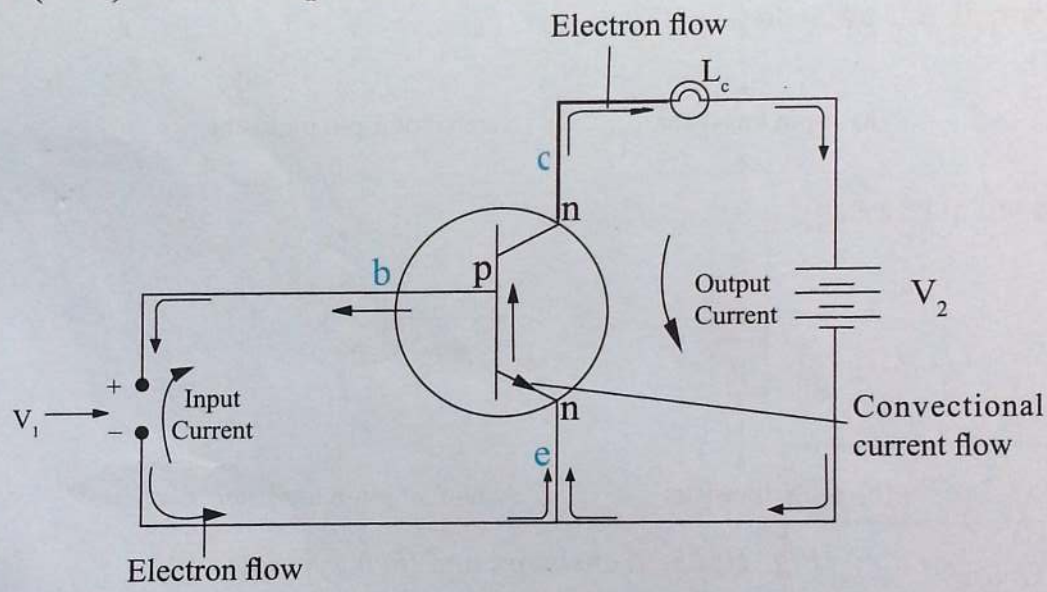


Fig. 10.27: Operation of a n-p-n transistor

When the output and input circuits are connected as shown in Fig. 10.27, the transmitter is said to be in *common-emitter* or (*CE) mode*. The n-type regions are the *emitter* and *collector* of the transistor; the p-type region is the *base*.

The output *of this transmitter* (collector-base junction) of this transmitter is reverse biased since the the positive and negative terminals of V_2 are connected to the collector (n) and base (p) respectively, hence no current flows. The input (emitter-base junction) is forward biased since the positive and negative terminals of V_1 are connected to the base and emitter respectively, hence current flows. This current that flows through the input greatly reduces the 'current blocking effect' (overcomes barrier voltage) of

the output (collector-base junction). When this happens, the output circuit starts to conduct and current flows between emitter and collector. Typically, a small current in the input (emitter-base junction) can cause a current many times larger to flow in the output (collector-base junction).

The transistor works in such a way that when the input side conducts i.e. current flows between base and emitter (base- emitter), then the output also conducts i.e. current flows between emitter and collector (collector-emitter) and so lamp L_C lights. When the input is off then the output is also off.

NB: For the input to be on, the v_1 must be equal or greater than a certain value.

The potential divider concept

In many circuits resistors are used as potential dividers. This is a circuit that proportionally divides a voltage in ratio of resistances. The potential divider shown in Fig. 10.28 has an input voltage of 6V.

In Form Three, we learnt that in a series circuit, the sum of individual potential differences (p.d.) across a circuit is equal to the total p.d. of the battery. Thus $V_1 + V_2 = 6V$ since R_1 is in series arrangement with R_2 and X (Fig. 10.28).

We also learnt that in a parallel circuit, the potential difference across each resistor is the same. Therefore, R_2 and X have the same p.d. (V_2) because they are in parallel (Fig. 10.28).

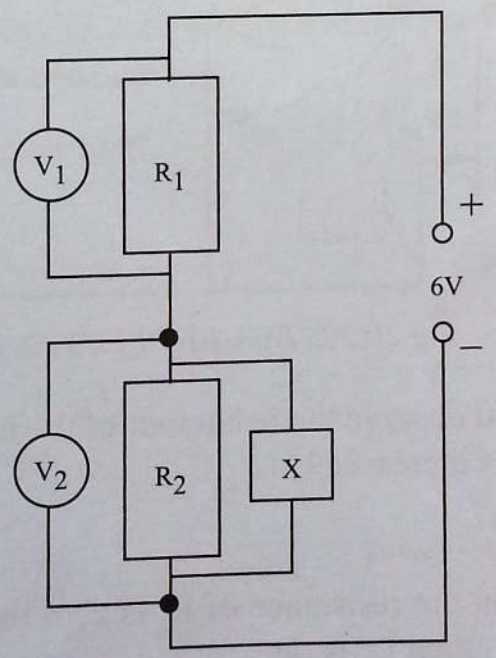


Fig. 10.28: Potential divider

We can extend the above concept to a transistor operated switch as we shall discuss in Experiment 10.5.

Experiment 10.5: To show the use of a transistor as a switch

Apparatus

- 2 resistors
- Protective resistor
- Transistor
- Lamp

Procedure

1. Connect the components as shown in Fig. 10.29 using the following values:
   - R_1 and R_2 having about 10KΩ each.
   - BC 108 or ZTX 300 transistor
   - 6 V, 100 mA lamp for L_C
   - 1kΩ protective resistor in series with the base.

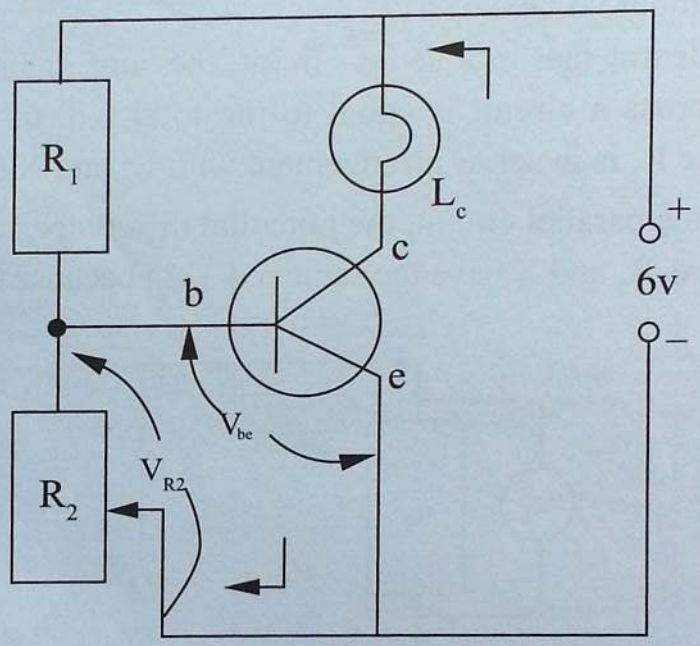


Fig 10.29: Transistor as a switch

2. Vary R_2 to zero and observe the behaviour of the lamp. What happens when the p.d across R_2 is increased?

Observation

It is observed that when the resistance of R_2 is zero then L_C is off and when the resistance of R_2 is high then L_C is on.

Discussion

The p.d. across resistor R_2 i.e., V_{R2} is equal to the p.d. across the input (base), V_{be}, i.e. base-emitter voltage because they are in parallel arrangement. Since R_2

is a variable resistor, we can vary its value of resistance from zero to maximum. This in turn causes the voltage (V_{be}) between the base and emitter to change in a range from zero to a maximum value. When V_{be} is zero, no current flows through the output (collector) thus lamp L_c is off. When V_{be} is large enough, it forward biases the b-e junction to conduct and so current flows through the output, which makes lamp L_c to light on.

Conclusion

From this experiment, we can conclude that a transistor behaves as a switch, i.e. the input (base) controls the output (collector).

Uses of transistors

There are very many uses of transistors most of which you will learn in other levels of your education. In most cases, several transistors are connected with other components such as diodes, capacitors and suitable resistors, they form devices called microchips which are core components in devices such as radios, computers, calculators, television, amplifiers etc.

Other electronic components

Light Dependent Resistor (LDR)

Light dependent resistor (LDR) is type of resistors that naturally have high resistance in the dark. When light energy falls on them electrons become more free to conduct and the resistance decreases considerably.

Fig. 10.30 shows symbol of an LDR.

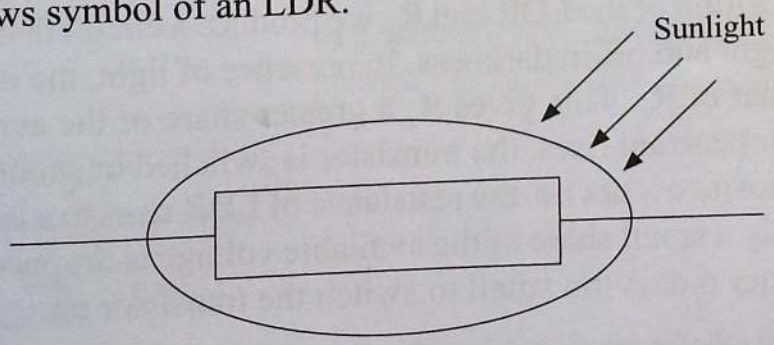


Fig. 10.30: Symbol for LDR

Working of light operated switch

LDR have many uses in electronic devices. One common use of LDR is in the making of a light operated switch discussed below.

Fig. 10.31 shows how a LDR is placed in a transistor circuit. This kind of circuit keeps the bulb on in darkness and off in presence of light. In darkness, the resistance

of LDR is very large compared to that of R_1. This gives it (LDR) a greater share of the available voltage. Thus, the input (base) current rises, the transistor is switched on and the bulb lights.

However, in presence of light the resistance of LDR drops significantly to a small value compared to that of R_1. Thus only a small share of the available voltage is dropped across it (LDR) and the input (base) current is too small to switch the transistor on.

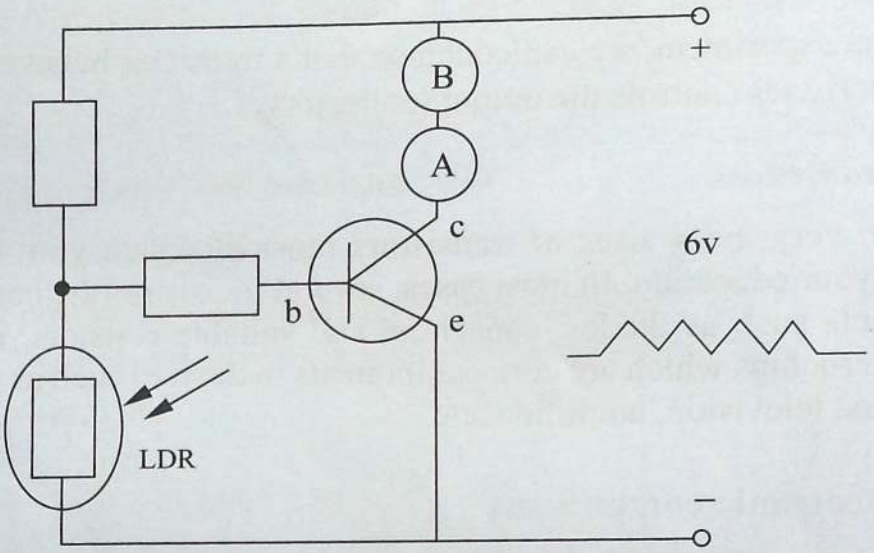


Fig. 10.31: Light operated switch

The LDR are thus used as light sensors in switching on circuits that require to be triggered by light. This kind of circuit can be used in automatic street lighting systems and also operating certain burglar alarms.

By swapping the position of the LDR and R_1, we produce a circuit that keeps the bulb on in presence of light and off in darkness. In presence of light, the resistance of the LDR is less than that of R_1. This gives R_1 a greater share of the available voltage. Thus the input (base) current rises, the transistor is switched on, and the bulb lights. In darkness the opposite occurs i.e. the resistance of LDR rises to a larger value than that of R_1. Thus, only a small share of the available voltage is dropped across R_1 and the input base-emitter p.d. is too small to switch the transistor on.

Note: There are other resistors that depend on change of temperature and are used as thermal sensors e.g. in security circuits that detect human body temperature. In this case, the LDR is replaced by a thermistor. The circuit used is similar to the one shown in Fig. 10.30 except that the positions of the thermistor and R_1 are swopped. When heat is applied to the thermistor its resistance drops and the transistor is switched on. Thus lamp L_c lights.

Note: The base must always be protected from excessive current that could easily blow up the transistor. A 1 KΩ resistor is suitable to protect the base in these experiments.

Think about this!

The LDR can simply be fitted on one side of door frame near the hinges side and supplied with light from the opposite side. Opening the door would cut off the light, increasing p.d. of input (base) and trigger on the output collector-emitter circuit to ring the alarm. The whole setup must be hidden.

Capacitors

A *capacitor* is a device that stores charges. It consists of two parallel metal plates held together and separated by an insulating medium called the *dielectric*. There are many types of capacitors depending on the dielectric used. The different type of capacitors include, electrolytic capacitors, metal foil type capacitors, variable capacitors etc.

Parallel plate capacitor

This consist of two parallel metal plates separated by an insulating material between them.

Fig. 10.32 (a) shows the structure of the capacitor while

Fig. 10.32(b) shows the symbol of a capacitor.

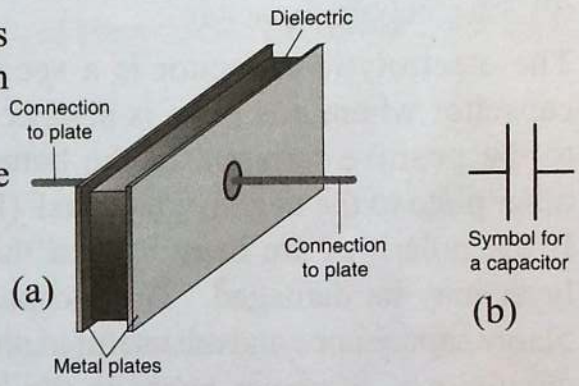


Fig. 10.32: A parallel capacitor

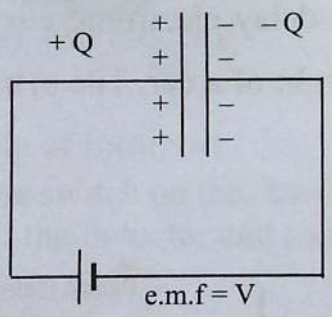


Fig. 10.33: A capacitor stores charge

If the two plates of the capacitor are connected to a battery, each plate gains equal and opposite charge. (Fig. 10.33).

Types of capacitors

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. 10.34.

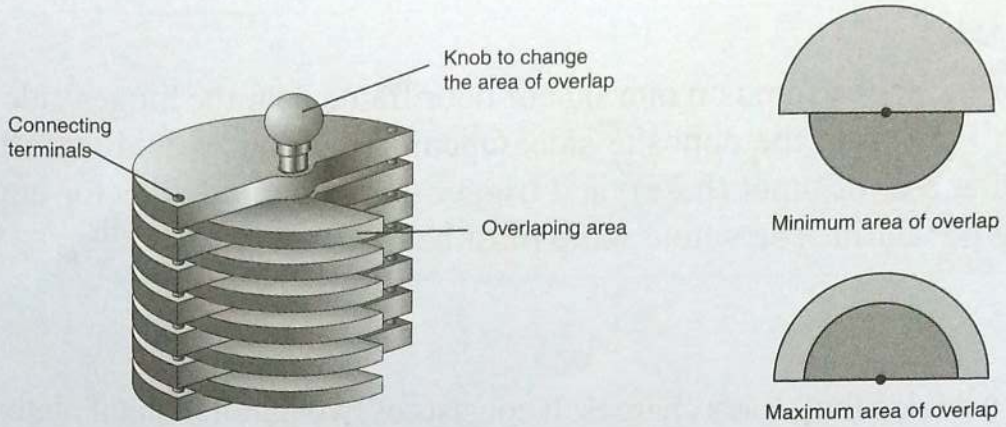


Fig. 10.34: Variable capacitor

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. 10.35). If the polarities are interchanged the dielectric layer may be damaged. These capacitors have 5large 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: $\overset{+}{-}\!\!\mid\ \mid\!\!\overset{-}{-}$

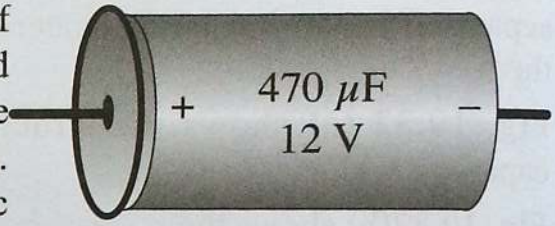


Fig. 10.35: Electrolytic capacitor

(c) Metal foil plastic capacitor

A metal foil capacitor has plastic as its dielectric. It has a small volume compared to others (Fig. 10.36). These capacitors are available in a variety of shapes and sizes.

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.

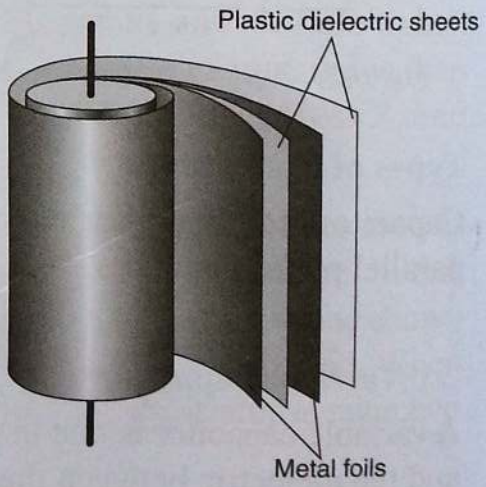


Fig. 10.36: Metal foil plastic capacitor.

Uses of capacitor

(a) Capacitors are used to maintain power to the memory of devices like calculators and mobile phones when batteries are being changed or charged, to avoid loss of data.

(b) Capacitors are used in rectifier circuits to smoothen the d.c. voltage signal obtained from rectification of alternating voltages i.e smoothening.

(c) Capacitors are used to absorb electrical signals that cause noise in sound systems.

(d) Capacitors are used in U.P.S (Un-interrupted Power Supply) in computers to store and supply power for a short time to a computer in the event of power blackout taking place unexpectedly.

Inductors

Inductor is an electronic component that stores energy in form of a magnetic filed. It consists of a wire loop or coil. The inductor measures inductance which is the behavior of a coil of wire in resisting any change of electric current through the coil. Fig. 10.37 shows inductor and its symbol.

(a) An inductor

(b) A symbol L is an inductor

Fig. 10.37 An indicator

Working of inductor

When we switch on the circuit without the inductor. The bulb lights normally. Now, Connect the inductor and switch on the circuit (Fig. 10.38) observe what happens.

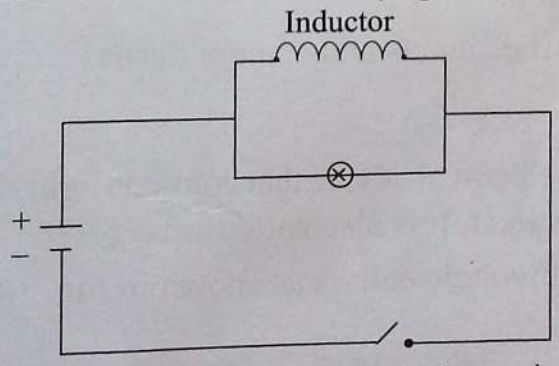


Fig. 10.38 A circuit diagram consisting an inductor

The bulb glows dimly. Most of the current should follow the low-resistance path through the loop but what happens the bulb burns brightly and then gets dimmer. When the circuit is switched off, the bulb lights brightly and then quickly goes out, why is this so?

When the current first flows in the coil, the loop builds up magnetic field. At this point, the coil inhibits the flow of current. Once the field is built, current can flow normally through the wire.

When the switch is opened, the magnetic field around the coil keeps current flowing in the coil until the field dies.

The current keeps the bulb lit for some times even though the switch is opened. This is why we define inductor as a device that store energy in its magnetic field and trends to resist any change in the amount of current flowing through it.

Uses of inductors

- Inductors are used in making traffic light sensors that use loop (coil).
- Inductors are used in the red light cameras that are used to curb traffic violations. This reduces road accidents.

Light emitting diodes (LEDs)

A light emitting diode (LED) is a two-lead semiconductor light source. This diode emits light when a current passes through it. This effect is called electroluminescence. The symbol of a light emitting diode is as shown in Fig. 10.39.

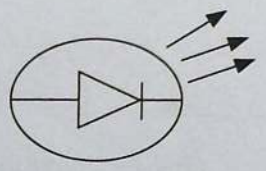


Fig. 10.39 A symbol of light emitting diode (LED)

Uses of light emitting diodes

Light emitting diodes are used in:

- Aviation lighting
- Automotive headlamps
- Advertising and traffic signals and camera flashes

Photovoltaic cell

A photovoltaic cell is an electrical device that converts light energy directly to electric energy by photovoltaic effect. It is also called solar cell.

The symbol for the photovoltaic cell is as shown in Fig. 10.40.

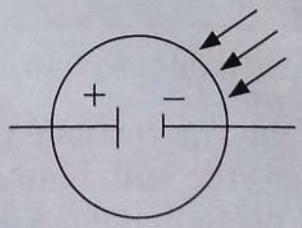


Fig. 10.40: A symbol of photovoltaic cells

Working of photovoltaic cell

When the sunlight fall on the solar cells, a potential is created across the cells. When the circuit is completed a current flow through the components connected in the circuit Fig. 10.41.

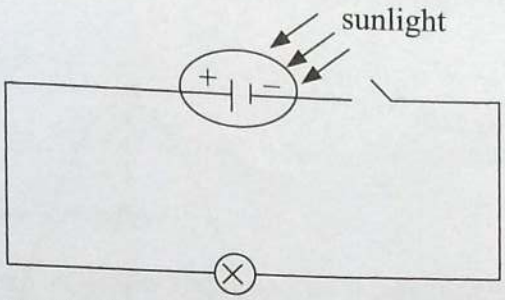


Fig. 10.41: Circuit connected to a photo voltaic cell

Uses of photovoltaic cell:

- Photovoltaic cells are used in the manufacture of solar panels.
- Can be used to power solar powered cars, boats and airplanes.

Thermistor

Thermistor is a resistor whose resistance varies significantly with temperature, its functioning depends on the temperature. Also a thermistor is defined as a temperature sensitive resistor.

Its symbol is as shown in Fig. 10.42

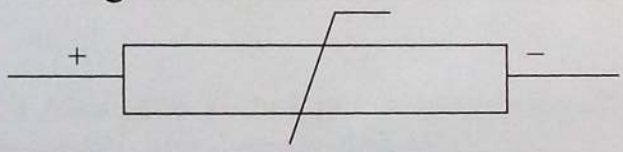


Fig. 10.42: A symbol of a thermistor

Uses of a thermistor:

- Used as current limiting devices for circuit protection.
- Thermistor, are used in making resistance thermometers used to measure very low temperatures.
- Thermistors can be used to monitor the temperature of an incubator.
- Used as timers in the degaussing coil circuit of most CRT displays.

10.5 Electronic circuit and signals

A number of electronic devices have their output inform of data, sound and video signals. Examples are radio (sound signals) computer, television and mobiles (sound, data and video signals)

These signals are classified as analogue and digital signals found in analogue and digital circuits respectively.

Analogue signal

Analogue circuits are electronic circuits that operate with currents and voltages that vary continuously with time and have no abrupt transitions between levels. Is a circuit with a continuous variable signal. Fig. 10.43 shows an analogue signals.

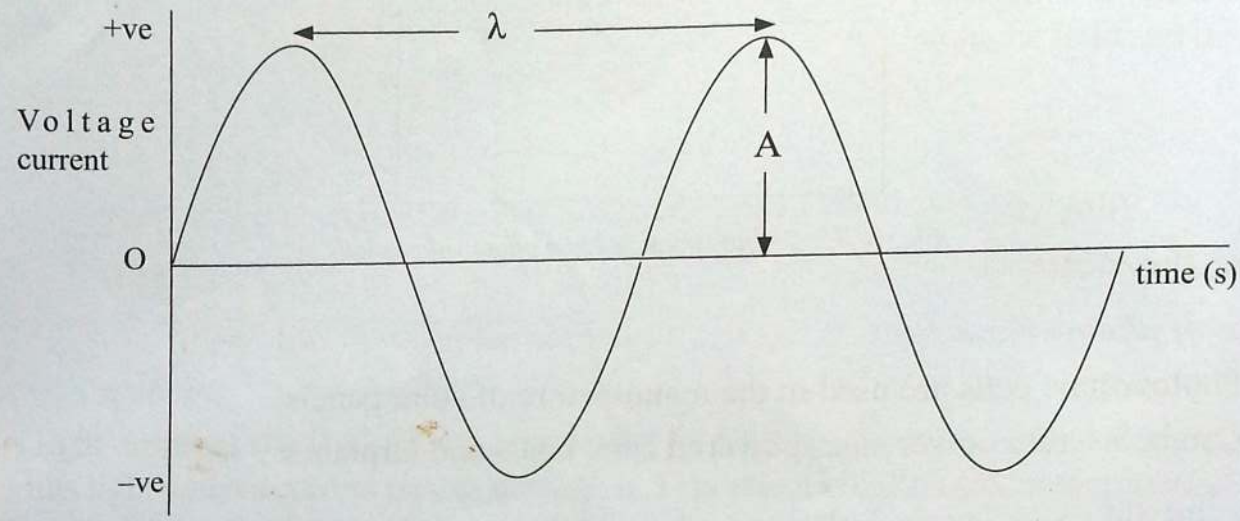


Fig. 10.43 A sinewave of an analogue signal

Characteristics of analogue signals

A simple analogue signal is a sine wave characterized by:

- Amplitude.
- Frequency
- Phase

Amplitude (A) is the maximum displacement of wave particles from the position it shows the highest amount of current or voltage.

Frequency (f) is the number of complete oscillation per second. It is measured in hertz (Hz).

Phase are two points on a wave-front that appears to be the same.

Wavelength (λ) is the distance between two successive points in phase.

Digital circuits and signals

Digital circuits is a circuit where the signal must be one of two discrete levels. The signal must be one or zero (1 and 0). This digital circuit produce digital signals.

Digital circuits can either be high (+ve) and lower (-ve). Fig. 10.44 shows digital signal.

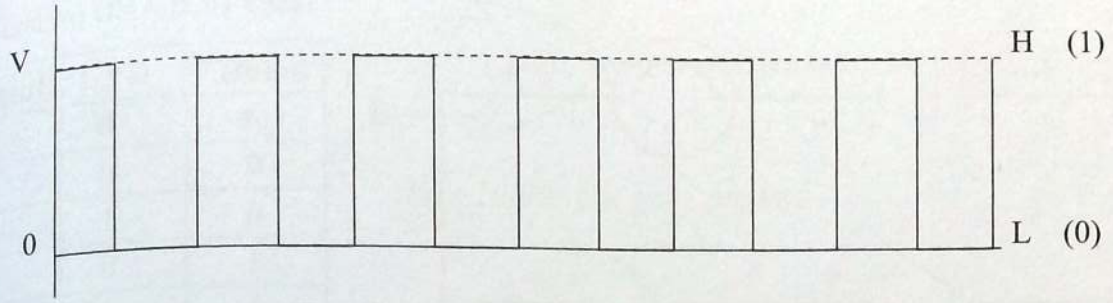


Fig. 10.44: A graph of digital circuits

Characteristics of Digital signals

- Bit intervals: This is the time required to send one single bit.
- Digital signals are descreate.
- The signal have limited number of defined values such as 1 and 0.
- Bit rate it's the number of bit intervals in one second.

Advantages of digital signals

- Digital data can be easily compressed and hence transmitted efficiently. This help in transmission of large volumes of voice, data, and image information.
- Digital signals are secure. There is minimal loss of data.
- Digital data transmission is cheaper compared to analogue data.

Note:
The process by which analogue signal is converted into digital signal is called modullation and the reverse is the demodullation.

10.6 Logic gates

Logic gates normally use tiny transistors as switches. They are of four main forms: the AND, OR, NOR, and NOT gates.

(a) AND gate

Let us use the simple circuit in Fig 10.45 to understand the AND gate. Let A and B represents the input circuits of a transistor respectively while lamp L represents the output circuit. Let us use 1 and 0 to represent the *on* and *off* states of any of the three circuits. The states of the two input circuits, A and B determines the state of the output circuit L. Table 10.2 summarises the possible states of the three circuits at an instant. This table is known as the AND truth table.

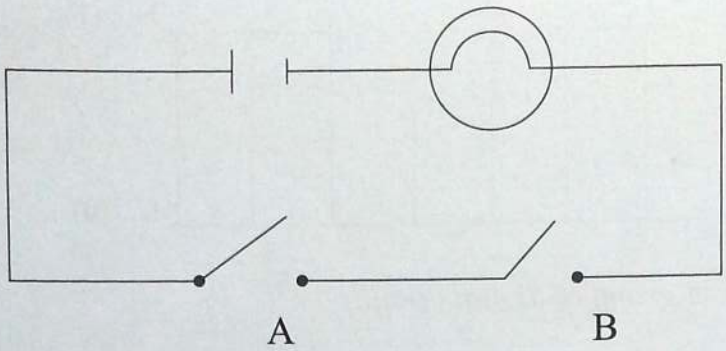


Fig. 10.45: AND gate circuit

Table 10.2: AND truth table

Inputs		Outputs
A	B	L
0	0	0
0	1	0
1	0	0
1	1	1

The circuit is called an AND gate because circuit A and circuit B must be on for the output circuit (lamp) L to be on.

In an electronic circuit the AND gate circuit is represented by the symbol in Fig. 10.46.

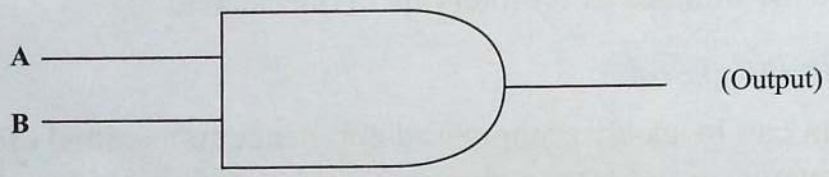


Fig 10.46: AND gate circuit

b) OR gate

Fig. 10.47 represent an OR gate circuit. The input circuits A and B are in parallel and their combined circuit in series with the output L. Table 10.3 is the truth table for the OR gate.

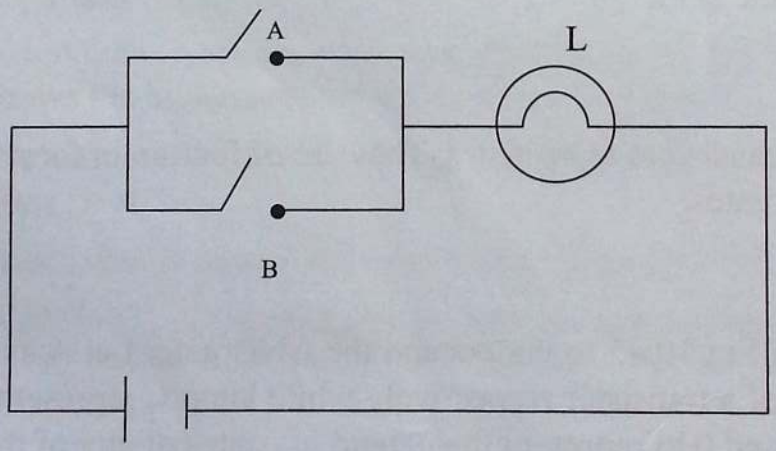


Table 10.3: OR gate truth table

Inputs		Outputs
A	B	L
0	0	0
0	1	1
1	0	1
1	1	1

Fig 10.47: OR gate circuit

From the truth table, we observe that the output circuit represented by the lamp L will only be on when either A *or* B *or* *both* are on.

Fig. 10.48 below shows the symbol for OR logic gate.

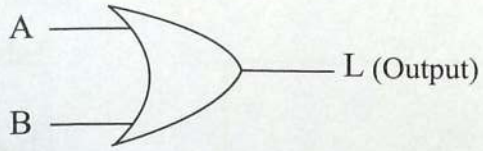


Fig. 10.48: OR gate symbol

c) NOR gate

Fig. 10.49 shows a NOR gate circuit. It consists of two input circuits A and B and one output circuit L. Table 10.4 is the truth table for the NOR gate.

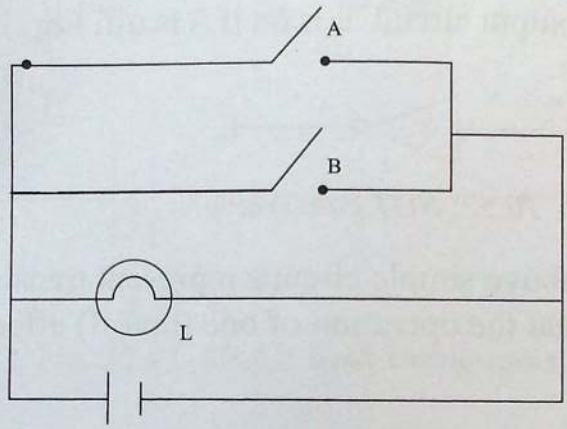


Fig. 10.49: NOR gate circuit

Table 10.40: Nore gate thruth table

Inputs		Outputs
A	B	L
0	0	1
1	0	0
0	1	0
1	1	0

In the NOR gate, neither A nor B should be on for Lamp L to be on. Fig. 10.48 below shows the symbol for NOR logic gate.

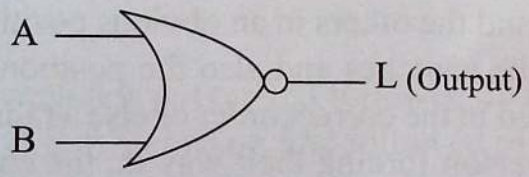


Fig 10.50: NOR gate symbol

d) NOT logic gate

Fig. 10.51 shows a NOT logic circuit. It consists of one input circuit (A) and one output circuit (L). Table 10.5 is the truth table for a NOT gate.

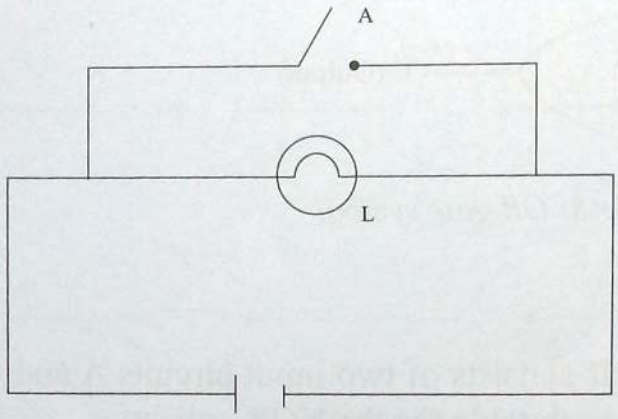


Fig. 10.51: NOT logic circuit

Table 10.5: NOT truth table

Inputs	Outputs
A	L
0	1
1	0

In the NOT logic gate the output circuit L is on if A is off. Fig. 10.52 shows the symbol for NOT logic gate.

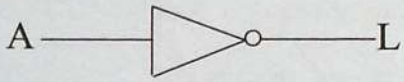


Fig. 10.52: NOT gate symbol

Note: The switches in all the above simple circuits represent transistors which are interconnected in such a way that the operation of one (on/off) affects the working of the next and so on.

Project

Simple bank strong-room security system

Introduction

A strong room is a room in which valuable items e.g. money or documents are securely kept. The strong room door lock is operated using two switches. One of the switches is hidden and the others in an obvious position. Only key people know the order of pressing the switches and also the position of the hidden switch, the switches must be pressed in the correct order or else a radio alarm should ring. Other than an unauthorised person forcing their way in, the entry should be able to open but also trigger an alarm (e.g. a manager at gun point can trigger the radio alarm without risking his life).

Suggested Materials

- A 3V buzzer (bell) to represent the radio alarm
- A 3V bulb to represent the door lock.
- 3 cells (size D) in a cell holder.
- About seven long connecting wires
- Soft board

- Thumb tacks
- 3 switches A, B and S_0

Construction

1. Arrange the apparatus as shown in Fig. 10.53.

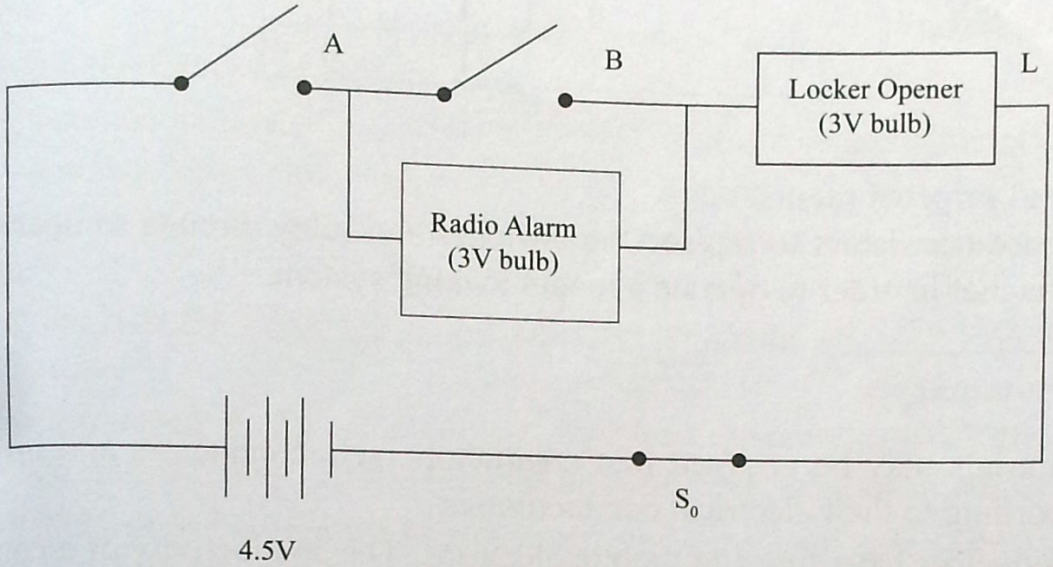


Fig. 10.53: Simple bank strong-room security system

2. Join the components and use the thumb tacks to make them secure.

Operation

1. Switch on so that the security circuit is on.
2. Switch on A followed by B and note the observations.
3. Switch on B followed by A and note the observations.

Observation

It is observed that when switch A is put on first followed by B, the radio alarm rings and the rock opens. When B is switched on first followed by A only the lock opens; the radio alarm does not ring.

Explanation

Switches A and B are in series arrangement. Therefore, when both are on, the same current passes through them. Switch B and radio alarm are in parallel arrangement and therefore current entering at the junction is equal to the sum of current leaving it. Thus when A is switched on first current flows through the alarm then through the locker and so the alarm rings and the lock opens. When B is switched on first followed by A, current does not flow through the alarm but flows through the locker. Thus the locker opens but the alarm does not ring. This is the correct order. Table 10.6 shows the outcome of such a circuit. Let L represent locker and R represent the radio alarm.

Table 10.6: Truth table

Input		Output	
A	B	L	R
0	0	0	0
0	1	0	0
1	0	1	1
1	1	1	0

Suggested improvements

We can use transistors to replace the switches and relay circuits to operate large electromagnet in order to operate a model locking system.

Unit Summary

- Materials may be grouped into conductors, semiconductors and insulators according to their electrical conductivities.
- Conductors have free and mobile electrons. The conductivity of a conductor decreases with the increase in temperature.
- Semiconductors have electrons which are held loosely by its structure. The conduction in a semiconductor increases with the increase in temperature.
- Insulators do not have free and mobile electrons.
- Pure semiconductors that depend only on the thermal electrons produced within itself for conduction of a current are called intrinsic semiconductors.
- Doping is a process of introducing minute impurities into a pure crystal of semiconductor so as to boost the electrical conductivity of the semiconductors.
- Semiconductors obtained through doping process are called extrinsic semiconductors.
- Atoms with three valence electrons are called acceptor atoms when used for doping.
- Atoms with five valence electrons are called donor atoms when used for doping.
- A p-type semiconductor is obtained when a pure semiconductor has been doped with trivalent atoms.
- An n-type semiconductor is obtained by doping a pure semiconductor with pentavalent atoms
- In p-type semiconductors, the majority charge carriers are the positive holes while in n-type semiconductors, the electrons are the majority charge carriers.
- A transistor is a 3 terminal device made up of 3 pieces of doped semiconductors
- The three terminals of a transistor are emitter, base and collector. The base is much smaller in size than the other two.

- Transistors when combined with other devices like diodes, resistors and capacitors are used in electronic circuits of radios, TV's, calculators, computers security systems amongst many others.

Unit Test 10

1. Explain the following terms
   (a) semiconductors. (b) intrinsic semiconductors.
   (c) extrinsic semiconductors. (d) doping
2. Distinguish between semiconductors and conductors. Give an example of each.
3. Describe how the following semiconductors are made
   (a) p-type (b) n-type
4. Draw the structure of a silicon crystal and show the bonding of electrons.
5.. Explain the statement, 'at low temperatures the resistance of silicon is high, but decreases at high temperatures'.
6. What is meant by "depletion layer" in a p-n junction diode?
7. Draw the symbol of a p-n junction diode. State one application of the diode.
8. Use circuit diagrams to distinguish between forward and reverse bias of a p-n junction diode.
9. A transistor is connected in a common-emitter mode,
   (a) Why is the input voltage necessary?
   (b) How does the current flow in the input circuit affect the output current.
10. Fig. 10.54 shows the use of a transistor as a switch. Study it carefully and answer the questions that follow.

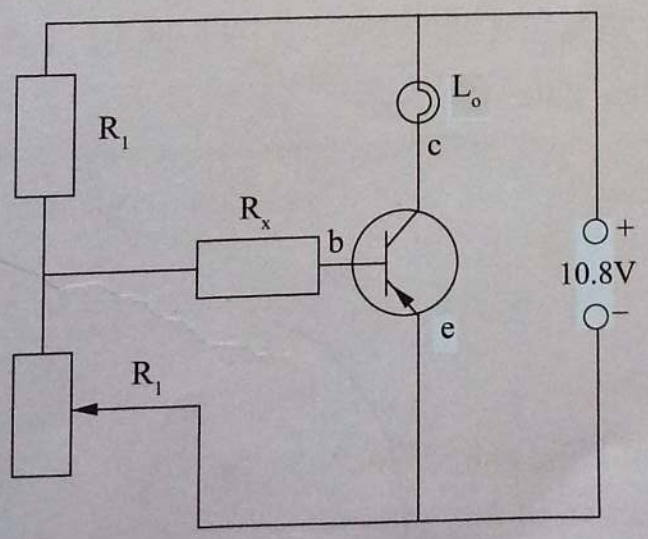


Fig. 10.54

a) State the meaning of the letters b,c and e.

b) What name is given to R_1 and R_2 combined, as used in the circuit?

c) What is the purpose of R_x?

d) What type of transistor is used in this circuit?

e) What would be the effect of adjusting R_2 to read zero?

11. Fig 10.54 shows a circuit that is used to switch a lamp automatically.

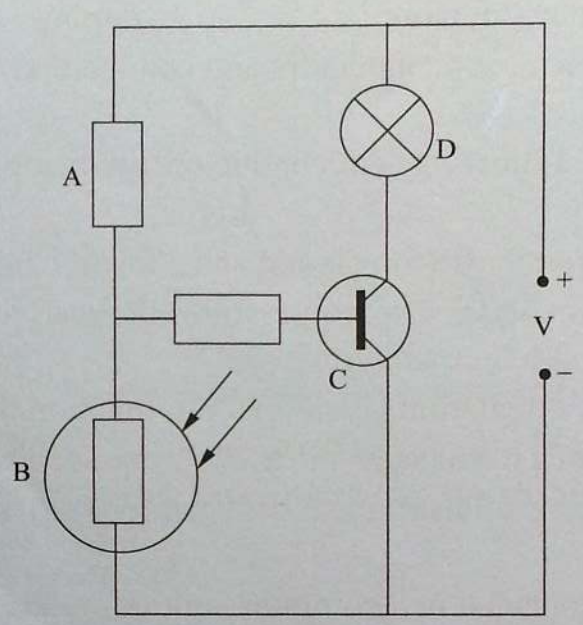


Fig. 10.54

a) Write down the name of the components labelled A,B and D.

b) Which of the four components A,B C or D acts as a switch?

c) Explain why the lamp lights on as it falls dark.

12. Fig. 10.55 is a logic gate.

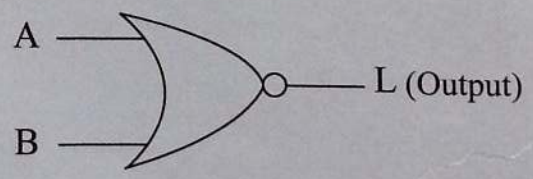


Fig. 10.55

(a) Which type of logic gate is this?

(b) Explain the action of this gate?

Oscillations and Waves

Outcome

The students will be able to understand and apply waves and their properties in designing and developing various technologies in communication, medicine, musical and military equipments.

Unit 11: Electromagnetic Spectrum

Unit 12: Light and Lenses

UNIT

11 Electromagnetic Spectrum

Success Criteria

By the end of this unit, you must be able to:

- Describe main components of electromagnetic spectrum.
- Explain the properties of electromagnetic waves.
- Describe the methods of detecting electromagnetic waves.
- Describe the application of electromagnetic waves.
- Apply wave equation in solving problems on electromagnetic waves.

Introduction to Electromagnetic Spectrum

As we already know, matter is made up of molecules or atoms. The molecules themselves are made up of atoms. An atom has a positively charged central *nucleus around which negatively charged electrons* revolve in paths called *orbits*.

When these charged particles undergo some change in their energy, they emit this energy in form of waves or radiations.

A change in energy may occur in a number of ways. These include:

1. Electron undergoing transition from an orbit of higher energy to one of lower energy (Fig. 11.1)

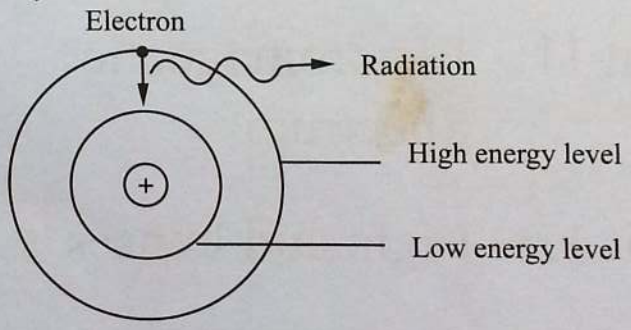


Fig 11.1: Electron undergoing transition

2. Oscilllation of electrons or nuclei – As the electrons or nuclei oscillate, their kinetic energy changes constantly. The rate of oscillation governs the nature of the radiation to be emitted.
3. Movement of a molecule – This includes vibration, bending, inversion or even the rotation of molecular arrangement.

In all these cases, the energy emitted is in form of a transverse waves. These waves consist of a varying electric and magnetic fields. The electric and magnetic fields produced are perpendicular to each other and travel in the same direction. This type of wave with both electric and magnetic fields are called *electromagnetic waves* or

radiation. Fig 11.2 shows an the electric and magnetic fields in an electromagnetic wave.

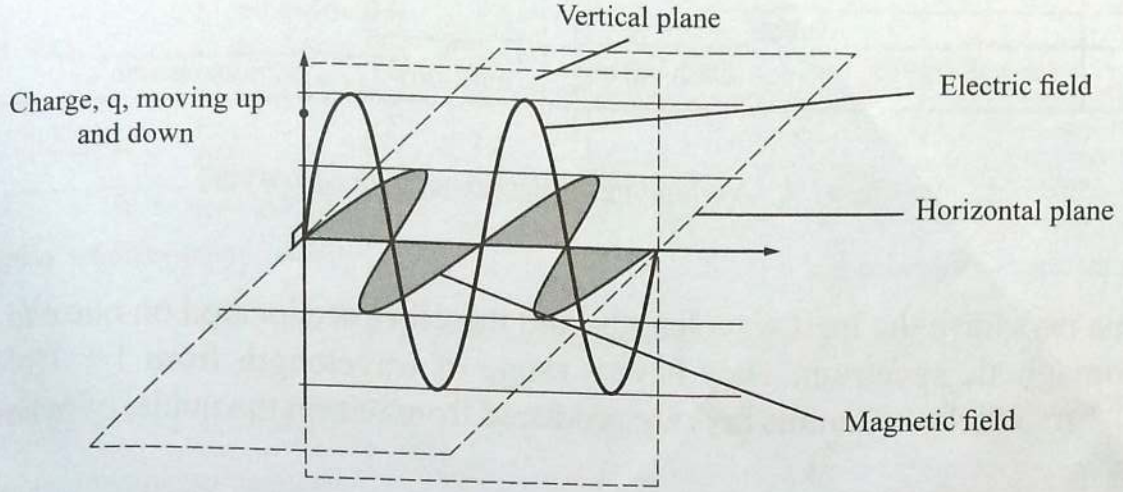


Fig. 11.2: Electric and magnetic fields

Depending on their source of origin, electromagnetic waves are emitted with varying wavelengths or frequencies. Despite their varying wavelengths, they form a family of waves called electromagnetic waves.

11.1 Complete electromagnetic spectrum

Each member of the electromagnetic family is produced with a range of wavelengths. The waves may be arranged in order of their increasing or decreasing wavelengths to form what is called the electromagnetic spectrum.

The spectrum consists of gamma rays (γ), X-rays, ultra-violet (UV), visible light, infra-red (IR), microwaves and radiowaves. Fig. 11.3 shows the complete electromagnetic spectrum with the waves arranged in an increasing order of their wavelengths.

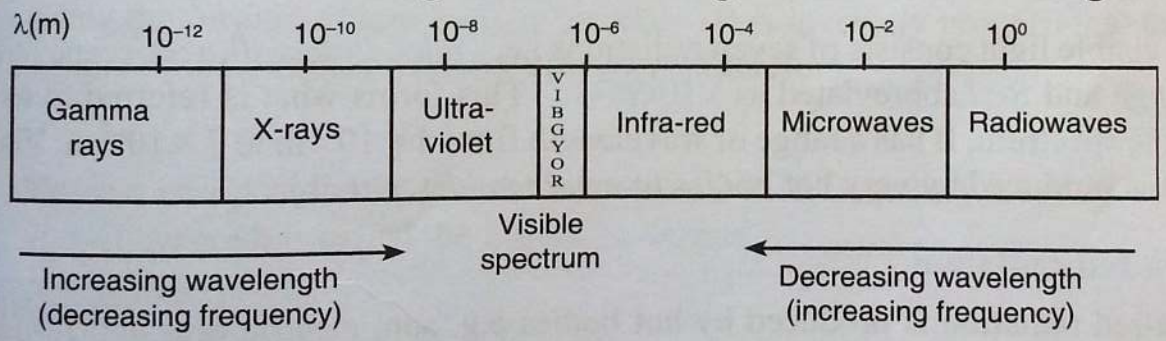


Fig. 11.3: Overlapping of electromagnetic spectrum

The electromagnetic spectrum is a continuous spectrum. This means that there is no sharp boundary between one radiation and the next. The different types of waves change gradually from one to another. Some radiations even overlap (Fig. 11.4). For example, X-rays overlap with both gamma rays and ultra-violet rays. So we have X-rays having the same wavelength with gamma and ultra-violet radiation.

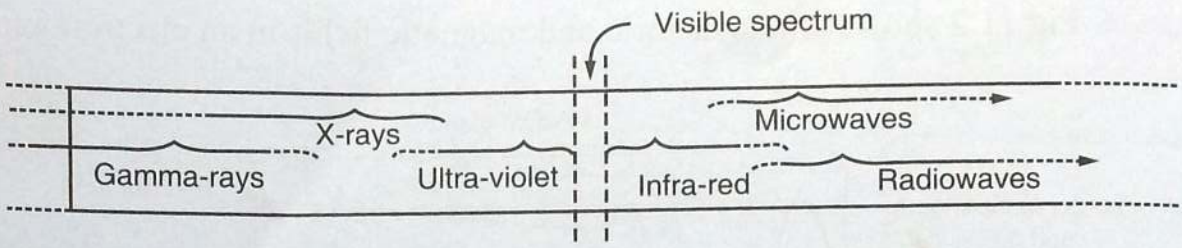


Fig. 11.4: Overlapping of electromagnetic spectrum

Gamma rays

Gamma rays have the least wavelengths and therefore are located on one end of the electromagnetic spectrum. They have a range of wavelength from 1×10^{-15} m to 1×10^{-11} m or below. Gamma rays are produced from within the nuclei of radioactive atoms.

X-rays

X-rays are produced when fast moving electrons strike and are stopped by a metal target. They have a wide range of wavelength from 1×10^{-13} m to 1×10^{-9} m. There is no clear boundary between the gamma rays and X-rays.

Ultra-violet radiation

Ultra-violet radiation is produced by arcs (e.g. Carbon arc lamp, electric spark), gas discharge tube, mercury vapour lamp, hot bodies and the sun. The radiation, as the name suggests, bounds the violet ends of the visible spectrum. It is produced with a range of wavelength of 1×10^{-9} m to 1×10^{-7}m. Ultra-violet rays, with short wavelengths overlap with the X-rays of long wavelengths.

Visible light

The visible light consists of seven radiations i.e. *Violet, Indigo, Blue, Green, Yellow, Orange* and *Red* abbreviated as VIBGYOR. This forms what is referred to as the visible spectrum. It has a range of wavelength from 4×10^{-7} m to 7×10^{-7} m. Visible light is produced by very hot bodies or any *incandescent* object.

Infra-red radiation

Infra-red radiation is produced by hot bodies e.g. sun, electric fires and furnaces. They have a range of wavelengths from 1×10^{-6} m to 1×10^{-3} m. Infra-red is a radiant energy. Red hot bodies emit red light and infra-red.

Radiowaves

Radiowaves are produced from electrons moving in conductors. Radiowaves have the greatest wavelengths and therefore are found on the other end of the spectrum. They have a wide range of wavelengths from 1×10^{-3} m to 1×10^{6} m. This region is subdivided into microwaves, radar and television waves. Fig. 11.5 shows the range

of wavelengths for the different radiations of electromagnetic spectrum.

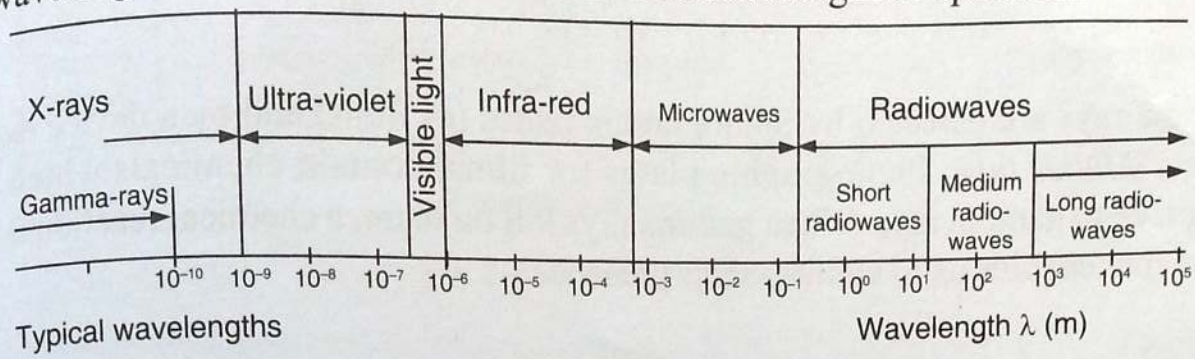


Fig. 11.5: Range of wavelengths for different radiations

11.2 Properties of electromagnetic waves

All electromagnetic waves:

(a) Carry no charge,

(b) Are transverse in nature,

(c) Under suitable conditions, they undergo reflection, refraction, diffraction and show interference effect,

(d) Do not need any material medium to travel i.e. they can travel through a vacuum,

(e) Obey the wave equation $c = f \times \lambda$, where c is the speed of light, f, frequency and λ the wavelength,

(f) Travel in free space (vacuum) at a speed of 3.0×10^8 m/s,

(g) Transfer energy from one place to another,

(h) Can be emitted or absorbed by matter,

(i) Obey the *inverse square law*, i.e intensity (I) is inversely proportional to the square of the distance from the source, r^2. Therefore;

$$I \propto \frac{1}{r^2}$$

(a) Possess energy E that is directly proportional to its frequency, i.e $E \propto f$. Hence $E = hf$ where h is called the *Planck's constant*.

Exercise 11.1

1. Draw a diagram to show the complete electromagnetic spectrum.
2. State five properties of electromagnetic radiations.
3. Name the sources of:
   (a) Visible light. (b) Radiowaves (c) X-rays.
4. Between ultra-violet wave and microwave, which one has the longest wavelength?

11.3 Methods of detecting electromagnetic waves

Gamma rays

Gamma rays are detected by photographic plates (or films) and by a device called *Geiger-Müller tube*. Photographic plates (or films) contain chemicals which are sensitive to gamma rays. When gamma rays fall on them, a chemical reaction takes place that enables us to confirm their presence.

X-rays

X-rays are detected by photographic plates (or films) and fluorescent screens. When X-rays fall on a fluorescent screen (a screen coated with Zinc sulphide), the screen glows. X-rays may also be detected by producing photoelectric effects on metals and the ionisation of gas.

Ultra-violet radiation

Ultra-violet radiations are detected by photographic films and by the fluorescence they cause in some mineral salts. Ultra-violet radiation from the sun causes sun burns on the human skin. Other detectors include photocells and light-dependent resistor.

Visible light

The visible part of electromagnetic spectrum is detected by the human eye, photographic film, photocell and light-dependent resistor. The human eye forms an image on the retina. Photographic films form images of object through chemical reaction triggered off by light. When light falls on a light-dependent resistor (LED) an electric current flows in the circuit due to the reduction of resistance in the circuit. Hence, a LED is also a good detector of visible light.

Infra-red radiation

Infra-red radiations can be detected by *a thermopile*, a blackened bulb of a sensitive thermometer and a heat sensitive paper (thermocromic paper) and a phototransistor. These detectors are sensitive to the heat produced by infra-red radiation.

Radiowaves

Radiowaves are detected by aerials, diodes and earphones in electric circuits. This is because they cause a small electric current to flow in electrical circuits containing such detectors.

It is worth noting that microwaves of shorter wavelengths, infra-red, visible light, ultra-violet and X-rays of longer wavelength all cause a heating effect. These waves are commonly known as *thermal radiation* (Fig. 11.6). It is for this reason that they are detected by instruments that are sensitive to changes in temperature.

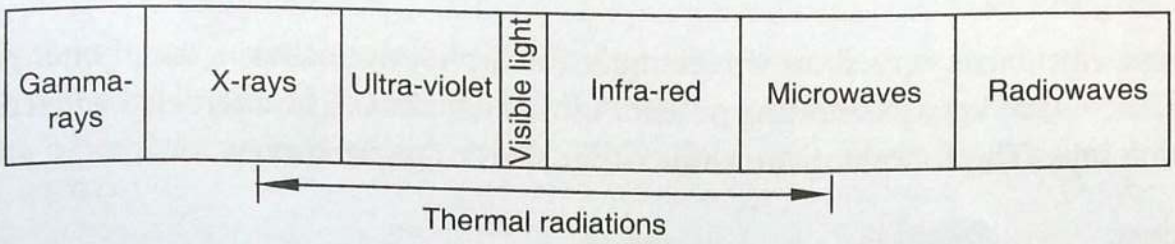


Fig. 11.6: Thermal radiations

Experiment 11.1: Experiment to demonstrate how infra-red radiation can be detected using a thermopile

Apparatus

- Water in a beaker
- Thermopile
- Copper container
- Galvanometer

Procedure

1. Heat some water in a beaker and transfer the water to a copper container. Connect a thermopile to a sensitive galvanometer.
2. Bring the thermopile close to the hot water in the container (Fig. 11.7). What happens to the galvanometer?

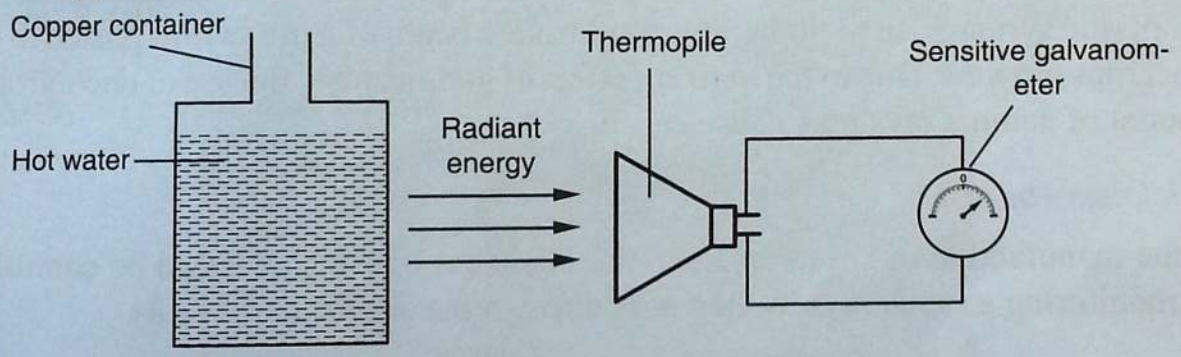


Fig. 11.7: Detecting infra-red radiation

Observation

The galvanometer shows some deflection showing that infra-red radiation has been detected.

11.4 Applications of electromagnetic waves

Electromagnetic radiations are used in many ways. Each member of the complete electromagnetic spectrum has its own uses.

(a) Gamma rays

Gamma rays have very short wavelength. Each photon possess a lot of energy. As such, they have very penetrating power. A lot of care has to be exercised when using gamma rays. The following are some of the uses of gamma rays.

Tracers

Gamma rays are used in medicine to locate internal body organs that are not functioning as expected. For example, if a doctor suspects that a person has non-functioning kidneys, a small amount of technetium-99 substance, that produces γ-rays, is injected into the blood system of person. After some few minutes, a gamma ray scan is taken. If the kidneys are functioning properly, they will extract the technetium-99 and pass it with urine into the bladder. The detector placed outside the body is then able to record a reduced amount of technetium-99 in the blood system. The use of gamma rays in this case is safe because gamma rays cause less ionisation and hence cannot cause any damage to the body cells.

Sterilising

Gamma rays can kill bacteria, mould and insects or worms in food. This helps to prevent the food from going bad quickly. The good thing in this type of sterilisation is that it can be done before or after the food has been packaged. In hospitals, gamma rays are used to sterilise equipments that would otherwise be damaged by heating e.g. plastic syringes. In radiotherapy, a controlled beam of gamma rays is used to kill cancerous growths. Due to the ionising effect of gamma rays, the use of uncontrolled amount of gamma rays may cause cancer.

Thickness control

In the manufacture of sheets of steel, the thickness of the sheets can be controlled by monitoring gamma rays as they pass through the sheets (Fig. 11.8).

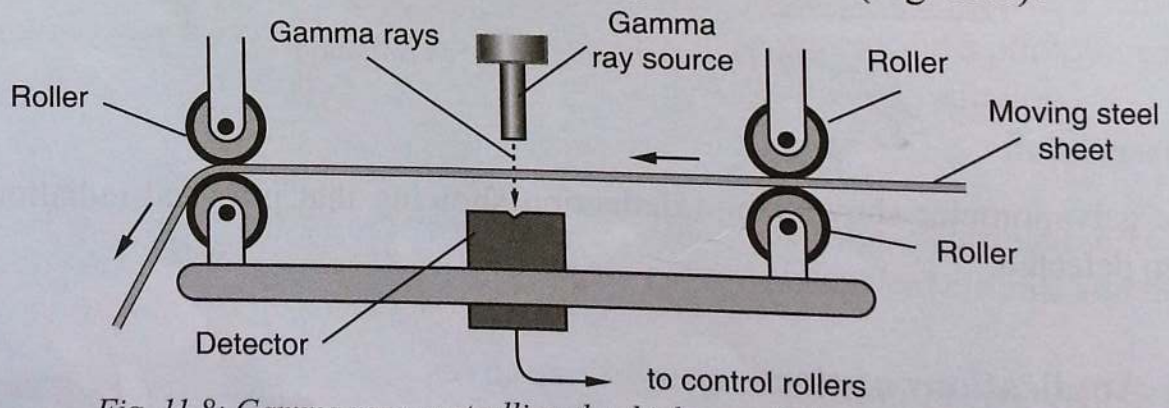


Fig. 11.8: Gamma rays controlling the thickness of sheets in a factory.

If the thickness changes, the current from the detectors automatically adjusts the rollers.

Detecting flaws and cracks

Gamma rays are used to check weak points e.g. in welded joints in materials. A gamma source is placed on one side of the welded material and a photographic film on the other side. In case of any cracks, air bubbles, etc., this shows up in the film (Fig. 11.9).

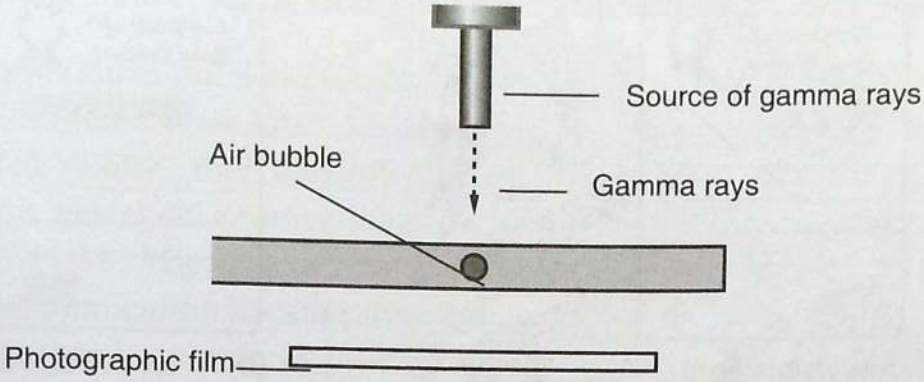


Fig. 11.9: Detecting flaws and cracks using gamma rays

(b) X-rays

X-rays, like gamma rays, have high penetrating power. The X-ray photographs (radiographs) are used by doctors to check on teeth and bones (Fig. 11.10). They are also used by engineers to check the welded metal joints. In factories, X-rays are used to check that food manufactured does not have foreign objects like metals and stones. X-rays are also used in hospitals in the management and treatment of skin disorders. The study of crystal structures (X-ray crystallography), employ the use of X-rays. They are also used in crime detection work e.g. forgery.

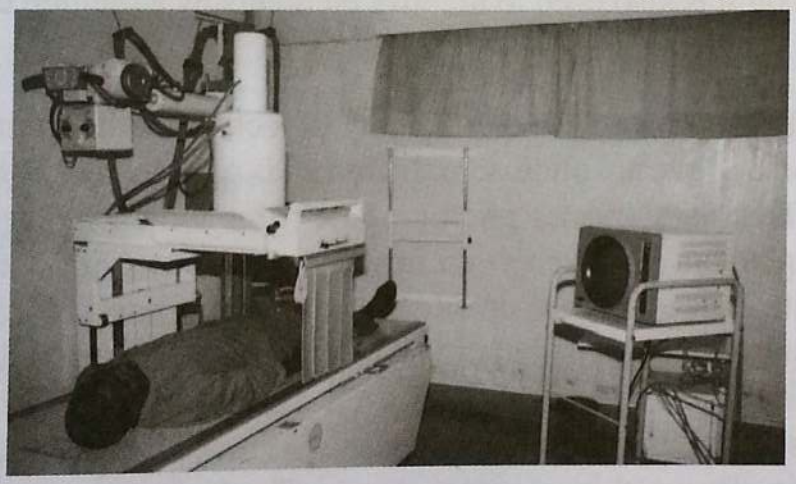
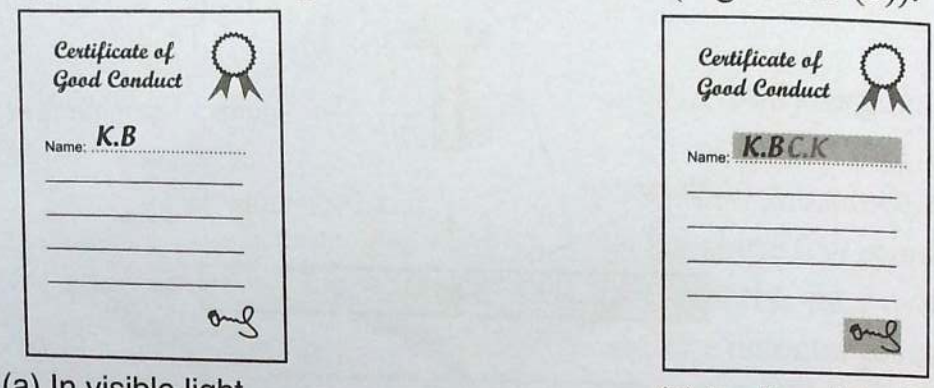


Fig. 11.10: Patient undergoing an X-ray scan

(c) Ultra-violet radiation

Some amounts of ultra-violet rays are useful to us. They produce the much needed Vitamin D in our skin. Large amounts should be avoided as they may damage our eyes and cause skin cancer. Darker skin absorbs less ultra-violet radiation and so less ultra-violet radiation passes through to the living cells. Some washing powders

containing some chemicals that fluoresce and absorb ultra-violet radiation. The absorbed ultra-violet radiation converts the energy to visible light. This makes the clothes washed with such powder look brighter in sunlight. Ultra-violet radiation are also used in detective work e.g. in detecting forgeries. For example, the certificate shown in Fig. 11.11 (a) belongs to C.K and not K.B (Fig. 11.11 (b)).



(a) In visible light (b) In ultra-violet light

Fig. 11.11: Detecting forgeries

Ultra-violet lamps are used to detect forged bank notes. Forged bank notes glow differently in ultra-violet light as compared to genuine ones. In medicine, the ultra-violet lamps are used for skin treatment. Ultra-violet light is also used to identify, stolen items, where a security pen is used to mark the items. This pen use ink that shows up only under ultra-violet light.

(d) Visible light

This is the radiation that helps us to see. Plants use visible light to make their food through *photosynthesis*. *Laser* and *optic fibres* use visible light in communication systems. Visible light is also used to identify elements by a method called *flame test*.

(e) Infra-red

Infra-red is emitted by *warm objects* i.e. any objects including human beings that have a temperature above absolute zero. Infra-red is used to take photographs called *thermographs*. This uses special photographic films which are sensitive to infra-red. Thermographs can be taken even in the dark. They only detect temperature differences. White images are seen on the thermograph for those objects that are losing a lot of heat. Images of objects that are losing less heat appear darker. In hospitals, thermographs are used to reveal the diseased part of the skin. Diseased parts are often hotter. In science, thermographs are used to study temperatures of planets and stars. Infra-red is also used in *burglar alarms*. The intruder emits infra-red which are detected by the burglar alarm. Infra-red which are detected heaters are used to dry wet paint quickly on newly sprayed cars.

(f) Radiowaves

Radiowaves have the longest wavelength in electromagnetic spectrum. They include microwaves, radar, ultra high frequency (UHF), very high frequency (VHF) radio,

short waves, medium waves and long waves. They are used in radio communication.

(g) Microwaves

Microwaves are used for cooking in microwave ovens, satellite communications (Fig. 11.12) and for radar navigation. In microwave oven, the microwaves are absorbed by water molecules in food. On heating up, the water cooks the food.

In satellite communication, a *microwave radio signal* is transmitted from a dish aerial up to the satellite. The satellite then transmit it down to another dish aerial in another location as shown in Fig. 11.12. Microwaves are used in this type of communication because they travel in a straight line and are able to pass through the earth's atmosphere without being affected.

In navigation, a radar uses the reflected microwaves to detect objects e.g. planes in the air (Fig. 11.13).

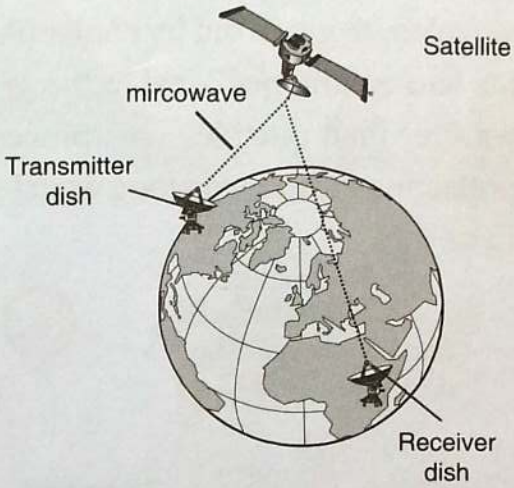


Fig. 11.12: Satellite communication

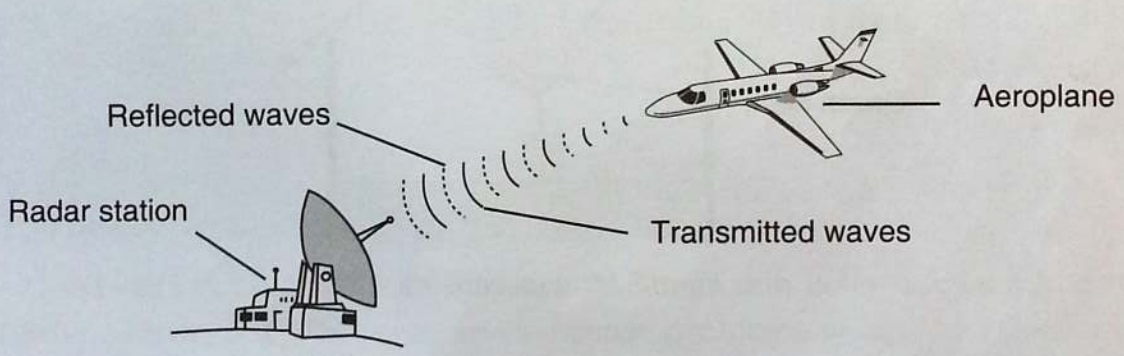


Fig. 11.13: Radar communication

Ultra high frequency (UHF) waves

They are used to transmit television programmes.

Very high frequency (VHF) waves

They are used to transmit local radio programmes and ambulances/ police messages.

Medium waves

They are used to transmit messages over long distance. Since they have long wavelengths, and are diffracted around the mountains, hills and curves of the earth.

11.5 Effects of electromagnetic waves

(a) Greenhouse effect

A greenhouse consists of a glass enclosure (house) with plants (green) being grown inside. Glass allows visible light and short wavelength radiations emitted by very hot bodies (sun) to pass through. On the other hand glass cannot transmit the long wavelength given out by cooler objects e.g. plants (Fig. 11.14). In this way heat from the sun is "trapped" inside the greenhouse. This makes the inside of a greenhouse warmer than outside. This process of allowing in short wavelength radiation and protecting the radiated long wavelengths from escaping is called the *greenhouse effect*.

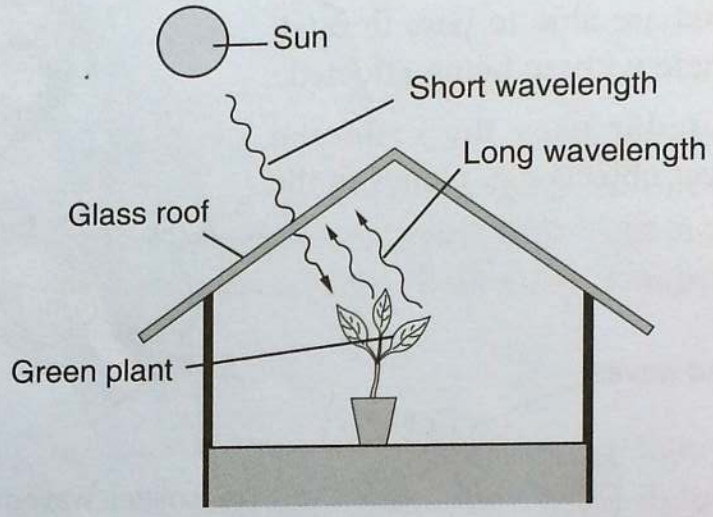


Fig. 11.14: A greenhouse

(b) Global warming

The greenhouse effect can explain what is called *global warming*. Fig. 11.15 illustrates how this takes place The atmosphere allows the short wave radiation from the sun to pass easily to the earth surface. This warms up the ground. The warmed ground radiates heat in form of infra-red radiation into the atmosphere. The atmospheric gases (carbon dioxide, water vapour, etc.) absorb the radiation from the earth. They in turn give out heat. Some of it is directed towards the outer space and the rest back towards the earth. Without carbon dioxide, this energy would be lost. Consequently, the earth gets warmer as a result.

As more and more carbon dioxide is being emitted by factories to the atmosphere, more and more radiation is being directed back to the earth's surface. This is called *global warming*.

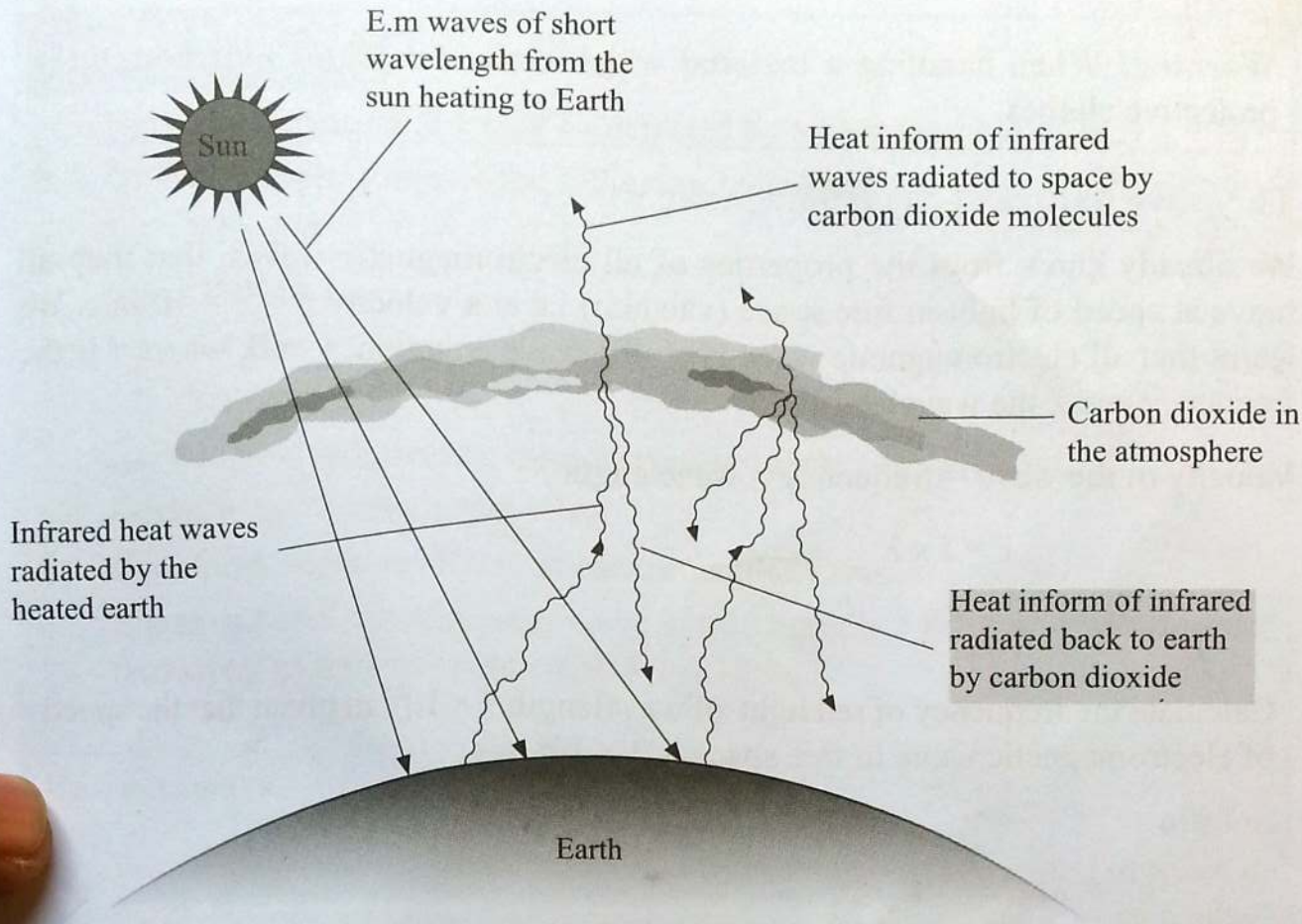


Fig. 11.15: Global warming

(c) Harmful effects of ultra violet radiation

Ultra violet rays causes sunburn that occurs when skin cells are damaged by the absorption of energy. These rays can also cause problems to aquatic ecosystems.

(d) Harmful effects of gamma rays

Gamma rays kill the cells. These rays when exposed to them they may kill body living cells.

The rays can also cause cell mutation.

(e) Effects of x-rays

X-rays can cause cell mutation i.e. DNA changes. They also can cause skin cancer i.e. abnormal growth of living cells.

X-rays can affect childbirth i.e. the rays can lead to deformity in the infant.

These rays can cause baldness i.e. loss of hair on the head.

Warning! When handling a material which emits dangerous radiation, wear protective clothes.

The wave nature of electromagnetic waves

We already know from the properties of all electromagnetic waves, that they all move at speed of light in free space (vacuum) i.e at a velocity $c = 3 \times 10^8$m/s. We learnt that all electromagnetic wave obey the wave equation, $v = f\lambda$ where f is the frequency and λ the wavelength.

Velocity of the wave = frequency × wavelength

$$c = f \times \lambda$$

Example 11.1

Calculate the frequency of red light of wavelength 7×10^{-7} m given that the speed of electromagnetic wave in free space is 3×10^8 m/s.

Solution

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

$$= \frac{3 \times 10^8}{7 \times 10^{-7}}$$

$$= 4.3 \times 10^{14} \text{ Hz}$$

Example 11.2

Red light travels through glass with a speed of 2.2×10^8 m/s. Calculate the wavelength of red light in glass. Comment on your answer.

Solution

From Example 11.1 above the frequency of red light is 4.3×10^{14} Hz. Since the frequency does not change as light travels from one medium to another,

$$\lambda = \frac{c}{f} = \frac{2.2 \times 10^8}{4.3 \times 10^{14}} = 5.1 \times 10^{-7} \text{ m}$$

The wavelength of red light is less in glass than in vacuum. Hence red light is refracted.

Exercise 11.2

1. Name the radiation that may be detected by a photographic plate.
2. Give two applications of the following radiations:
   (a) Infra red
   (b) Ultra violet
   (c) X-rays
   (d) Visible light
3. Explain how radiowaves, microwaves and x-rays are detected.
4. Describe the "Greenhouse effect."
5. Give three negative effects of electromagnetic waves.
6. The speed of electromagnetic wave in free space is 3×10^8m/s. Calculate the frequency of light of wavelength 8.1×10^{-7}m.

Unit summary

- Electromagnetic waves are transverse waves that are propagated in space or matter by oscillation of electric and magnetic field at right angle to each other.
- Electromagnetic radiations are emitted by different sources. Table 11.1 summarises the production of the electromagnetic waves.

Table 11.1

Types of radiation	Production
Gamma rays	Gamma rays are emitted by some radioactive materials. They come from within the nucleus when large energy changes occur within the nucleus.
X-rays	X-rays are produced when very fast moving electrons are suddenly stopped by a heavy metal e.g. tungsten. The production takes place in an X-ray tube.
Ultra-violet	Emitted by very hot bodies, spark and arc wedding metals, carbon arcs lamp, discharge tubes mercury vapour lamp and the sun.
Visible light	Light is produced by sun, flames, hot bodies, lamps, lasers, etc.
Infra-red	Emitted by the sun, warm and hot bodies such as people and fires.
Radiowaves	Produced from electrons moving in conductors and aerials.

- Table 11.2 summarises the applications of electromagnetic radiations.

Table 11.2

Types of radiation	Applications
Gamma rays	In medicine, gamma rays are used in gamma ray therapy i.e. they are used to destroy cancerous cells in human beings. However, care is usually taken not to kill healthy human cells. The rays are also used in sterilisation of equipment in industries, the rays are used in detecting flaws in metal casting. One advantage of gamma rays application is that no high voltage are required.
X-rays	In medicine, X-rays are used in X-ray photography and in the treatment of cancerous cells and tumours. In agriculture, X-rays are used to control pests. In industries, they are used in the detection of flaws and cracks in metal castings. High voltage are required to operate X-rays machines.
Ultra-violet	Ultra-violet radiations are used in burglar alarms, automatic door openers, counters, detecting forged bank notes, photo finishing in races. Ultra-violet from the sun is used by the skin (human) to produce vitamin D. Excessive ultra-violet is harmful to the eye and skin. Since they cause fluorescence, they are used in advertising signs.
Visible light	Visible light is used by the human eye to enable us to see. Plants use visible light to manufacture their food in the process called photosynthesis. Ordinary photography uses visible light.
Infra-red	Infra-red is used in infra-red photography, drying of objects and as a source of warmth.
Radiowaves	Used in radio and television communication and also in radar detection. Microwaves are used in cooking and radar communication.

- Speed of electromagnetic waves is 3×10^8 m/s in air (vacuum).
- Electromagnetic waves are arranged in order of their wavelengths. This forms an electromagnetic spectrum.
- Greenhouse effect is the trapping of energy from hot bodies as the energy travel through a material and changing it to energy of longer wavelength which cannot escape through the material.

- Electromagnetic waves can be detected using various detectors as shown in Table 11.3.

Table 11.3

Types of radiation	Detectors
Gamma rays	• Geiger-Müller tube
X-rays	• Photographic plates and films • Fluorescent screen
Ultra-violet	• Photographic film • Photocells • Light-dependent resistor
Visible light	• Eye • Photographic film • Photocells • Light-dependent resistor
Infra-red	• Special photographic film • Skin • Light-dependent resistor • Thermopile • Blackened bulb of a sensitive thermometer • Special heat sensitive paper
Radiowaves	• Aerials in radio and television.

Unit Test 11

1. A wave that have got both electric and magnetic field is called
   A. Electric wave B. Nuclear wave
   C. Electromagnetic wave D. Sound
2. Which one of the following is odd one out?
   A. Infra-red B. Sound
   C. Light D. X-rays
3. Among x-rays, visible light, gamma rays and radiowave, which one has a highest frequency?
   A. X-rays B. Visible light
   C. Light D. Gamma-rays

4. A red hot body produces the following types of radiation
   - **A.** Visible light and infra-red
   - **B.** X-rays and radiowaves
   - **C.** Gamma and x-rays
   - **D.** Visible light and microwave
5. Name an electromagnetic wave that is used in baking
   - **A.** X-rays
   - **B.** Gamma-ray
   - **C.** Ultra-violet
   - **D.** Microwave
6. The following are properties of electromagnetic waves, which one is not.
   - **A.** They carry charges.
   - **B.** They are transverse in nature.
   - **C.** They carry no charge.
   - **D.** They transfer energy.
7. A radiowave has a wavelength of 2×10^2 m. If the speed of light is 3×10^8 m/s. Calculate the frequency of the radiowave.
   - **A.** 6×10^{16} Hz
   - **B.** 1.5×10^6 Hz
   - **C.** 1.5×10^6 m
   - **D.** 6×10^6 m/s
8. Infra-red radiation is detected by
   - **A.** Photographic film
   - **B.** Thermopile
   - **C.** Human eye
   - **D.** Fluorescent screen
9. The following are uses of gamma rays. Which one is exceptional
   - **A.** Gamma rays are used as tracers
   - **B.** Gamma rays are used as a sterilizer
   - **C.** Gamma rays are used to control thickness of materials.
   - **D.** Gamma rays used in oven.
10. Explain why radiation emitted by a very hot body is different from that emitted by a warm body.
11. What is global warming effect?
12. Fig. 11.15 shows regions of electromagnetic spectrum. Name the region marked by the letters A, B, C and D.

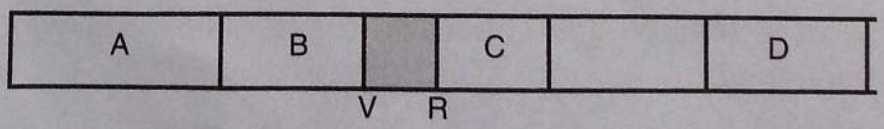


Fig. 11.15: Electromagnetic spectrum

13. State one difference between ultra-violet and X-rays.
14. A broadcasting station sends out radiowaves of wavelength 1 500 m. Calculate the frequency of the waves. (Take $c = 3 \times 10^8$ m/s)
15. Draw an electromagnetic spectrum and indicate the:
    (a) Regions of the spectrum that ionise air,
    (b) Region that cause fluorescence.
16. Explain two uses of Gamma rays

UNIT

12 Light and Lenses

Specific outcomes

By the end of this unit, you must be able to: -

- Describe converging and diverging lenses.
- Determine the focal length of a converging lens.
- Explain image formation by converging lens.
- Describe image formation using ray diagrams.
- Solve problems involving the lens and manification formulae.
- Describe the application of lenses in various optical devices.
- Explain image formation in the human eye
- Describe the defects of vision in the human eye and how they are corrected.

Introduction

We have already learnt that light waves are refracted when they travel from one medium to another medium of different optical density. In this unit, we shall learn about the refraction of light rays at transparent curved surfaces (lenses). We will also learn about how the knowledge of formation of images by thin lenses is applied in the making of instruments like cameras, telescopes, microscopes etc.

12.1 Types of lenses

Converging (convex) lenses and diverging (concave) lenses

A lens is a transparent medium bound between two surfaces of definite geometrical shape. Lenses are made in different shapes and from different types of glasses. There are mainly two types of lenses namely convex (converging) lens and concave (diverging) lens.

(a) **A convex lens** is thicker at its centre than at its edges. It converges light rays incident on it. A *bi-convex* or *double convex* lens has both its surfaces 'curving out'. Other convex lenses are *plano-convex* and *concavo-convex* or *converging meniscus* (Fig. 12.1).

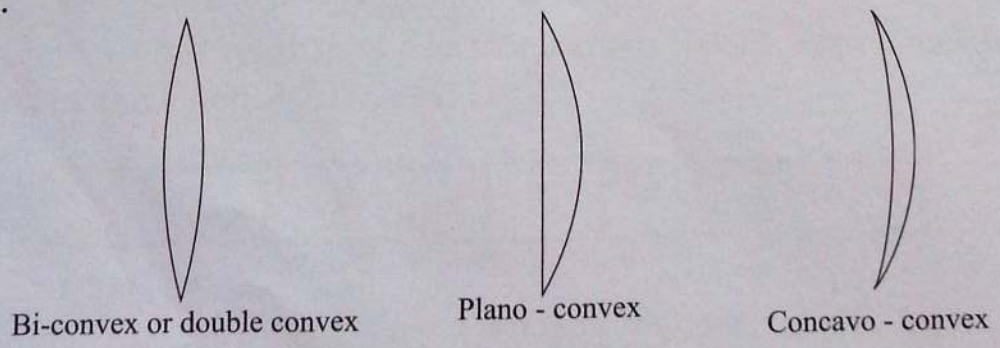


Fig. 12.1: Types of convex lenses

(b) **A concave lens** is thicker at its edges than at its centre and diverges the light rays incident on it. A *bi-concave* or *double concave* lens has both its surfaces 'curving in'. Other concave lenses are *plano-concave* and *convexo-concave* or diverging meniscus (Fig. 12.2).

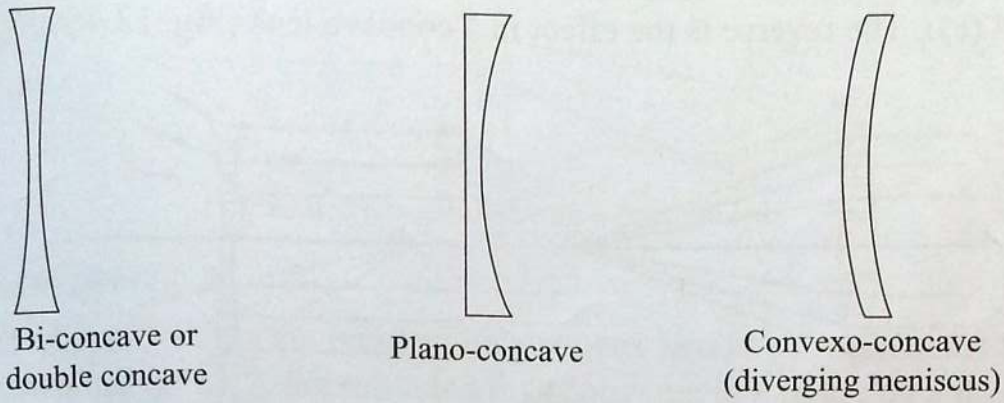


Fig. 12.2: Types of concave lenses

12.2 Terms used in thin lenses

The following terms are commonly used in thin lenses:

(a) The centre of curvature (C)

The centre of curvature of the surface of a lens is the *centre of the sphere* of which the surface forms a part (Fig. 12.3 (a) and (b)). For each spherical lens there are two centres of curvature (c_1, c_2) due to the two curved surface.

(b) The radius of curvature (r)

The radius of curvature of the surface of a lens is the *radius of the sphere* of which the surface forms a part (Fig. 12.3 (a) and (b)). Each surface has its own radius of curvature (r_1 and r_2).

(c) Principal axis

The principle axis of a lens is a line passing through the two centres of curvature (c_1 and c_2) as shown in Fig. 12.3.

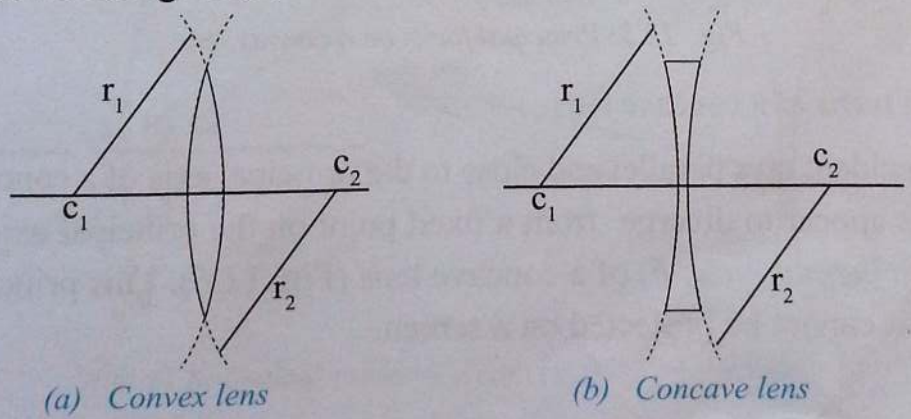


Fig. 12.3: Principal axis

(d) The principal focus

A prism always deviates the light passing through it towards its base. A convex lens may be regarded as being made up of large portions of triangular prisms as shown below. The emergent beam, therefore, becomes convergent in a convex lens (Fig. 12.4 (a)). The reverse is the effect in a concave lens (Fig. 12.4(b)).

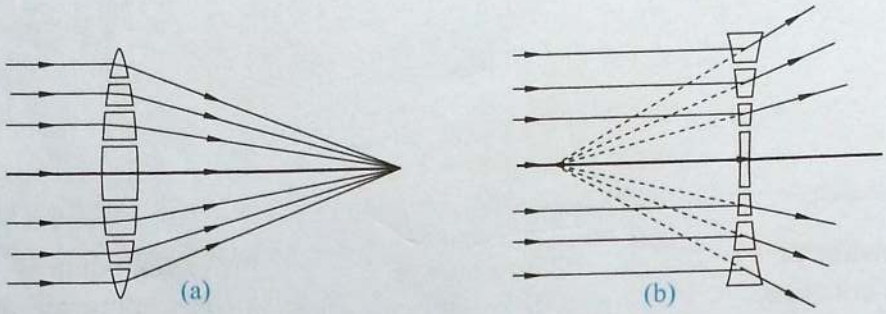


Fig. 12.4: Action of lenses compared with prisms

(i) Principal focus of a convex lens

Consider a set of incident rays parallel and close to the principal axis of a convex lens (Fig. 12.5). These rays, after refraction through the lens, pass through point F on the principal axis. Since all the rays converge at this point, it is called *principal focus*. Since this point can be projected on a screen, it is said to be a *real principal focus*.

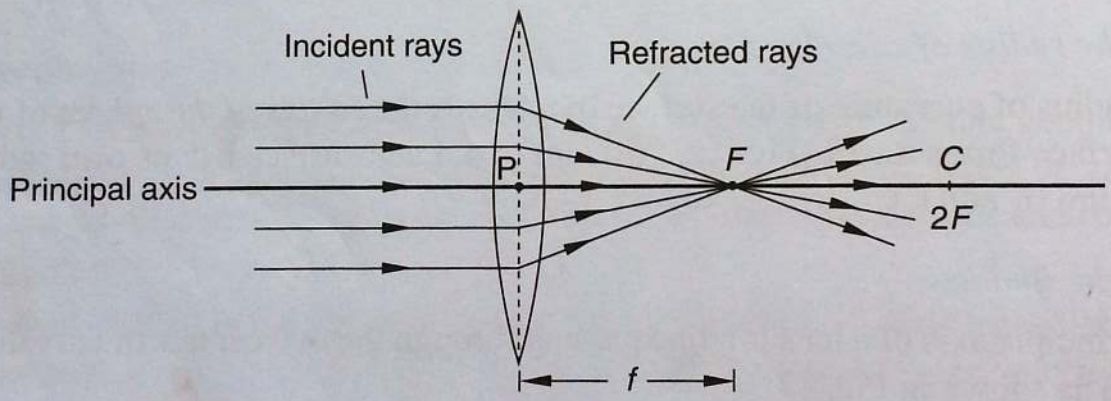


Fig. 12.5: Principal focus on a convex lens

(ii) Principal focus of a concave lens

For a set of incident rays parallel and close to the principal axis of a concave lens, the refracted rays appear to diverge from a fixed point on the principal axis. This point is called the *principal focus F*, of a concave lens (Fig. 12.6). This principal focus is virtual since it cannot be projected on a screen.

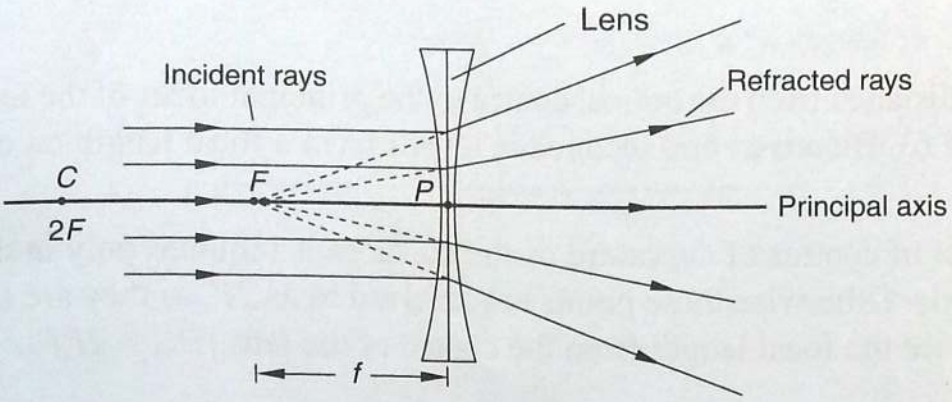


Fig. 12.6: Principal focus on a concave lens

(e) The focal plane

When a set of parallel rays are incident on a convex lens at an angle to the principal axis, as shown in Fig. 12.7, the refracted rays converge to a point, on a line passing through F and perpendicular to the principal axis. The plane passing through F is the *focal plane*.

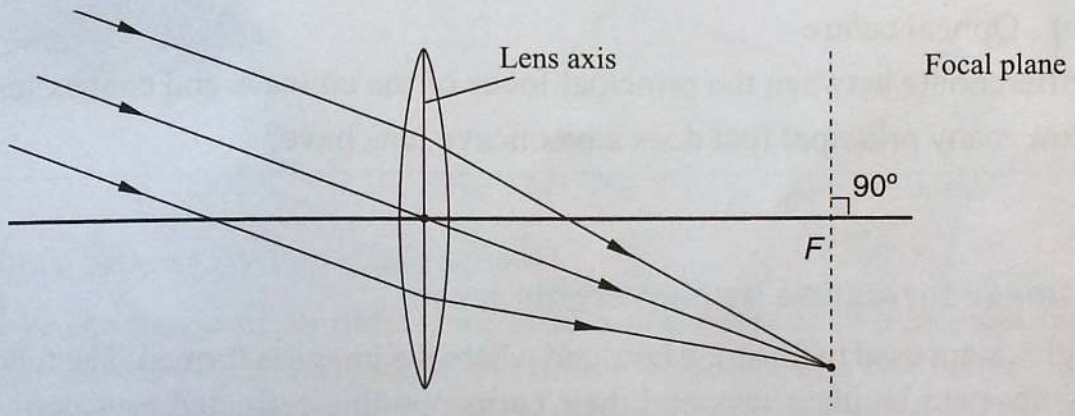


Fig. 12.7: Focal plane of a convex lens

(f) The optical centre (P)

The *optical centre* of a lens is a point which lies exactly in the middle of the lens (PA = PB) as shown in Fig. 12.8(a) and (b). Light rays going through this point go straight through without any deviation or displacement.

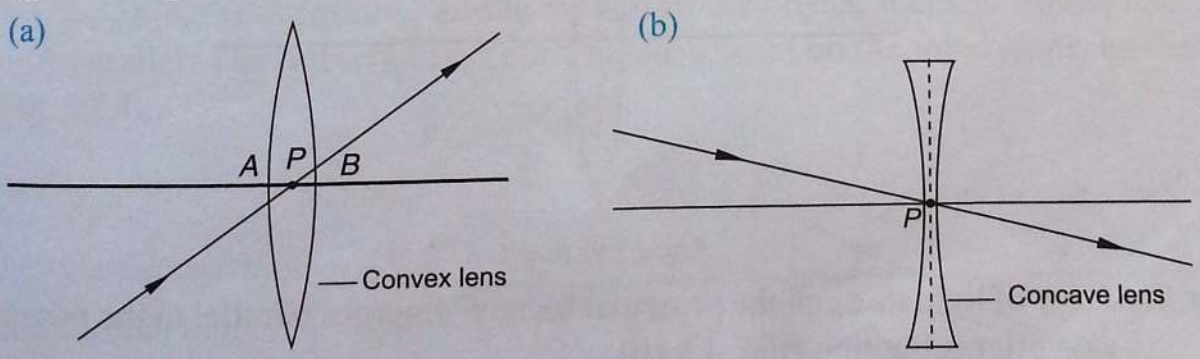


Fig. 12.8: Optical centre of a convex and concave lenses

(g) The focal length of a lens (f)

This is the distance from the optical centre to the principal focus of the lens (see Fig. 12.5 and 12.6). Biconvex and biconcave lenses have a focal length on each side of the lens.

The concept of centres of curvature of the surfaces is required only in drawing the principal axis. Otherwise these points are referred to as *2F*, as they are situated at a distance twice the focal length from the centre of the lens *(PC = 2PF)*.

Exercise 12.1

1. Distinguish between converging and diverging lenses.
2. Define the following:
   (a) Principal axis
   (b) Optical centre
3. Differentiate between the principal focus of the concave and convex lens.
4. How many principal foci does a biconcave lens have?

12.3 Image formation by converging lenses

Ray diagrams are used to illustrate how and where the image is formed. The following are the important incident rays and their corresponding refracted rays used in the construction of ray diagrams.

Ray 1: A ray of light parallel and close to the principal axis, passes through the principal focus *F* (Fig. 12.9).

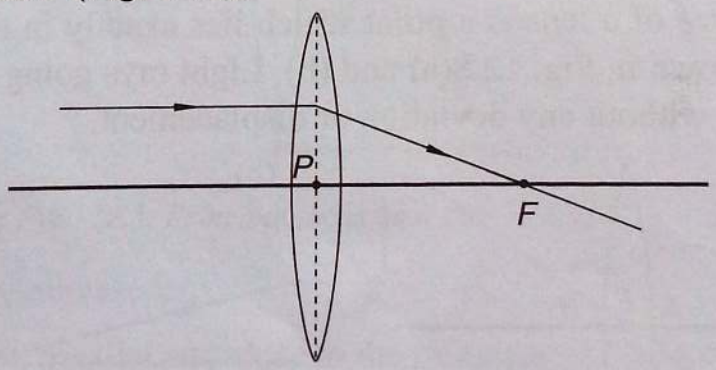


Fig. 12.9: Ray 1

Ray 2: A ray of light through the principal focus *F* emerges parallel to the principal axis after refraction (Fig. 12.10).

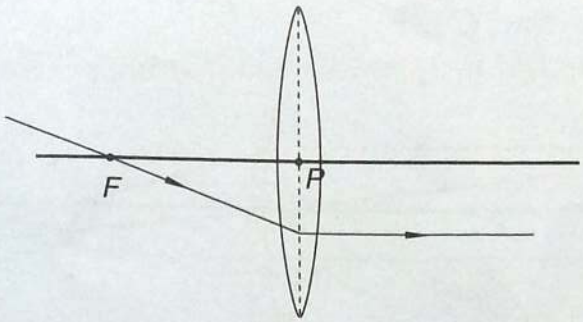


Fig. 12.10: Ray 2

Ray 3: A ray through the optical centre, *P* is undeviated after refraction through the lens (Fig. 12.11).

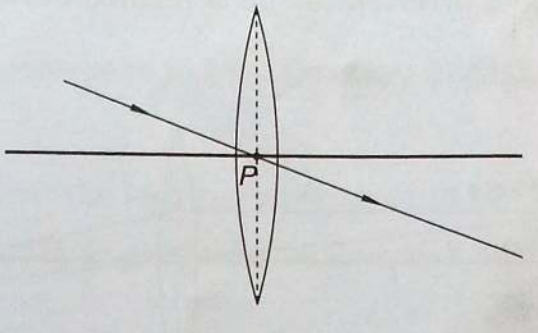


Fig. 12.11: Ray 3

Locating images by ray diagrams

To locate the image of an object, we need a minimum of two incident rays from the object. From the three standard rays discussed above, any two incident rays and their corresponding refracted rays can be drawn to locate the image. If the refracted rays converge, a *real image* is obtained. If the refracted rays diverge, then a virtual image is obtained.

Convex lens

(a) Object far away from the lens (at infinity)

Since the object is at infinity, all the rays from the object, incident on the lens are almost parallel. The refracted rays converge at a point on the focal plane, as shown in Fig. 12.12.

Image characteristics

A *diminished, real and inverted* image is formed at *F*.

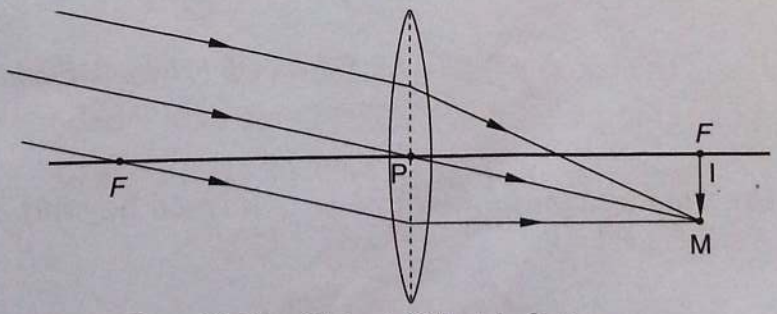


Fig. 12.12: Object OB at infinity

(b) Object OB just beyond C (2F)

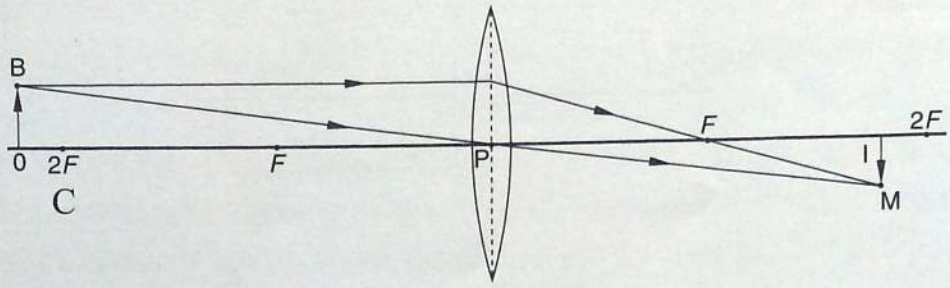


Fig. 12.13: Object OB just beyond 2F

Image characteristics

A *diminished, real and inverted* image is formed between *F* and 2*F(c)*.

(c) Object OB at 2F (C)

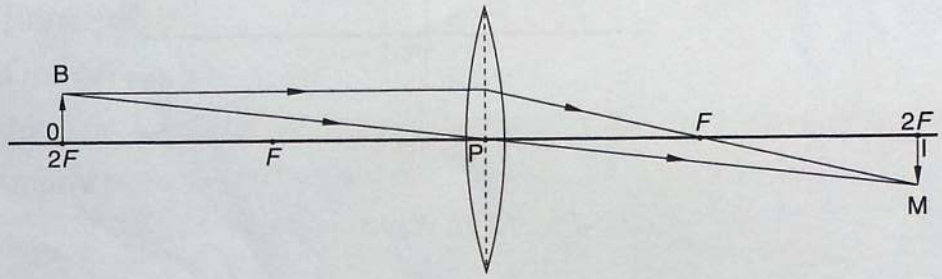


Fig. 12.14: Object OB at 2F

Image characteristics

A *real and inverted* image of the *same size* as the object is formed at 2*F*

(d) Object OB between 2F and F

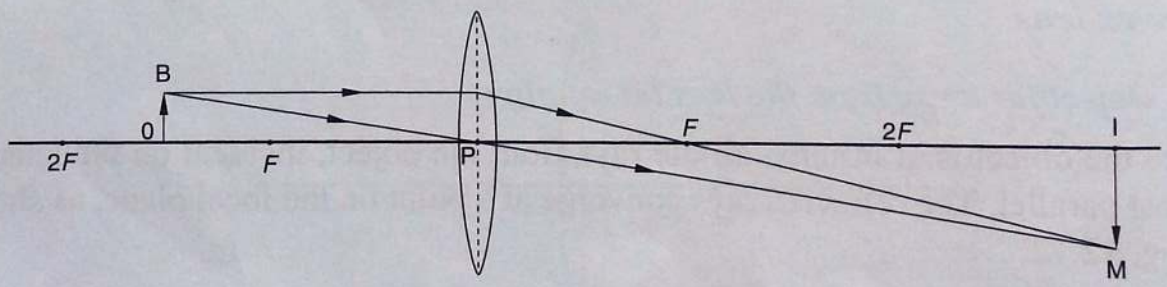


Fig. 12.15: Object OB between 2F and F

Image characteristics

A *real, inverted* and *magnified* image is formed beyond 2*F*.

(e) Object OB at F

The refracted rays are nearly parallel and converge at infinity (Fig. 12.16).

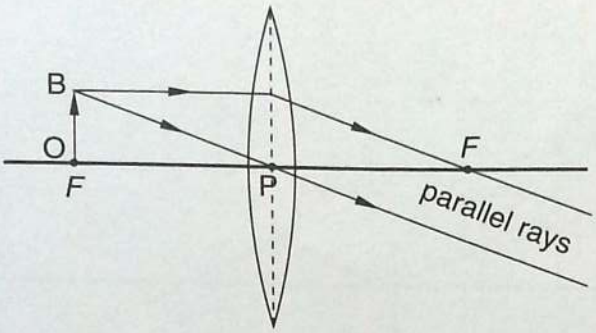


Fig. 12.16: Object OB at F

Image characteristics

A *real, inverted and magnified* image is formed far away from the lens i.e. at infinity (cannot be described).

(f) Object OB between F and the lens i.e. very close to the lens

The refracted rays diverge and when produced backwards a virtual image is formed (Fig. 12.17).

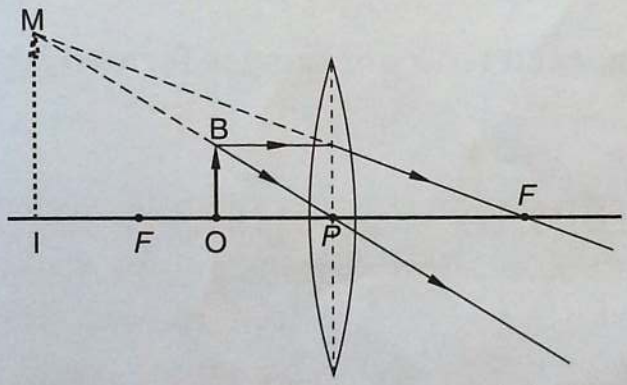


Fig. 12.17: Object OB between F and the lens.

Image characteristics

A *magnified, upright* and *virtual* image is formed on the same side as object.

Example 12.1

A convex lens has a focal length of 12 cm and a real object 6 cm tall is placed at 18 cm from the centre of the lens. By means of an accurate scale diagram, find the position, size and nature of the image formed.

Solution

Using rays 1 and 3 of the image construction, two incident rays are drawn from B

and the corresponding refracted rays through the lens. The refracted rays converge at M where the image of B is formed.

Scale chosen: 1 cm = 6 cm.

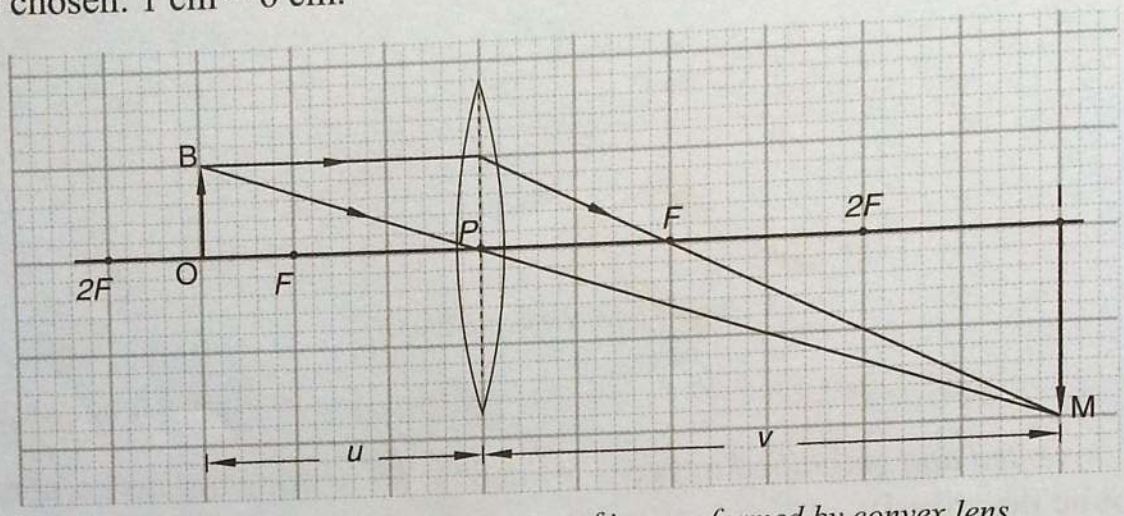


Fig. 12.18: Graphical construction of images formed by convex lens

The image of O is formed at I. IM is the real image formed at 6 cm from the lens. The height of the image is 2 cm. Since the scale is 1 cm represents 6 cm, the image is 36 cm from the lens and the height of the image is 12 cm (Fig. 12.18).

Investigating the characteristics of images formed by thin lenses

Convex lens

Experiment 12.1: To determine the characteristics of images formed by convex lenses

(a) Object at infinity

Apparatus

- White screen
- tree
- lens
- metre rule

Procedure

1. Position a convex lens vertically in front of a tree far away from the lens (through a window).
2. Place a white screen on the other side of the lens as shown in Fig. 12.19. Adjust the screen until you see a sharp image of the tree.
3. Compare the size of the image with that of the object (tree). Is the image bigger or smaller? Is it upright or inverted?
4. Measure the distance from the lens to the screen. What does this distance represent in this set up?

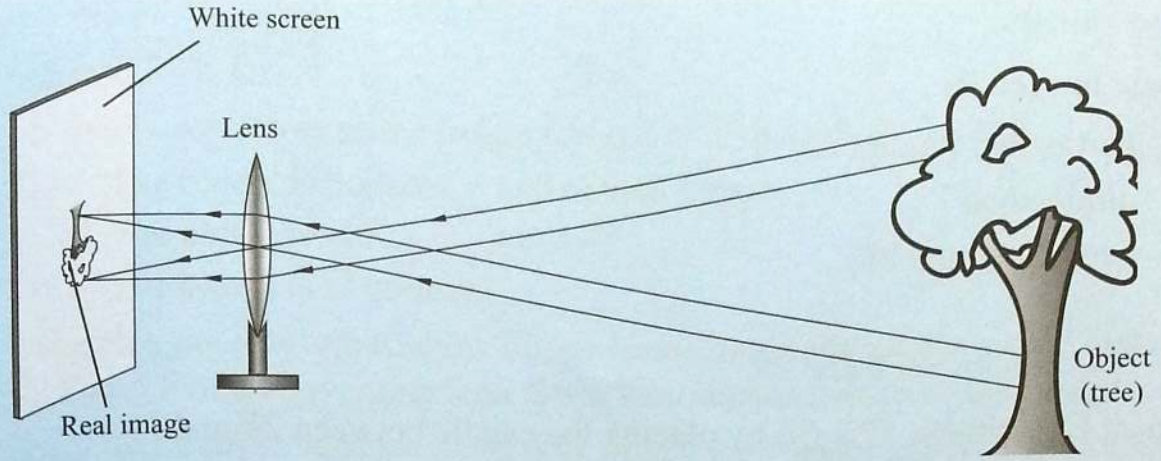


Fig. 12.19: Object at infinity

Note: The distance from the centre of the lens to the screen is nearly equal to the focal length, *f*, of the lens.

Observation

The image formed is:

- inverted
- smaller than the object
- at F

(b) Object beyond 2F

Apparatus

- Screen
- lens
- candle

Procedure

1. Mark the positions of the principal focus *F* and 2*F* on both sides of the lens with a piece of chalk. Place a lit candle on the table along the principal axis of the lens, slightly away from 2*F*.
2. Place a white screen, on the other side of the len perpendicular to the principal axis of the lens and adjust its position until a sharp image is formed (Fig. 12.20).

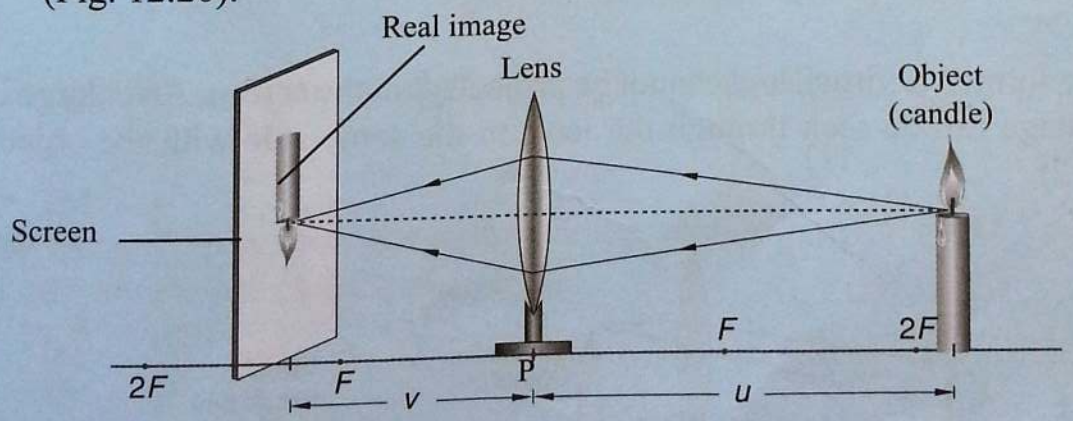


Fig. 12.20: Object beyond 2F

What are the characteristics of the image formed?

Observation

Image formed is:

- vertically inverted
- diminished
- between F and 2F.

(c) Object between F and 2F

Repeat Experiment 12.1 (b) by placing the candle between $2F$ and F.

What can you say about the characteristics of the image formed on the screen (Fig. 12.21)?

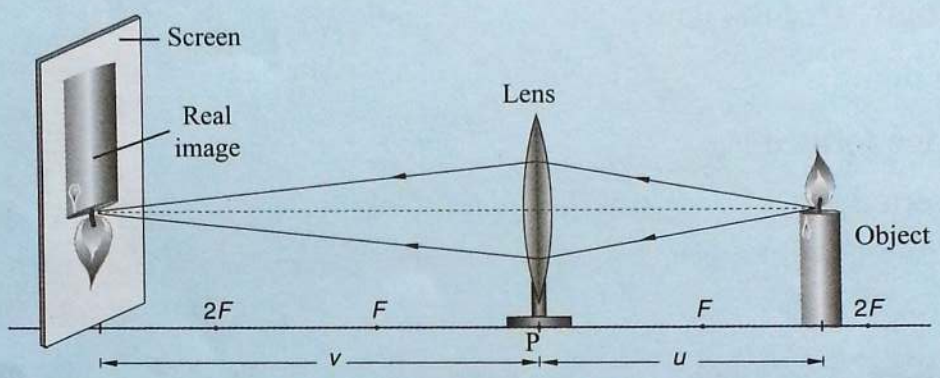


Fig. 12.21: Object between 2F and F

Observation

The image formed is *inverted*, *between F and 2F*, and *larger than objects*.

(d) Object between F and P

Repeat experiment 12.1 (c) by keeping the candle close to the lens, between F and P. Can you get an image on the screen?

Observation

The image formed is virtual and cannot be projected on the screen. An enlarged, upright image can be seen through the lens on the same side with the object (Fig. 12.22).

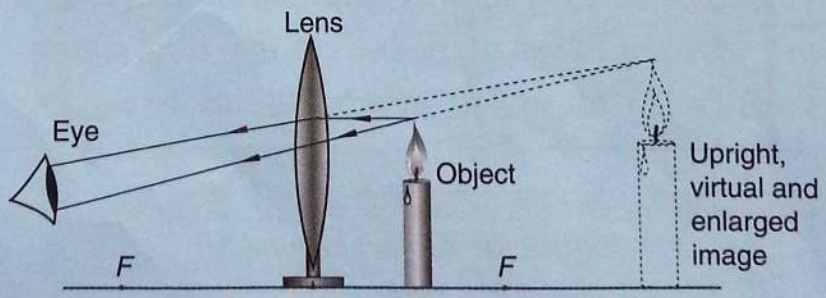


Fig. 12.22: Object between F and P

Exercise 12.2

1. Name two features of the image formed by a convex lens when:
   (a) The object is between F and optical centre.
   (b) The object is at F.
   (c) The object is at infinity.
2. Sketch a ray diagram to show image formation for an object placed between 2 F and F of a converging lens. State four characteristics of the image.
3. (a) If a convex lens picks up rays from a very distant object, where is the image formed?
   (b) If the object is moved towards the lens, what happens to the position and size of the image?
4. An object 2 cm high is placed 12 cm away from a convex lens of focal length 6 cm. By using an accurate drawing on graph paper, find the position, height and type of image.

12.4 The lens formula

The lens formula is a formula relating the focal length, image and object distance.

Consider a convex lens of focal length, *f*, which forms a real image IM of an object OB as shown in Fig. 12.23.

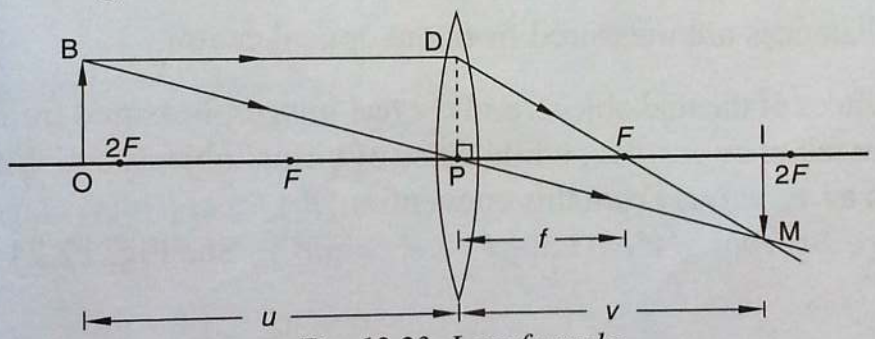


Fig. 12.23: Lens formula

Triangles OBP and IMP are similar (3 angles are equal)

$$\therefore \frac{OB}{IM} = \frac{OP}{IP} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

Draw a line DP perpendicular to the principal axis where DP = BO. Triangles PDF and IMF are similar (3 angles are equal)

$$\therefore \frac{DP}{IM} = \frac{PF}{IF} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

Since DP = OB, from equations (1) and (2),

$$\frac{OP}{IP} = \frac{PF}{IF}$$

$$\frac{u}{v} = \frac{f}{v-f}$$

Cross multiplying, $uv - uf = vf$

Dividing both sides by uvf

$$\frac{uv}{uvf} - \frac{uf}{uvf} = \frac{vf}{uvf} \Rightarrow \frac{1}{f} - \frac{1}{v} = \frac{1}{u}.$$

Hence $\frac{1}{f} = \frac{1}{u} + \frac{1}{v}$. This is the Lens formula.

Symbols used for different distances:

u stands for the distance of the object from the optical centre (object distance).

v stands for the distance of the image from the optical centre. (image distance).

f stands for the focal length of the lens.

Sign Convention (Real is positive)

There are several sign conventions used when the distances of the object and the image are measured from the lens. In this book, we shall adopt the *real is positive* in which:

1. All the distances are measured from the optical centre.
2. The distances of the real objects and the real images measured from the optical centre are taken as *positive*, while those of virtual objects and virtual images are taken as *negative*. From this convention, *the focal length of a convex lens is positive and that of a concave lens is negative*. See Fig. 12.24 (a) and (b).

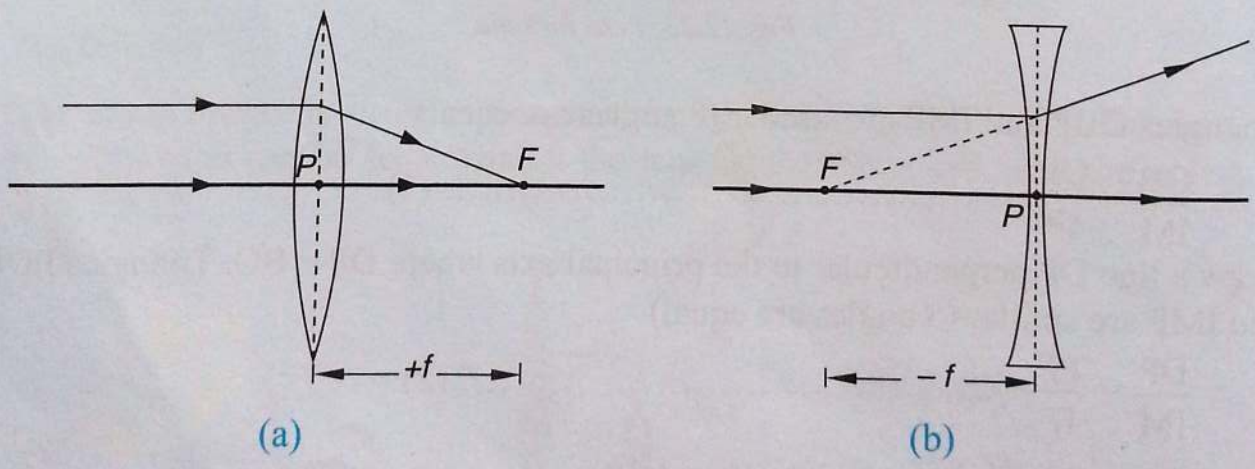


Fig. 12.24: Real and virtual focal lengths of lenses

Example 12.2

An object is placed 24 cm from the centre of a convex lens of focal length 20 cm. Calculate the distance of the image from the lens.

Solution

From $\frac{1}{f} = \frac{1}{v} + \frac{1}{u}$

$$\Rightarrow \frac{1}{v} = \frac{1}{f} - \frac{1}{u}$$

$u - 24\ cm\ and\ f = 20\ cm$

$$= \frac{1}{20} - \frac{1}{24}$$

$$= \frac{6-5}{120} = \frac{1}{120}$$

The image distance (v) = 120 cm

Example 12.3

An object is placed 12 cm from the centre of a concave lens of focal length 20 cm. Calculate the distance of the image from the lens.

Solution

From lens formula; $\frac{1}{f} = \frac{1}{v} + \frac{1}{u}$

$$\Rightarrow \frac{1}{v} = \frac{1}{f} - \frac{1}{u}$$

$u = 24\ cm\ and\ f = 20\ cm$

$$= \frac{1}{-20} + \frac{1}{12}$$

$$= \frac{^-3-5}{60} = \frac{^-8}{60}$$

$$v = \frac{^-60}{8} = {}^-7.5\ cm$$

v is negative because the image is virtual.

12.5 Magnification formula

The term magnification refers to how many times an image is bigger than the object. Linear magnification (m) is defined as the ratio of the height of the image to the height of the object.

$$\text{Linear magnification } (m) = \frac{\text{height of the image}}{\text{height of the object}} = \frac{h_1}{h_0}$$

$$= \frac{\text{image distance (v)}}{\text{object distance (u)}} = \frac{v}{u}$$

Sometimes it becomes difficult to measure the height of the image or the object accurately. In such cases, magnification can be calculated in terms of object distances ***u*** and image distance ***v***. For example, consider a convex lens where a magnified image is formed (Fig. 12.25).

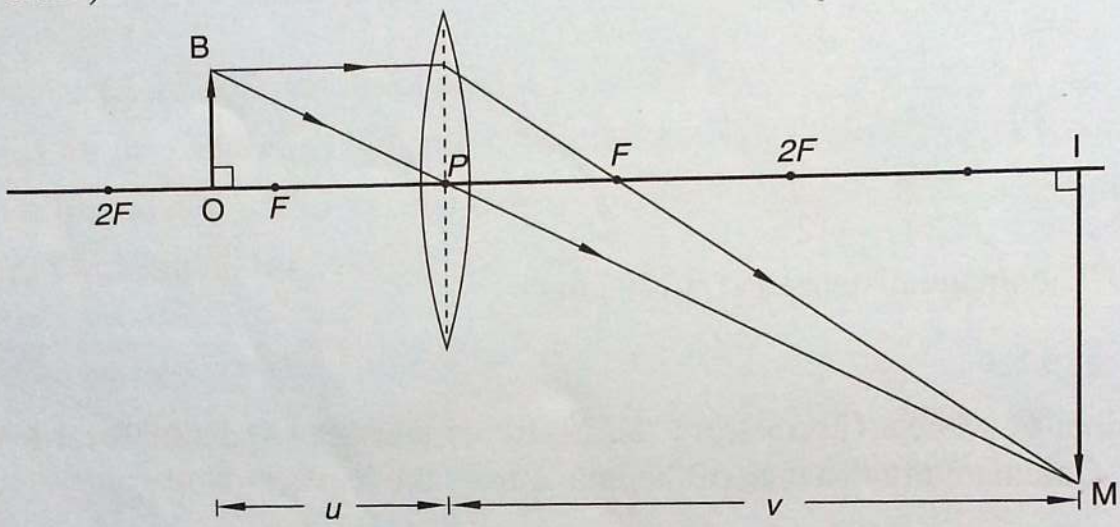


Fig. 12.25: Magnification

Since triangles OBP and IMP are similar (3 angles are equal), the ratios of corresponding sides are equal i.e,

$$\frac{IM}{IP} = \frac{OB}{OP}$$

$$\therefore \frac{IM}{OB} = \frac{IP}{OP} = \frac{v}{u}$$

Hence magnification, $m = \frac{IM}{OB} = \frac{v}{u}$

$$m = \frac{\text{image distance (v)}}{\text{object distance (u)}}$$

$$m = \frac{v}{u}$$

$$\therefore m = \frac{h_1}{h_0} = \frac{v}{u}$$

i.e, the ratio of image to object sizes $\left(\frac{h_i}{h_o}\right)$ is also equal to the ratio of image to object distances $\left(\frac{v}{u}\right)$ measured from the optical centre.

Example 12.4

An object of height 2 cm is placed 20 cm infront of a convex lens. A real image is formed 80 cm from the lens. Calculate the height of the image.

Solution

$$m = \frac{h_i}{h_0} = \frac{v}{u}$$

$h_0 = 2$ cm, $u = 20$ cm, $v = 80$ cm

$$\Rightarrow \frac{h_i}{2} = \frac{80}{20}$$

$$\therefore h_i = \frac{\cancel{80}^{1} \times \cancel{2}}{\cancel{20}_{1}} = 8 \text{ cm}$$

Example 12.5

An object placed 30 cm from a convex lens produces an image of magnification 1. What is the focal length of the lens?

Solution

Magnification, $m = \frac{OB}{IM} = \frac{OP}{IP} = 1$. (Fig. 12.26)

$u = 30$ cm

Since $m = 1$; then $v = u$

This occurs when object is at $2f$.

Hence $2f = 30$

$\therefore \quad f = 15$ cm

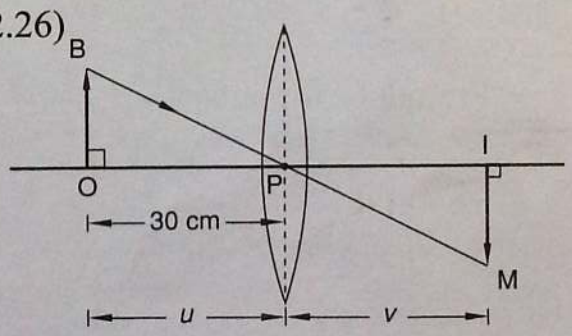


Fig. 12.26: Image formed by convex lens

Example 12.6

An object of height 1.2 cm is placed 12 cm from a convex lens and real image is formed at 36 cm from the lens. Calculate

(a) the focal length of the lens

(b) magnification produced by the lens

(c) the size of the image.

Solution

(a) From lens formula, $\frac{1}{u} + \frac{1}{v} = \frac{1}{f}$

$$\frac{1}{12} + \frac{1}{36} = \frac{1}{f}$$

$$\frac{3+1}{36} = \frac{4}{36} = \frac{1}{f}$$

$$\frac{1}{9} = \frac{1}{f} \Rightarrow f = 9 \text{ cm}$$

Focal length of the lens = 9 cm

(b) $m = \frac{v}{u} = \frac{36}{12} = 3$

(c) $m = \frac{h_i}{h_0}$

$\therefore h_i = 3 \times 1.2 = 3.6$

Size of the image = 3.6 cm

Example 12.7

An object of height 2 cm is placed 8 cm from a convex lens and a virtual image is formed on the same side as the object at 24 cm from the lens. Calculate:

(a) the focal length of the lens (b) the height of the image formed.

Solution

(a) From lens formula, $\frac{1}{u} + \frac{1}{v} = \frac{1}{f}$

$$\frac{1}{8} + \frac{1}{^{-}24} = \frac{1}{f} \quad (v = -24 \text{ cm because the image is virtual})$$

$$\frac{3-1}{24} = \frac{1}{f} \Rightarrow \frac{1}{12} = \frac{1}{f}$$

$\therefore$ focal length, f = 12 cm

(b) Magnification $m = \frac{v}{u} = \frac{h_1}{h_0} \Rightarrow \frac{^{-}24}{8} = \frac{h_1}{2}$

$$\therefore h_i = \frac{-24 \times 2}{8} = {}^{-}6 \text{ cm (negative sign indicate image is virtual)}$$

Example 12.8

A convex lens produces a real image of an object and the image is 3 times the size of the object. The distance between the object and the image is 80 cm. Calculate the focal length of the lens.

Solution

Magnification $m = \frac{v}{u} = 3$

$\therefore v = 3u$ ..... (1)

$u + v = 80$ ..... (2)

Solving equations (1) and (2)

$u + 3u = 80 \Rightarrow 4u = 80$

$\therefore u = 20$ cm

Hence $v = 3u = 60$ cm

From lens formula $\frac{1}{f} = \frac{1}{u} + \frac{1}{v} = \frac{1}{20} + \frac{1}{60}$

$= \frac{3+1}{60} = \frac{4}{60}$

$= \frac{1}{15}$

$\therefore$ focal length, $f = 15$ cm

Exercise 12.3

1. Define magnification of the lens.
2. With the help of a diagram, show the action of a convex lens as a converging lens.
3. (a) A convex lens is used to form an upright, magnified image of an object placed 6 cm from the lens. Calculate the focal length of the lens, if the magnification produced is 4.

   (b) An object 3 cm high is placed 20 cm from a lens of focal length $^-25$ cm. Find the position, size and the nature of the image formed.
4. An object 3 cm high is placed 30 cm from a convex lens of focal length 20 cm.

   (a) Find the position, size and the nature of the image formed

   (b) If the same object is now moved by 20 cm towards the lens, calculate the magnification produced by the lens.

12.6 Determining the focal length of a convex lens

Activity 12.1

- Position a convex lens vertically in front of the classroom furthest from the lens.
- Place a white screen on the other side of the lens. Adjust the screen until you are able to see a sharp image of the classroom.
- Measure the distance from the lens to the screen. What does this distance represent?

From Activity 12.1, we note that an inverted, real and diminished image of the classroom is formed at the focal plane of the lens. This method of determining the focal length of a lens is referred to as the *estimation method* due to uncertainty of the actual position of a well defined image at F.

From the lens formula, $\frac{1}{u} + \frac{1}{v} = \frac{1}{f}$

$u = \infty$, since the object is far away from the lens i.e object was at infinity.

$$\frac{1}{\infty} + \frac{1}{v} = \frac{1}{f}$$

$$\therefore \frac{1}{v} = \frac{1}{f} \quad (\text{since } \frac{1}{\infty} = 0)$$

Hence, the image distance v = the focal length of the convex lens f.

The following experiments will help us to determine the focal length accurately.

Experiment 12.2: To determine the focal length of a convex lens using an illuminated object and a mirror

Apparatus

- Mounted plane mirror
- Cross wire on screen
- Convex lens
- Candle

Procedure

1. Position a convex lens vertically with a plane mirror behind it so that light passing through the lens is reflected back as shown in Fig. 12.27. The object used is a hole and cross-wires on a white screen illuminated by a candle or an electric lamp.

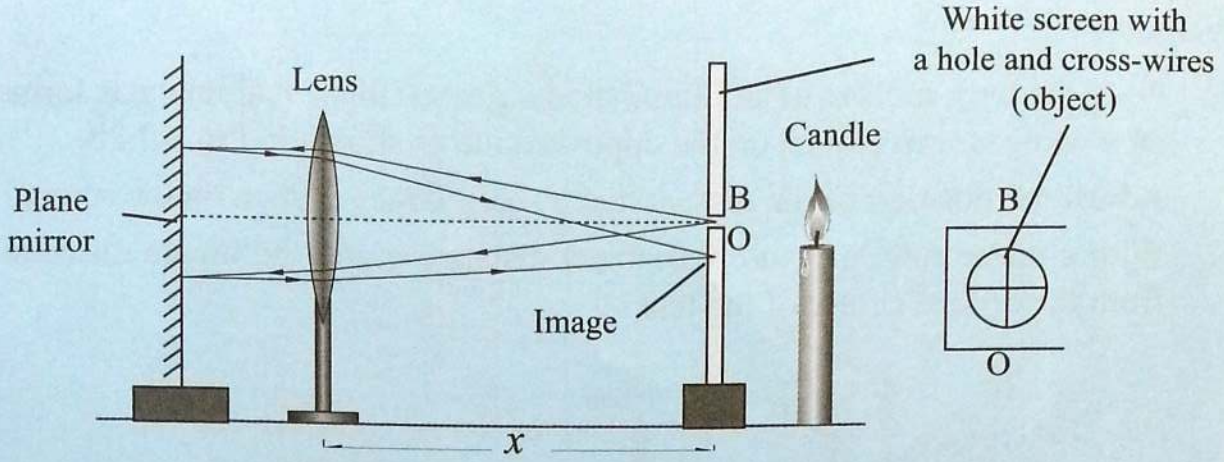


Fig. 12.27: Focal length of a convex lens by lens - mirror method

2. Adjust the position of the lens until a sharp image IM of the cross wire is formed alongside the object OB.
3. Measure the distance x between the optical centre P of the lens and the screen.
4. Record the value of x.
5. Repeat the procedure two more times.
6. Work out the average value of x.

Results

x_1 = ... cm, x_2 = ... cm, and x_3 = ... cm

Average value, $X_{av} = \dfrac{x_1 + x_2 + x_3}{3}$ = ... cm.

The average value of x = focal length of the lens.

Discussion

Since the reflected rays from the plane mirror are almost parallel, the refracted rays from the lens converge at the principal focus of the lens. Hence the distance x is the focal length f of the lens.

Experiment 12.3: To determine the focal length of a convex lens using an illuminated object and the lens formula.

Apparatus

- Lens
- White screen
- Illuminated object

Procedure

1. Place the lens, in front of an illuminated object so that a real image is formed on a white screen placed on the opposite side as shown in Fig. 12.28.
2. Adjust the position of the lens so that a sharp image is seen on the screen.
3. With a metre rule, measure the object distance ***u*** and the image distance ***v*** from the optical centre of the lens.

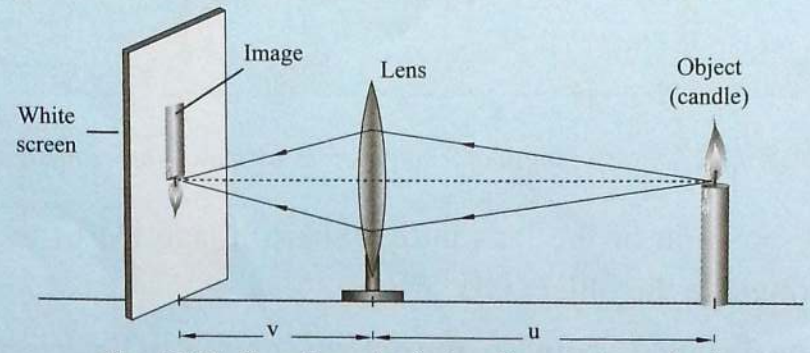


Fig. 12.28: Focal length of a lens by u and v method

4. Repeat the experiment for different values of ***u*** and measure ***v*** each time. Record these distances in a table (Table 12.1). Complete the other columns in the table.

Table 12.1

u (cm)	v(cm)	$\frac{1}{u}$ (cm)$^{-1}$	$\frac{1}{v}$ (cm)$^{-1}$

5. Plot a graph of $\frac{1}{v}$ against $\frac{1}{u}$.

Discussion

If your results were accurate and the graph plotted well, you obtain a straight line graph as shown in Fig. 12.29.

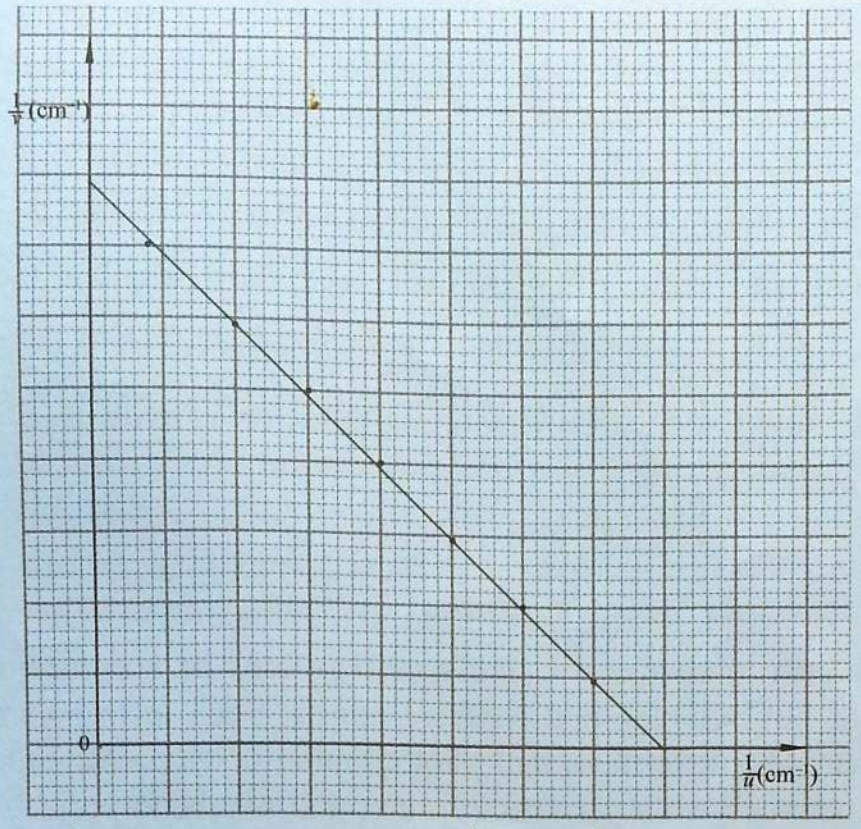


Fig. 12.29: Graph $\frac{1}{v}$ *against* $\frac{1}{u}$

We already know the lens equation which is $\frac{1}{u} + \frac{1}{v} = \frac{1}{f}$

Rearranging this equation, we obtain $\frac{1}{v} = \frac{-1}{u} + \frac{1}{f}$

which is the same as $\frac{1}{v} = -1\left(\frac{1}{u}\right) + \frac{1}{f}$ ..... (1)

This equation is similar to $y = -mx + c$ ..... (2)

This is an equation for a straight line with a negative gradient and a positive y-intercept c.

Comparing equations (1) and (2),

The y-intercept $c = \frac{1}{f}$ and the gradient of the line $m = -1$.

From the graph, we can find the value of intercept c on the y-axis and then calculate the focal length f of the convex lens from the equation $f = \frac{1}{c}$

Alternatively, from the lens formula,

$$\frac{1}{u} + \frac{1}{v} = \frac{1}{f}$$

If $\frac{1}{u} = 0$, then $0 + \frac{1}{v} = \frac{1}{f}$, and hence $\frac{1}{v} = \frac{1}{f}$ which is the intercept on the y-axis.

Also if $\frac{1}{v} = 0$, then $\frac{1}{u} + 0 = \frac{1}{f}$ and hence $\frac{1}{u} = \frac{1}{f}$ which is the intercept on the x-axis.

Find from the graph, we can calculate the values of the y-intercept and the x-intercept and get a value of $\frac{1}{f}$ in each case, then calculate the mean value, which is equal to $\frac{1}{f}$ and finally calculate the focal length f of the convex lens.

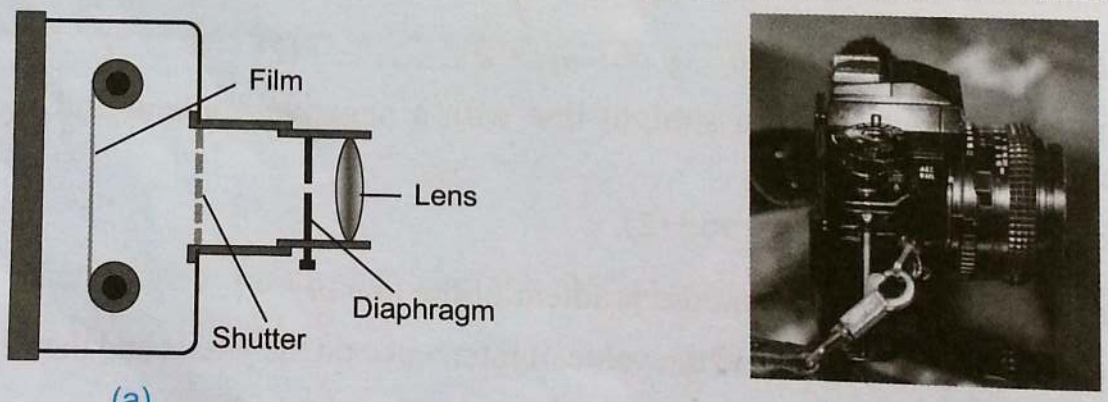
This method minimises the errors resulting in the measurements of ***u*** and ***v*** using a metre rule and by parallax.

12.7 Applications of lenses in optical devices

Many optical instruments use a single convex lens or a system of lenses or a combination of both convex and concave lenses. Such instruments are a simple photographic camera, a professional photographic or video camera, microscopes, telescopes, binoculars, enlarger spectrometer and overhead projector (LCD). The human eye also make use of lenses that help in the formation of the image on the retina. The following are some of the uses of lenses.

(a) The camera

A camera is a device used to take photographs. A human eye, though in principle is similar to a camera, is far superior than the finest camera ever made by man. Fig. 12.30 (a) shows some parts of a lens camera. Fig. 12.30(b) shows a commercial camera.



(a) (b)

Fig. 12.30: A camera

A camera consists of a converging lens and a light sensitive film or plate enclosed in a light-tight box, blackened from inside. The *lens* focuses light from an object to form a real, diminished and inverted image on the film. Focusing of objects is done by adjusting the distance between the lens and the film. The amount of light entering the camera through the lens is regulated with the help of a *diaphragm*, with an adjustable opening in the middle.

Light is admitted by the *shutter*, which opens for different required intervals of time and then closes automatically. During this interval of time, the film is exposed to light from the object. The film contains light sensitive chemicals that change on exposure to light. The film is then developed to get what is called a *negative*. From the negative, a photograph (positive) may be printed.

Example 12.9

A lens camera is used to take photograph of a distant building. A well focused image is formed on the film. The lens of the camera is 6 cm from the film.

(a) What is the focal length of the lens? Give reasons for your answer.

(b) If the camera is then used to take a photograph of a person 2.0 m away from the lens, without moving the camera, in which direction should the lens be moved in order to produce the best possible image?

Solution

(a) Focal length of the lens = 6 cm. Since the object is a distant building, the light rays incident on the lens are almost parallel and are brought to focus at the principal focus of the lens.

(b) As the object distance is only 2.0 m i.e. object distance, u, has decreased as compared to the distance in part (a). Hence the image distance, v, must be increased. To achieve this, has to be moved forward towards the person.

(b) The human eye

The human eye consists of a nearly spherical ball of about 2.5 cm diameter except for a slight bulge at the front. Fig. 12.31 shows the cross-section of the human eye with the optic nerve leading to the brain.

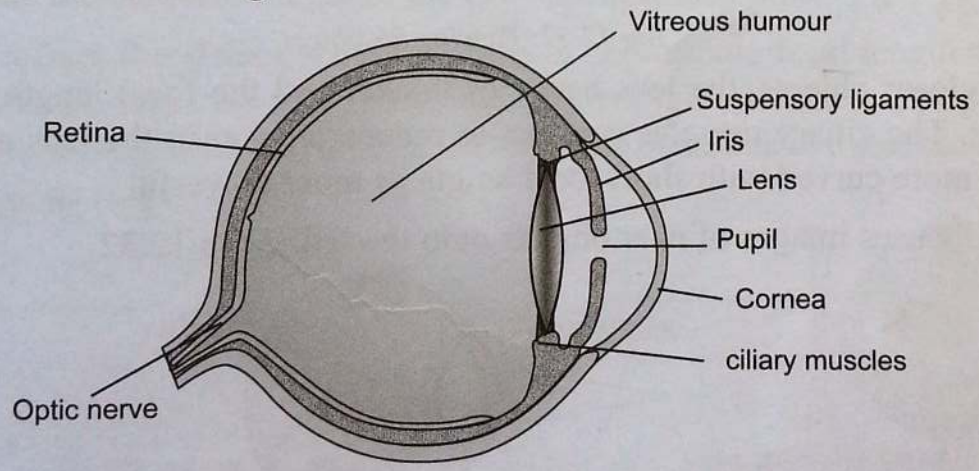


Fig. 12.31: A cross-section of a human eye.

The front portion of the eye is known as the *cornea* and is slightly bulged outwards and transparent in nature. Behind the cornea, there is a diaphragm called the *iris*, with a hole in the middle known as the *pupil*.

Behind the iris is a *crystalline lens*. This is a biconvex converging lens made of a large number of jelly-like layers which are flexible and transparent in nature. The lens is suspended inside the eye with the help of *suspensory ligaments* which fasten it to the *ciliary muscles*. These muscles control the shape of the lens.

The lens forms a real, diminished and inverted image on the *retina*. Light falling on the retina produces a sensation in the cells which then send the electrical signals to the brain by the nerve known as the *optic nerve*.

The amount of light reaching the retina is regulated by the size of the pupil. When a bright object is viewed, the iris reduces the size of the pupil so as to admit less light, whereas in dark light the iris dilates so as to admit as much light as possible.

An image formed by the eye lens leaves an impression on the retina for about 0.1 second. This persistence of the vision enables us to "see" cinema or television pictures which appear to change smoothly from one image to the next without any interruption. In a cinema theatre or television screen about 20 pictures are projected per second. During the time interval between the pictures, the eye "remembers" the previous picture (Persistence of vision).

Image formation in the eye

When one looks at far objects, the eye lens becomes thinner and focal length of the lens increases. The ciliary muscle is relaxed and the lens has the longest focal length. This enables it to focus rays from distant objects onto the retina Fig 12.32.

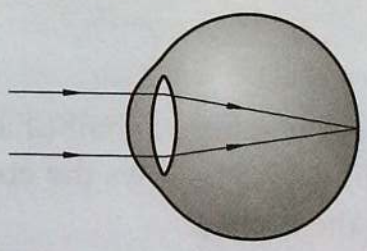


Fig 12.32: Viewing far object

To view closer objects, the lens becomes thicker and the focal length of the lens decreases. The ciliary muscles contract to reduce tension in the lens and the lens becomes more curved with short focal length as more powerful.

The lens focuses images of near objects onto the retina Fig 12.32.

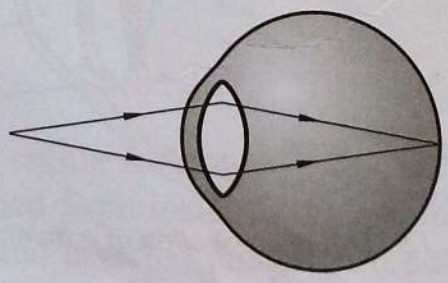


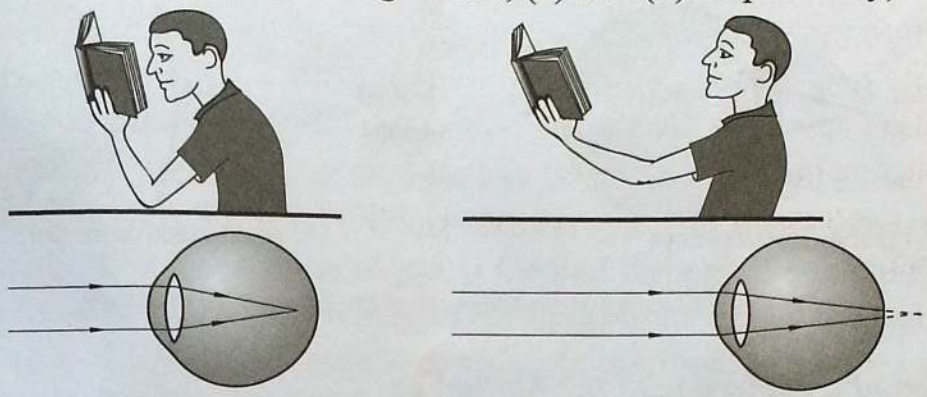
Fig 12.33: An eye viewing close object.

The process by which the lens of the eye changes its focal length and produces focused images of both distant and near objects on the retina is called accommodation.

Defects of vision

A normal human eye can accommodate the range of distances from far off objects to objects close to the eye. There is, however, a limit to the power of accommodation of the eye. As a person grows older, the power of accommodation gradually decreases. Also, despite the ability of the eye to adjust its focal length by changing the lens shape, some eyes cannot produce clear images over the normal range of vision. This type of defect may arise due to the eyeball being slightly too long or too short compared to the normal spherical ball or due to the curvature of the cornea being defective.

The most common defects of vision are *short-sightedness (myopia)* and *long-sightedness (hypermetropia)* (See Fig. 12.34, (a) and (b) respectively).



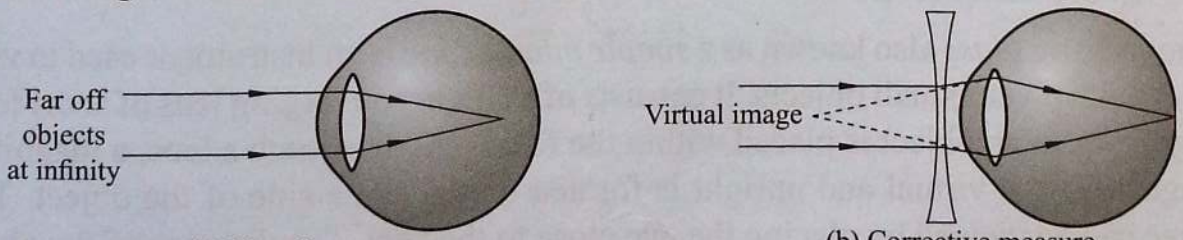
(a) Short-sightedness (b) Long-sightedness

Fig. 12.34: Short-sightedness and long-sightedness

Short-sightedness or Myopia

A person suffering from short-sightedness can only see nearby objects. The image of a distant object is formed in front of the retina as shown in Fig. 12.35 (a). This defect arises due to the eyeball being too long or more refraction takes place at the cornea and hence the focal length of the eye lens becomes short.

In order to correct this defect, a concave lens of appropriate focal length should be used. This lens diverges the rays from a distant objects so that they appear to come from a virtual image formed at a point closer to the lens. The eye can focus on this virtual image, as shown in Fig. 12.35 (b).



(a) Myopic eye (b) Corrective measure

Fig. 12.35: Short-sightedness and corrective measure

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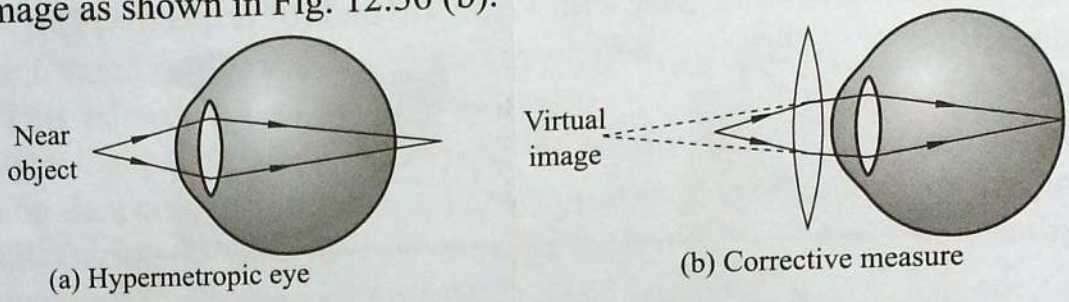
Long-sightedness or Hypermetropia

A person suffering from long-sightedness can see distant objects clearly, but cannot see distinctly objects lying closer than a certain distance. The image of a nearby object is formed behind the retina as shown in Fig. 12.36 (a). The defect arises due to the eyeball being too short or due to the curvature of the cornea being defective and the focal length of the eye lens becoming longer.

In order to correct this defect, a convex lens of appropriate focal length should be used. This lens converges the ray from a near object so that they appear to come from a virtual image formed at a point far off from the lens. The eye focuses on this virtual image as shown in Fig. 12.36 (b).



(a) Hypermetropic eye (b) Corrective measure

Fig. 12.36: Long-sightedness and the corrective measure.

Comparison of a camera with the human eye

Table 12.2

Similarities	*Differences*
1. Both use converging lenses	1. Focal length of the lens changes with the thickness of the lens.
2. Both produce real, inverted, diminished images.	2. Distance between the lens and the retina is a constant.
3. Both can control the amount of light entering the device.	3. Focuses objects between 25 cm from the lens to infinity.
4. Both are black inside.	4. Form temporary images at the retina.

(c) Simple microscope

A *magnifying glass* also known as a *simple microscope* is an instrument used to view the details of very small objects. It consists of a single converging lens of short focal length. When an object is placed within the focal length of such a lens, a magnified image which is virtual and upright is formed on the same side of the object. This image can be viewed by placing the eye close to the lens. The distance of the object from the lens is adjusted till an enlarged image is formed at a distance D, which is about 25 cm from the unaided eye. The distance D is referred to as the *least distance of distinct vision*. Fig. 12.37 illustrates the operations of a simple microscope.

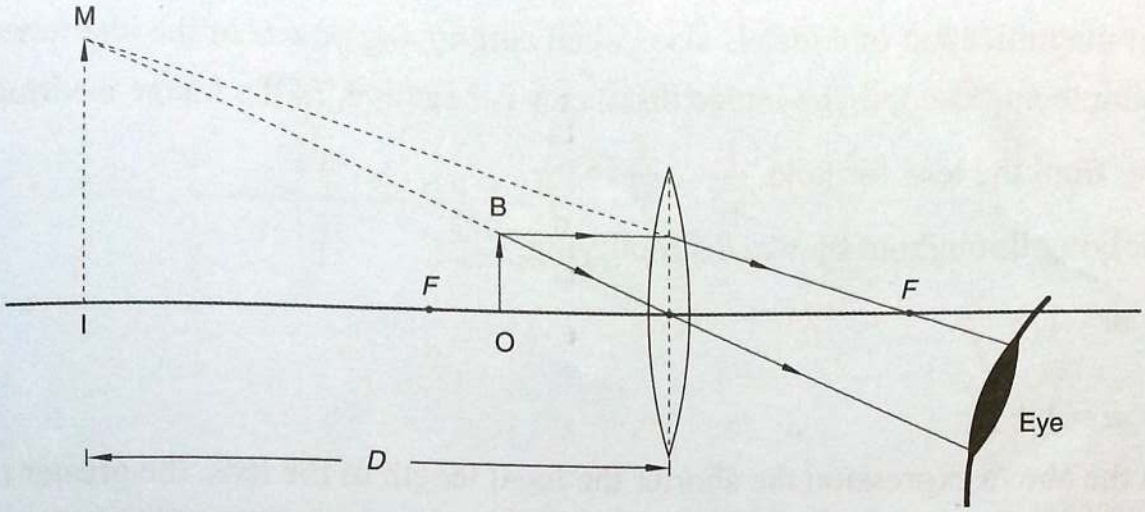


Fig. 12.37: A simple microscope.

The action of a simple microscope

The object OB, when viewed by an unaided eye, cannot be brought closer to the eye, than the distance D (Fig. 12.38 (a)). Otherwise the image as seen by the eye will not be clearly visible. When the same object is viewed through the magnifying glass, it moves nearer to the eye so that a magnified image is formed at the same distance D as before (Fig. 12.38 (b)). Therefore, a simple microscope enables us to bring an object very close to the eye making it appear magnified and yet clearly visible.

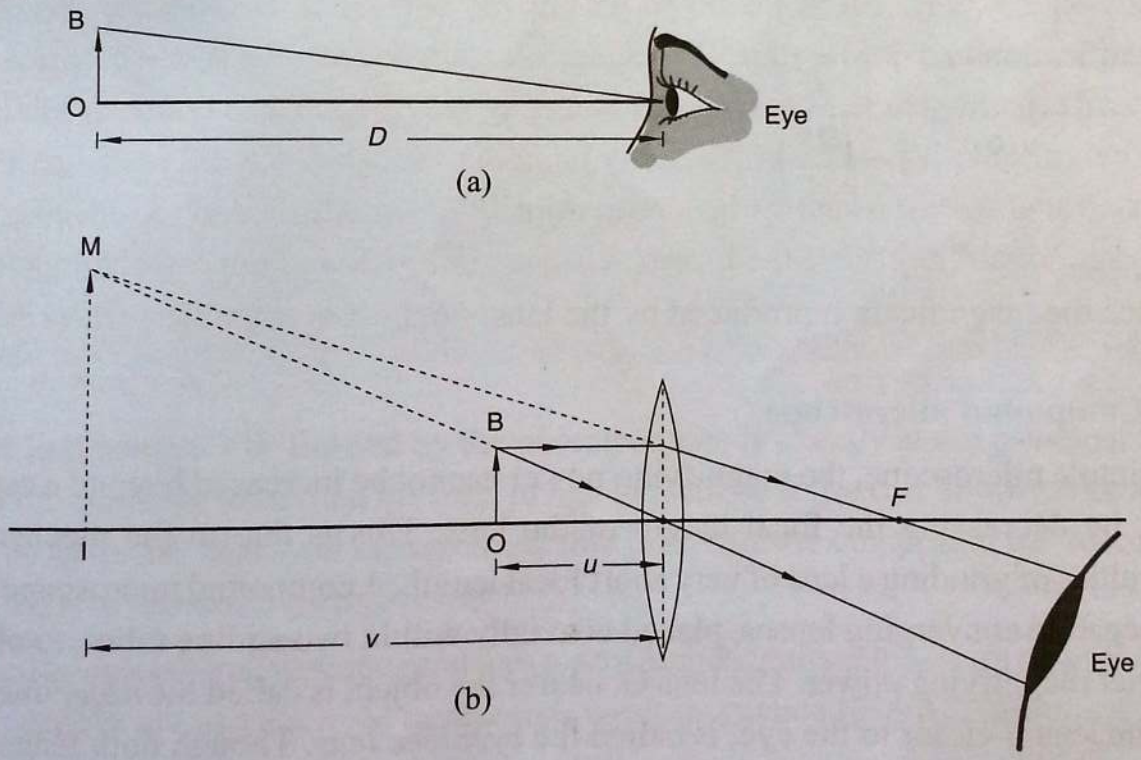


Fig. 12.38. Working of a simple microscope

Magnifying power of a simple microscope

Linear magnification $m = \dfrac{\text{IM}}{\text{OB}} = \dfrac{v}{u}$

Linear magnification of a lens is also called *magnifying power* of the instrument.

In a simple microscope, the image distance v is negative, as the image is virtual.

Hence, from the lens formula $\frac{1}{u} - \frac{1}{v} = \frac{1}{f}$

Multiplying throughout by v and simplifying,

$$m - 1 = \frac{v}{f}$$

$$m = 1 + \frac{v}{f}$$

From the above expression the shorter the focal length of the lens, the greater is the magnifying power of the instrument. Hence a simple microscope uses a converging lens of short focal length.

Example 12.10

Calculate the magnification produced by a lens of focal length 5.0 cm used in a simple microscope, the least distance of distinct vision being 25 cm.

Solution

In this example, the image distance $v = D = 25$ cm.

Magnification $m = 1 + \frac{v}{f}$

$$= 1 + \left(\frac{25}{5}\right)$$

$$= 1 + 5 = 6$$

Hence the magnification produced by the lens = 6.

(d) Compound microscope

In a simple microscope, the magnifying power cannot be increased beyond a certain limit, by decreasing the focal length of the lens. This is due to the mechanical difficulties of grinding a lens of very short focal length. A compound microscope uses two separate converging lenses, placed coaxially within two sliding tubes, to obtain a higher magnifying power. The lens O, nearer the object is called the *objective lens* and the lens E closer to the eye, is called the *eyepiece lens*. Though both lenses are of short focal lengths, the eyepiece has a comparatively larger focal length than the objective lens. The final image formed is magnified, virtual and inverted as shown in Fig. 12.39.

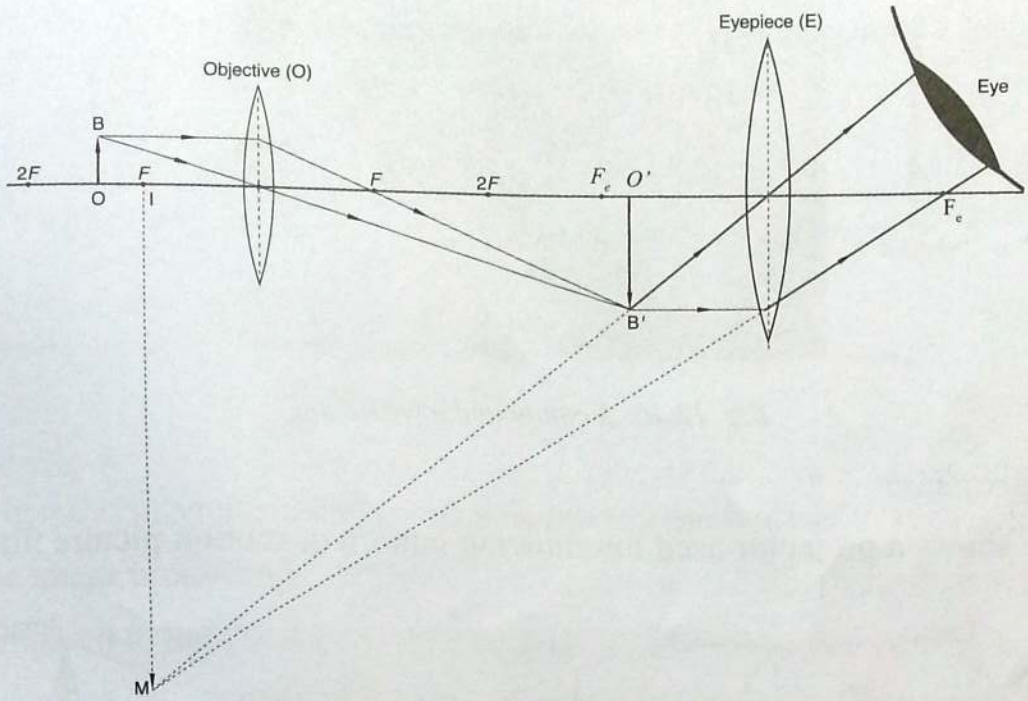


Fig. 12.39: A compound microscope

Action of a compound microscope

The object OB is placed between F and $2F$ of the objective lens. A real, inverted, magnified image O′ B′ is formed beyond $2F$ of the objective lens. The position of the eyepiece lens is adjusted so that this image O′ B′ falls within its focal length. The eyepiece then acts as a magnifying glass and produces a final magnified, virtual and inverted image IM at a distance of distinct vision D from the eye, placed very close to the eyepiece. If m_1 is the magnification produced by the objective lens and m_2 is the magnification produced by the eyepiece lens, then the magnification produced by the system of lenses m is given by,

$$m = m_1 \times m_2$$

If the first image O′B′ formed by the objective lens is exactly at the principal focus F_e of the eyepiece lens, then the final image IM will be formed at infinity. The image will be inverted and well enlarged. At this position, the compound microscope is said to be in *normal adjustment*.

A good compound microscope produces a very high magnification. High magnification microscopes are usually used in research work in science (Fig. 12.40).

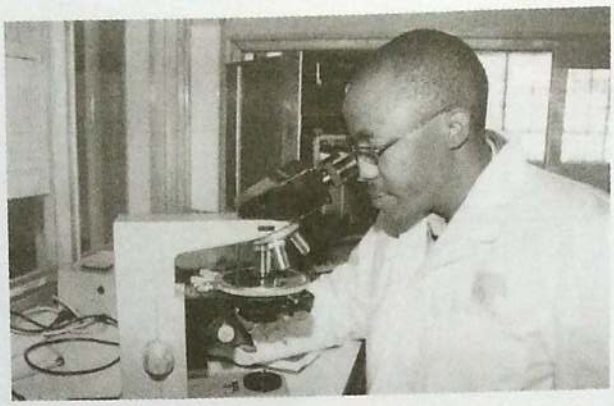


Fig. 12.40: A compound microscope

(e) The projector

Fig. 12.41 shows a projector used for showing lantern or motion-picture film.

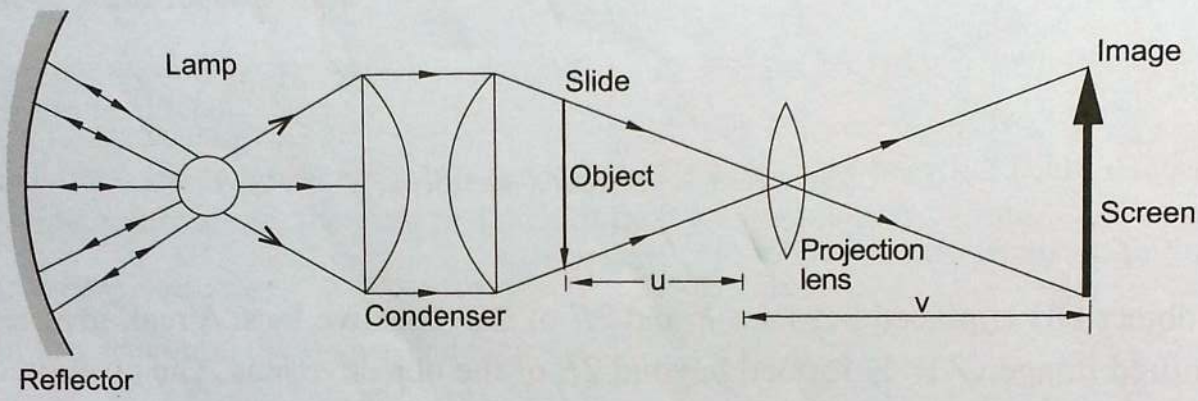


Fig. 12.41: A projector for motion picture film

The projector has the following parts:

- *A Quartz-Halide lamp* placed at the centre of curvature of a concave reflector. This is a very bright source of light.
- *Reflector* - reduces loss of light produced.
- *Condenser* - Consists of plano-convex lens arrangement which concentrates the light energy from the lamp in the direction of the slide. The convex lens has a short focal length. The condenser and the lamp are arranged such that the image of the lamp is formed at the projection lens position. This is to ensure that all the light passes through the projection lens and the image of the lamp is not formed on the screen.
- *The slide* - contains the pictures to be viewed on the screen. The slide is introduced into the project upside down so that the images seen on the screen are the right way up. The slide is positioned such that $2f>u>f$ to form magnified real images.
- *Projector lens* - The projector uses one lens to form an image on the screen (Fig. 12.42).

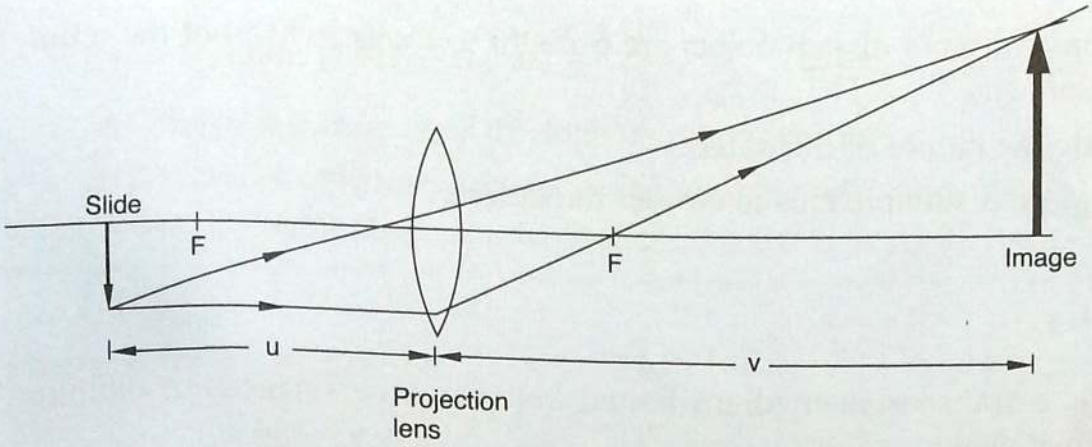


Fig. 12.42: Image formation by projection lens

The image produced is *real*, *magnified* and *inverted*. Since the distance v is large compared to the distance u, the image is highly magnified ($m = \frac{u}{v}$)

- *Condensing lens*: - consists of a pair of converging lens called condenser. It controls the beam of light so as to evenly illuminate the slide i.e. it concentrates as much as possible the light energy onto slide.
- The *screen* is where the image is formed. The further away the screen is the bigger the magnification.

Exercise 12.4

1. Give two ways in which the amount of light entering a camera can be controlled.
2. Which part of the eye:
   (a) Controls the amount of light entering the eye?
   (b) Does most of the converges of the light?
   (c) Acts as a screen on which the image is formed?
3. If an object moves away from the eye, the lens has to adjust to focus the image.
   (a) What is this process called?
   (b) How does the lens make focussing adjustments?
4. Why must the film be put into a projector upside down?
5. In a projector, what is the function of the:
   (a) Condenser lens.
   (b) Projector lens.
6. Define the term 'accommodation' of a human eye.

7. Parallel rays from a distant object are brought to focus in front of the retina in a human eye.
   (a) State the nature of the defect.
   (b) Suggest a suitable lens to correct the defect.

Unit summary

- A lens is a transparent medium bound between two surfaces of definite geometrical shape.
- Thin lenses may either be converging (Convex) or diverging (Concave).
- A convex lens is thicker at its centre than its edges and converges the light incident on.
- A concave lens is thicker at its edges than at the centre and diverges the light incident on it.
- Some of the important terms used in spherical lenses: principal axis, optical centre, principal focus, focal length.
- The focal length of a convex lens is positive, while that of a concave lens is negative.
- The characteristics of the image formed by a converging lens depends on the position of the object (see Table 12.3).

Table 12.3

Position of object	Position of image formed	Nature of image compared to object	Size of image formed object
At infinity (far away)	*F*	real and inverted	diminished
Beyond 2*F*	Between *F* and 2*F*	real and inverted	diminished
At 2*F*	At 2*F*	real and inverted	Same size
Between 2*F* and *F*	Beyond 2*F*	real and inverted	Magnified
At *F*	At infinity (far away)	real and inverted	Magnified
Between *F* and *P*	Same side as object	Virtual and upright	Magnified

- A diverging lens always forms a virtual, upright, diminished image between *F* and *P* (except when the object is at infinity).
- Magnification (m) is defined as the ratio of the height of the image to the height of the object.

$$\text{Magnification (m)} = \frac{\text{height of the image}}{\text{height of the object}} = \frac{h_i}{h_0} = \frac{\text{image distance (v)}}{\text{object distance (u)}} = \frac{v}{u}$$

- Lens formula is given by $\frac{1}{u} + \frac{1}{v} = \frac{1}{f}$ where u is the object distance, v the image distance and f the focal length of the lens.
- A camera, simple microscope, compound microscope are some examples of optical instruments.

Unit Test 12

1. Name the lens used to diverge light rays.
   A. Convex lens B. Concave lens
   C. Parabola D. Shielding lens
2. Give the nature of the image formed on a convex lens when the object is between focal point and centre of curvature.
   A. Beyond centre of curvature.
   B. Between focal point and the optical centre
   C. At focal point.
   D. At centre of curvature.
3. The focal length of a convex lens is _____.
   A. Virtual B. Real
   C. Upright D. Lateral
4. An object 6 m tall in front of a convex lens is focused to a screen as 3 m. Calculate the magnification.
   A. 18 m B. 18
   C. 2 m D. 2
5. An object is placed 10 cm from a convex lens and real image is formed at 30 cm from the lens. Calculate the focal length of the lens.
   A. 300 B. 7.5 cm
   C. 0.133 cm D. 15 m
6. How can one correct short-sightedness in human eye?
   A. Use of spectacles made of convex lenses.
   B. Use of glasses made of concave mirrors.
   C. Use of spectacles made of convex mirrors.
   D. Use of spectacles made of concave lenses.
7. The diagram in Fig. 12.43 shows three parallel rays of light emerging from a thin converging lens of focal length 4 cm. Copy and complete the diagram

Topic 5: Nuclear Physics

Outcome

The students will be able to appreciate principles of radioactivity and how radioactive materials are safely handled, used and stored.

Unit 13: Isotopes

Unit 14: Radioactivity

UNIT

13 Isotopes

Success Criteria

By the end of this unit, you must be able to:

- Describe the structure of an atom
- Describe isotopes.

Introduction to Isotopes

In Form 2, we learnt that matter is made up of chemical materials called elements. An element is a pure chemical substance which cannot be split into any simpler form by any chemical means. An element is made up of tiny particles called *atoms*.

13.1 The structure of the atom

An atom is the smallest electrically neutral particle of an element that carries all properties of that element and can take part in a chemical reaction.

Atoms are made up of three sub-atomic particles called protons, neutrons and electrons (Fig 13.1) which are held together by nuclear forces. These particles are located in specific parts of the atom. Protons, which are positively charged particles, and neutrons which carry no charge, are located at the centre of the atom called the nucleus; they are therefore called nucleons. The electrons, which are negatively charged, are found in the space moving around the nucleus called shells or energy levels where they orbit like planets in the solar system (Fig. 13.1).

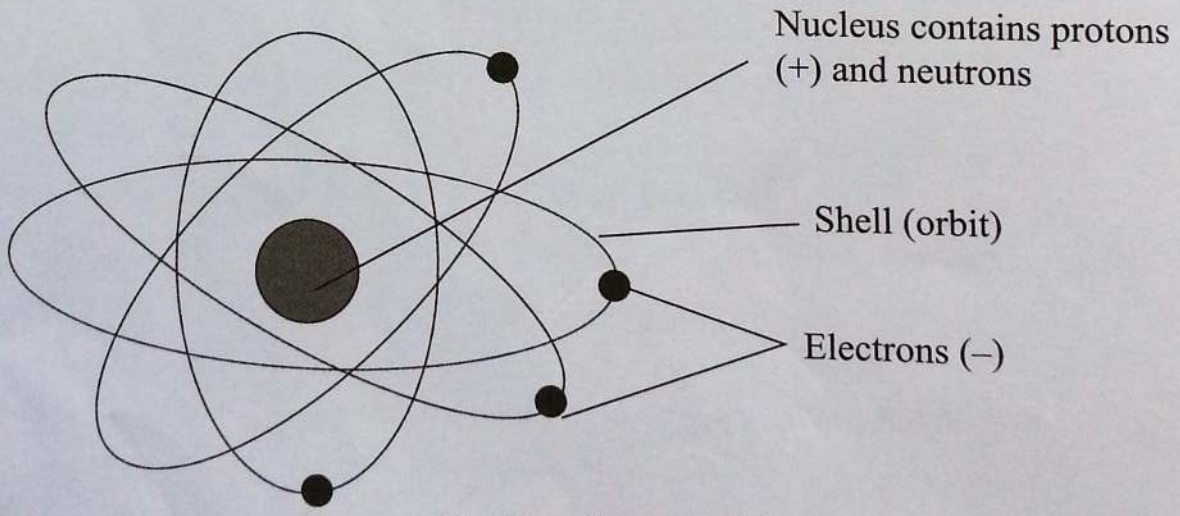


Fig. 13.1: Structure of the atom

Table 13.1 shows the properties of sub-atomic particles.

Table 13.1

Particle	Symbol	Charge	Mass (kg)	Relative mass
Proton	P	+1	1.6726×10^{-27}	1.000
Neutron	n	0	1.6749×10^{-27}	0
Electron	e	–1	9.1094×10^{-31}	$\frac{1}{1836}$

Atomic number (Z)

The atomic number is the number of protons in the nucleus of an atom. In a neutral atom, the number of protons (positive charges) is equals the to the number of electrons (negative charges). Thus, the atom is electrically *neutral*.

The atomic number identifies a particular element. *No two elements can have the same atomic number*. Thus, the identity of an element is its atomic number. For example, all nuclei of hydrogen atoms contain 1 proton while all nuclei of carbon contain 6 protons.

Atomic number is indicated on the left lower side of the symbol of an element. This position is called subscript position and the number is referred as subscript number.

For example, the atomic number of sodium is 11. It is written as $_{11}Na$. Atomic number Potassium is 19 hence written as $_{19}K$, calcium is 20 written as $_{20}Ca$ and oxygen is 8 written as $_{8}O$.

The symbol for atomic number is Z.

Mass number (A)

The mass number of an atom is the sum of the protons and neutrons in the nucleus of the atom or the total number of nucleons (protons and neutrons) in the nucleus of an atom. It is also called atomic mass and is indicated on the upper left side of the symbol of an element. This position is called superscript position and the number is referred as superscript number.

For example, the mass number of sodium is 23. It is written as ^{23}Na. For carbon the mass number is 12 written as ^{12}C, Potassium has a mass number of 39 written as ^{39}K, Calcium is 40 written as ^{40}Ca while Oxygen is 16 written as ^{16}O.

We can also say that the mass number is the sum of the atomic number and the number of neutrons.

The symbol for *mass number* is *A*.

Therefore: $A = Z + N$

Where N = number of neutrons.

For example, for helium atom which has atomic number 2 and mass number 4 it can be represented as ${}^{4}_{2}He$. A sodium atom will be represented as ${}^{23}_{11}Na$, Potassium as ${}^{39}_{19}K$, Calcium as ${}^{40}_{20}Ca$, Carbon as ${}^{12}_{6}C$, while Oxygen ${}^{16}_{8}O$.

In general, an atom of *element X* with *mass number A* and *atomic number Z* can be denoted as follows: ${}^{A}_{Z}X$.

13.2 Isotopes

While the atomic number of all atoms of a particular element is always the same, the mass number can be different in those atoms. The difference in masses, is due to the difference in the number of neutrons in their nuclei. *Isotopes are atoms of the same element with the same atomic number, but different mass numbers or are atoms of the same element with the same number of protons but different numbers of neutrons.*

For example, hydrogen has three isotopes, hydrogen, deuterium and tritium. Hydrogen (protium) has one proton and no neutron. Its mass number is 1. Deuterium has one proton and one neutron, so its mass number is 2. Tritium has one proton and two neutrons, so its mass number is 3.

${}^{1}_{1}H$	${}^{2}_{1}H$	${}^{3}_{1}H$
Hydrogen	Deuterium	Tritium

To differentiate between different isotopes of an element, the mass number of the isotope is attached to the name of the element. For example, isotopes of hydrogen can be named as Hydrogen –1, deuterium –2 and tritium –3. For carbon, we have carbon –12, carbon –13 and carbon –14. Since the atomic number does not change for the same elements, it is usually omitted from the name.

Example 13.1

A certain element has is represented as ${}^{37}_{17}E$. Calculate:

(a) The number of neutrons,

(b) The number of protons,

(c) The charge in Coulombs, on the nucleus of this element.
(Take $e = 1.602 \times 10^{-19}$ coulombs).

Solution

Mass number, A = 37; Atomic number; Z = 17, e = 1.602×10^{-19} Coulombs

(a) The number of neutrons, N

$37 = 17 + N$

$N = 37 - 17$

$= 20$

(b) The number of protons = Z = 17

(c) The charge, Q

$Q = Ze$

$= 17 \times 1.602 \times 10^{-19}$ Coulombs.

$= 2.7234 \times 10^{-18}$ Coulombs

Example 13.2

A nuclide of nickel is represented as; $^{60}_{28}Ni$.

(a) What does the superscript represent?

(b) How many neutrons does this nuclide have?

Solution

(a) The superscript represent mass number, A.

(b) The nuclide has 60 – 28 = 32 neutrons.

Relative Atomic Mass

The relative atomic mass (RAM) of an element is a relative quantity.

It is the mass of one atom of an atom of an element compared to the mass of one carbon –12 atom.

The relative atomic mass (RAM) is used to obtain the atomic mass (or mass number) of an element which has isotopes. It is calculated using following formula:

$$\text{RAM} = \frac{\left(\begin{matrix}\text{Abundance}\\ \text{of isotope}\\ 1\end{matrix} \times \begin{matrix}\text{Mass of}\\ \text{isotope}\\ 1\end{matrix}\right) + \left(\begin{matrix}\text{Abundance}\\ \text{of isotope}\\ 2\end{matrix} \times \begin{matrix}\text{Mass of}\\ \text{isotope}\\ 2\end{matrix}\right) + \left(\begin{matrix}\text{Abundance}\\ \text{of isotope}\\ 3\end{matrix} \times \begin{matrix}\text{Mass of}\\ \text{isotope}\\ 3\end{matrix}\right)}{100}$$

Example 13.3

Chlorine has two isotopes, Chloride –37 and Chlorine –35. Chlorine – 37 has an abundance of 25% while Chlorine –35 has an abundance of 75%. Determine the relative atomic mass (RAM) of Chlorine.

Solution

$$\text{R.A.M} = \frac{(25 \times 37) + (75 \times 35)}{100} = \frac{925 + (2625)}{100}$$

$$= 35.5$$

Unit summary

- An atom is the smallest electrically neutral particle of an element that carries all properties of that element and can take part in a chemical reaction.
- Atomic number is the number of protons in the nucleus of an atom.
- Protons are positively charged particles.
- Neutrons are negatively charged particles.
- Isotopes are atoms of the same element having the same atomic number but different atomic masses

Unit Test 13

1. Define the following:
   (a) Mass number (b) Atomic number (c) Isotope
2. A nuclide is represented as $^{233}_{91}Pa$.
   (a) What is its mass number?
   (b) Calculate the number of neutrons
   (c) What does the subscript represent?
3. A sodium atom is represented $^{24}_{11}Na$.
   (a) How many protons does it have?
   (b) Calculate the number of neutrons
   (c) Calculate its charge. ($e = 1.602 \times 10^{-19}$ Coulombs)
4. Magnesium has three isotopes, Mg –24, Mg –25 and Mg –26. The percentage of each is 78.70%, 10.13% and 11.17% respectively. Determine the relative atomic mass of magnesium.
5. Calculate the percentage composition of boron given that the relative atomic mass of boron is 10.8 and the mass number of the two isotopes are 10 and 11.
6. Atoms of a certain isotope have 73 neutrons and a mass number of 123. Determine the:
   (a) Atomic number (b) Number of electrons (c) Name of the element
7. Given the two particles; $^{19}_{9}X$ and $^{20}_{9}X$.
   (a) Indicate the number of neutrons in $^{19}_{9}X$.
   (b) Indicate the number of electrons in $^{20}_{9}X$.
   (c) What phenomenon does X show?

UNIT

14 Radioactivity

Success Criteria

By the end of this unit, you must be able to:

- Explain radioactivity
- Describe radioactive emission

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 how radioactivity takes place, its applications and dangers.

14.1 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 unit, radioactivity can take place naturally (or natural radioactivity) or can be artifically induced (artificial radioactivity).

14.2 A model of radioactive decay

Experiment 14.1: To illustrate the randomness and the experimental nature of radioactive decay

Apparatus

- 256 bottle tops
- Carton

Procedure

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 carbon.
5. Repeat the experiment about 12 times.
6. Record the results as shown in Table 14.1.
7. Plot a graph of the number of tops remaining against the number of tops throws.

Results

You will obtain values similar to the ones in Table 14.1 below.

Table 14.1

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

Discussion

On plotting, a graph similar to the one in Fig. 14.1 is obtained.

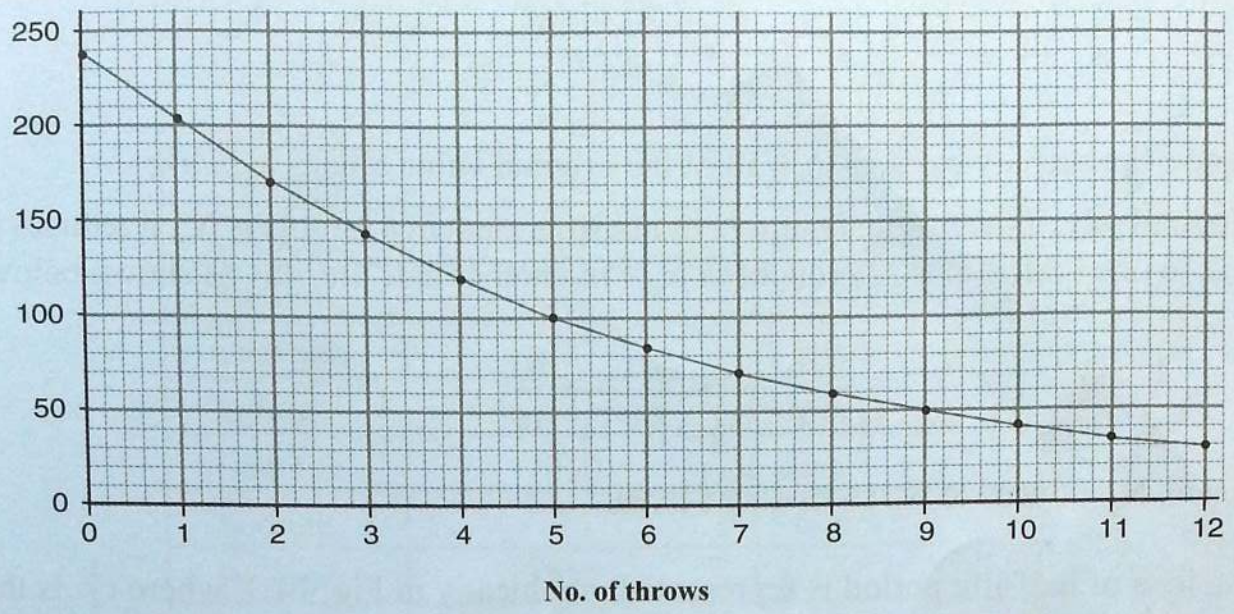


Fig. 14.1: Graph a model of radioactive decay model.

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 with the painted side upwards.

Conclusion

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.

14.3 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. 14.3, where $t_{\frac{1}{2}}$ is the half-life of a radioactive sample. The activity decreases exponentially with time.

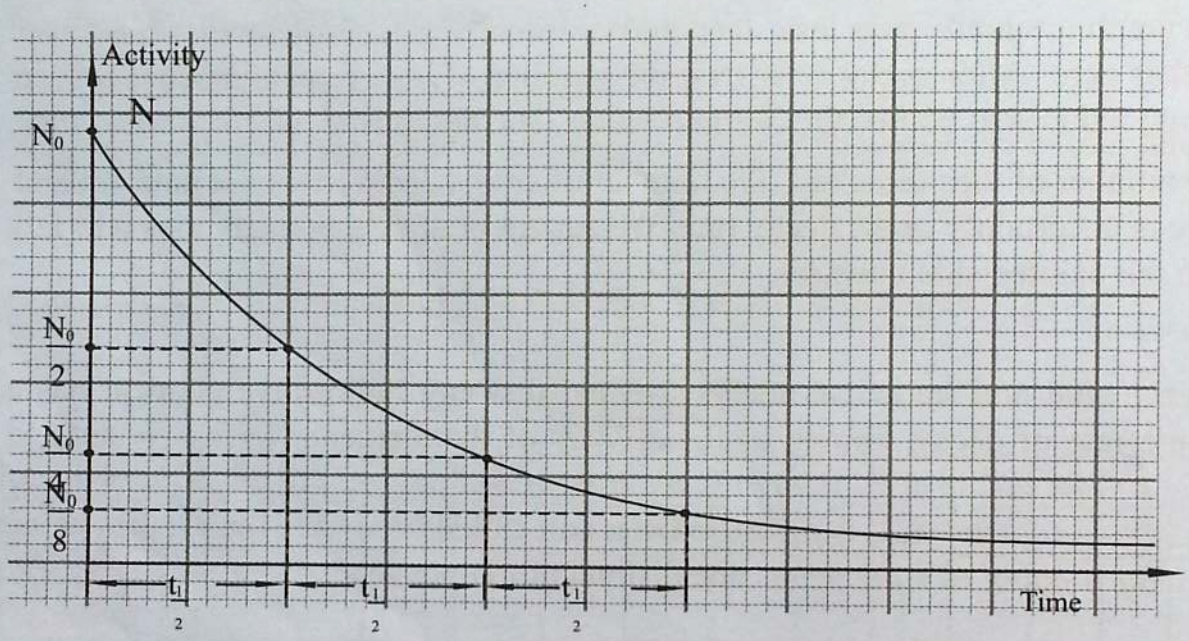


Fig. 14.2: Decay curve for a radioactive material

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 14.2 shows the half-life of some elements.

Table 14.2

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 preset 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 14.1

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.

$$1 \longrightarrow \frac{1}{2} \longrightarrow \frac{1}{4} \longrightarrow \frac{1}{8} \longrightarrow \frac{1}{16} \longrightarrow \frac{1}{32} \longrightarrow \frac{1}{64}$$

Alternatively by using the formula

$N_0 = 1g$, $t = 8$ days, $T = 48$ days, $N = ?$

$$N = N_0(\tfrac{1}{2})^{\frac{T}{t}} = 1 \times (\tfrac{1}{2})^{\frac{48}{8}} = 1 \times (\tfrac{1}{2})^6 = \tfrac{1}{64}g$$

Hence the mass of iodine left behind after 48 days = $\frac{1}{64}$ g.

Example 14.2

A radioactive substance has decayed to $\frac{1}{128}$ 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, $t = ?$

$$N = N_0\left(\frac{1}{2}\right)^{\frac{T}{t}} \Rightarrow \frac{x}{128} = x\left(\frac{1}{2}\right)^{\frac{49}{t}}$$

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

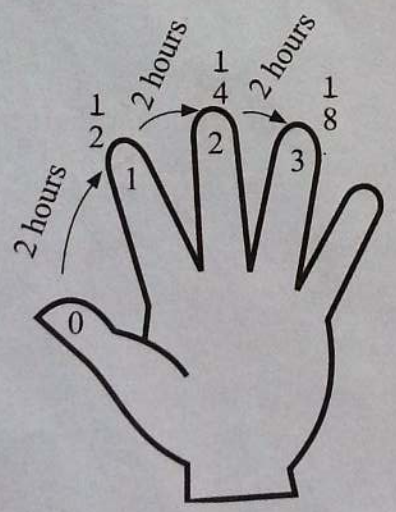
$\therefore$ Half-life of the substance $= \frac{49}{7} = 7$ days

Example 14.3

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 14.3)



- **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.14.3: 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 14.4

A radioactive element is giving count rate of 15 counts per second. What was its count rate hours ago if its half life is 2 hrs?

Solution

$N = 15, t = 2\text{ h}, T = 8\text{ h}, N = ?$

$N = N_0(\frac{1}{2})^{\frac{T}{t}} \Rightarrow 15 = N_0(\frac{1}{2})^{\frac{8}{2}}$

$$15 = N_0(\frac{1}{16}) = No = 15 \times 16 = 240$$

Its count rate 8 hours ago is 240 counts per second

Example 14.5

A nucleid of radium has half life of 1622 year. How long will 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 $\text{Log } 0.015625 = \text{Log } (0.5)^n$

$$\log 0.015625 = n \log (0.5)$$

$$n = \frac{\log 0.0156\,25}{\log (0.5)}$$

$$= \frac{\log (0.5)6}{\log (0.5)}$$

$$= \frac{\log (0.5)}{\log (0.5)} = 6 \text{ half lives}$$

Total time taken = 1 622 yrs × 6 = 9732

14.4 Background radiation

Background radiation is the 'stray' radiation present in the atmosphere and it is not due to any particular radioactive material.

The possible causes of these background radiations include cosmic radiation which originates 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.

Experiment 14.2: To detect background radiation at a place

Apparatus

- GM tube
- Scale counter

Procedure

1. With no radioactivity material nearby, switch on a Geiger-Müller tube connected to a scaler-counter.
2. Observe the counter readings at 1 minute interval for a few minutes and record these values. What information can be deduced from these readings.

Observations

The Geiger-Müller counter registers some radiations, though there are no radioactive sources nearby. The readings are almost constant but shows considerable random fluctuations (see Table 14.3).

Table 14.3

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

Discussion and conclusion

The detector is recording the *background radiation*, which is present in the atmosphere. 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.

Corrected count rate = counter reading – background reading.

If the experiment is repeated with a radioactive source near the mica window of a Geiger-Müller tube, the readings shown in Table 14.4 is obtained.

Table 14.4

Time (min)	1	2	3	4	5	6	7	8	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

Example 14.8

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: 30, 31, 27, 30, 31, 29, 31, 31.

(a) What was the average background count in the laboratory?

(b) Using the average background radiation in (a) above, complete Table 14.5.

Table 14.5

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 (count per minute)	–	–	–	–	–	–	–	–
Corrected count rate (count per minute)	–	–	–	–	–	–	–	–

(c) Plot a graph of the corrected count rate against time. Determine the half-life of the radioactive substance.

Solution

(a) The average background radiation $= \dfrac{30 + 31 + 27 + 30 + 31 + 29 + 31 + 31}{8}$

$= 30$ counts/minute

(b) 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 14.6).

Table 14.6

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

(c) Fig. 14.4 shows a graph of count rate (counts per minute) against time.

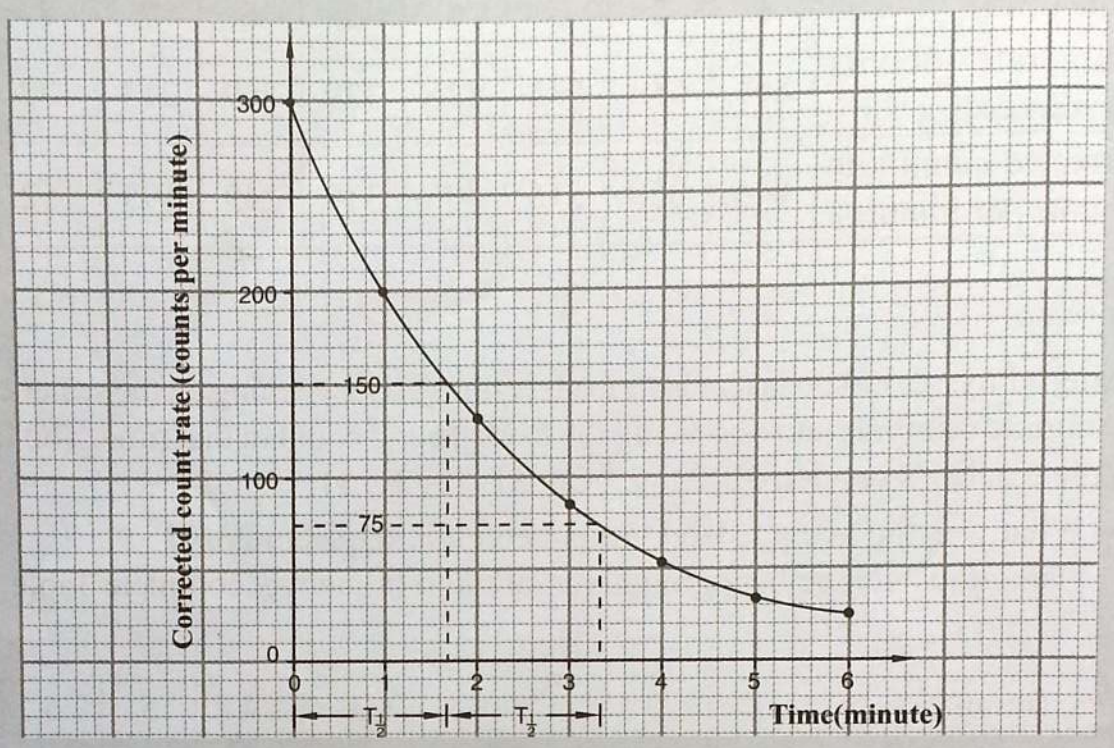


Fig. 14.4: Determining half life of a radioactive element

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 14.1

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 14.7.

Table 14.7

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 radioactive 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;

(a) value of (M)

(b) 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 14.8.

Table 14.8

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 14.9 shows the results obtained in an experiment to study the absorption of beta particles by thin sheets of aluminium.

Table 14.9

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 3mm.

14.5 Types of radiations emitted and their properties

It has been established that the radiations emitted by *radioactive substances* are of three different types: *alpha* (α), *beta* (β) and *gamma* (γ) rays. A radioactive element does not necessarily emit all the three types of radiations.

(a) Alpha particles (α)

Alpha (α) particles are the nucleus of a helium atom with atomic number 2 and mass number 4 i.e. ${}^{4}_{2}\alpha$ or ${}^{4}_{2}He$

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 + 2. It has a mass number 4 and atomic number 2.
2. Alpha particles travel in straight lines in free space.
3. Due to their heavy mass, alpha particles possess a lot of kinetic energy.
4. They affect photographic papers, — the 'fogging' effect is prominent.
5. They ionise the gas through which they travel.
6. They cause fluorescence on certain substances like zinc sulphide, barium, platinocyanide, etc.
7. Their range in air is about 5 - 7 cm. Within this distance, they ionise the air molecules and lose their energy almost completely.
8. Since they lose their energy in the ionisation process, their penetration power is limited. They can be stopped by piece of paper
9. Alpha particles are deflected by both magnetic and electric fields.
10. Alpha particles get scattered while passing through thin metal foils.

Detection of alpha particles in a magnetic field

A small amount of element americium-241 is placed at the bottom of a small hole drilled in a thick lead block as shown in Fig. 14.5(a). Radiations that strike the walls of the block are usually absorbed. The whole arrangement is left 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.

A strong uniform magnetic field is applied to the chamber acting at right angles to the plane of the paper and directed into the paper, away from the reader. The radiation from the source S move into the plane of the paper and at 90° to the direction of the magnetic field.

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.

Detecting alpha particles in a uniform electric field

If a uniform electric field is applied instead of magnetic field (Fig. 14.5 (b)), 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*.

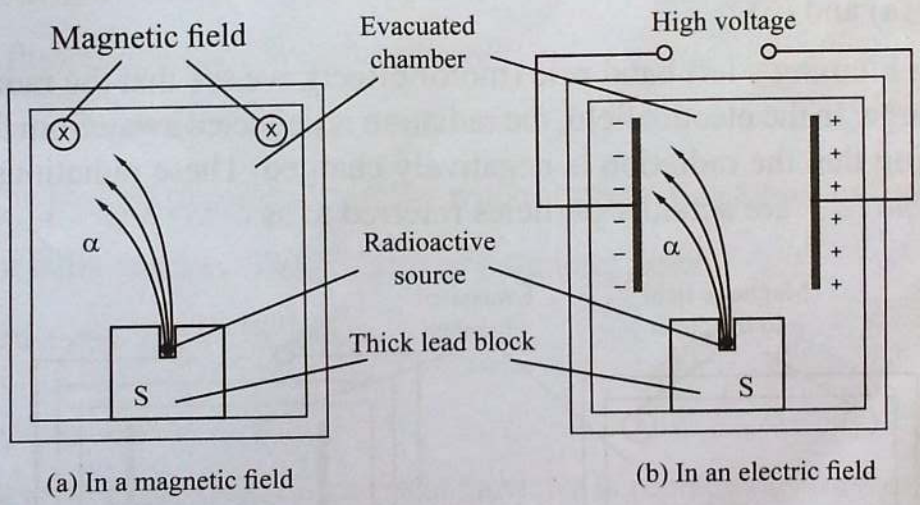


Fig. 14.5: Defection of alpha particles

(b) Beta particles (β)

Beta (β) particles are *fast moving electrons* from the nucleus. Its denoted by $^{0}_{-1}\beta$.

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.

$$\text{neutron} \longrightarrow \text{proton} + \text{electron.}$$

2. Beta particles do not have a well defined path like alpha particles.
3. The 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.

Detection of beta particles (β)

If the source used in the detection of alpha particles is replaced by element strontium-90, and the experiments carried out in both magnetic and electric fields, then the radiations emerging out of the hole of the lead block are deflected as shown in Fig. 14.2 (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 particles referred to as *beta particles*.

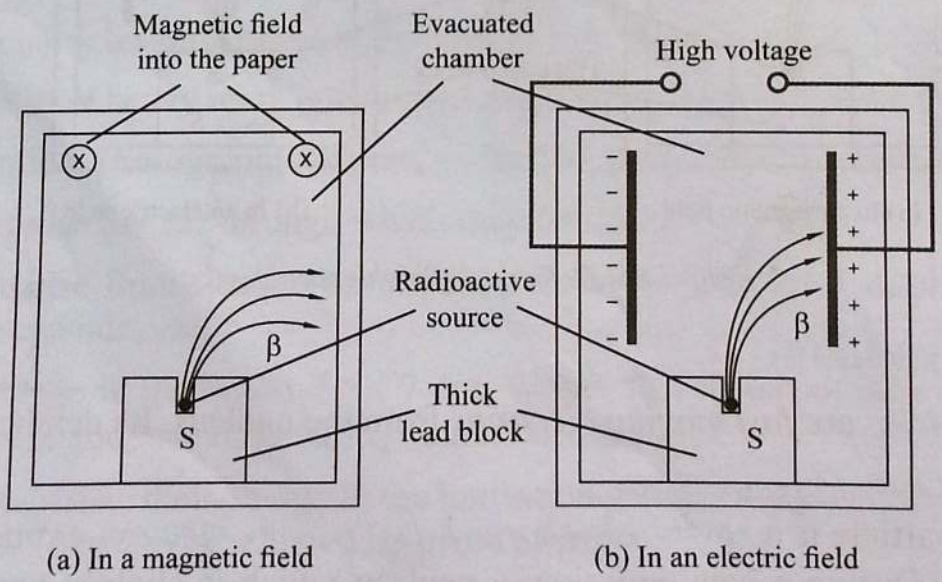


Fig. 14.2: Detection of beta particles

(c) Gamma (γ) rays

Gamma (γ) rays are part of electromagnetic spectrum waves of very short wavelength. They have *no mass* and carry *not charge*. Its denoted by $^{0}_{0}\gamma$

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} m – 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*.
5. Affect photographic papers, but the effect is the least 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. Are transverse waves in nature.

Detection of gamma (γ) rays

If the source used in the detection of beta particles is replaced by element cobalt-60, and the experiments carried out in both magnetic and the electric fields, 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*.

Summary of types of radiation

Table 14.10

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	$1 \times 107 - 1 \times 10^8$m/s	3×10^8m/s
Energy	Possess maximum K.E and are no 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 □–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 particles. Paper cannot 'stop' them, 4mm thick aluminium or a thin lead sheet can 'stop' them	Highest penetrating power. Paper or aluminium 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	Americam - 214 (Am) Strontium - 90 (Sr)		Cobalt - 60 (Co)

14.6 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

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. 14.7 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.

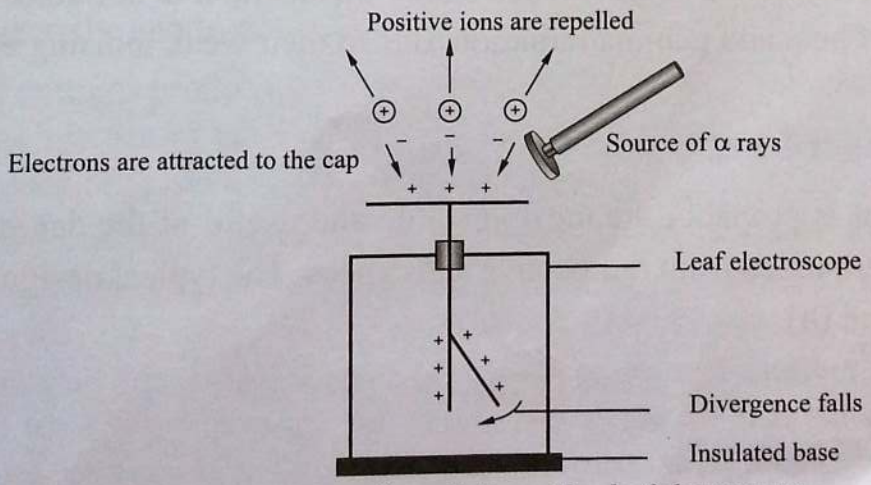


Fig. 14.7: Detection of a radiation with a leaf electroscope

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. 14.8 below shows a spark counter.

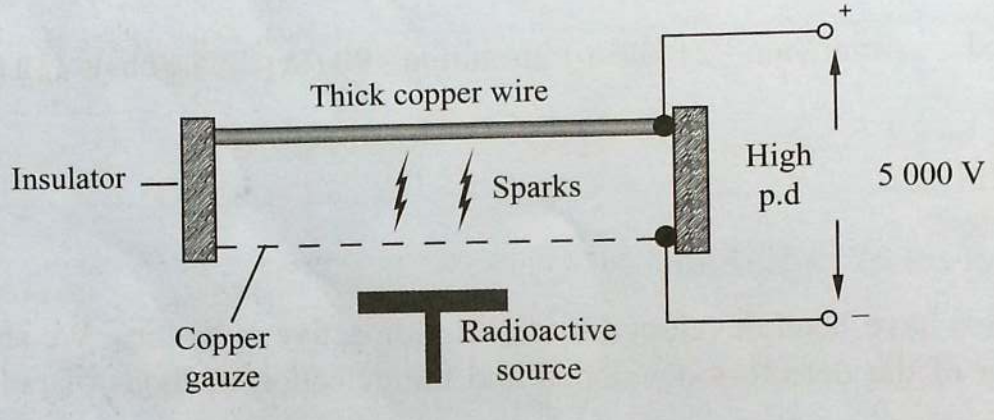


Fig. 14.8: A spark counter

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. 14.9 (a) and (b).

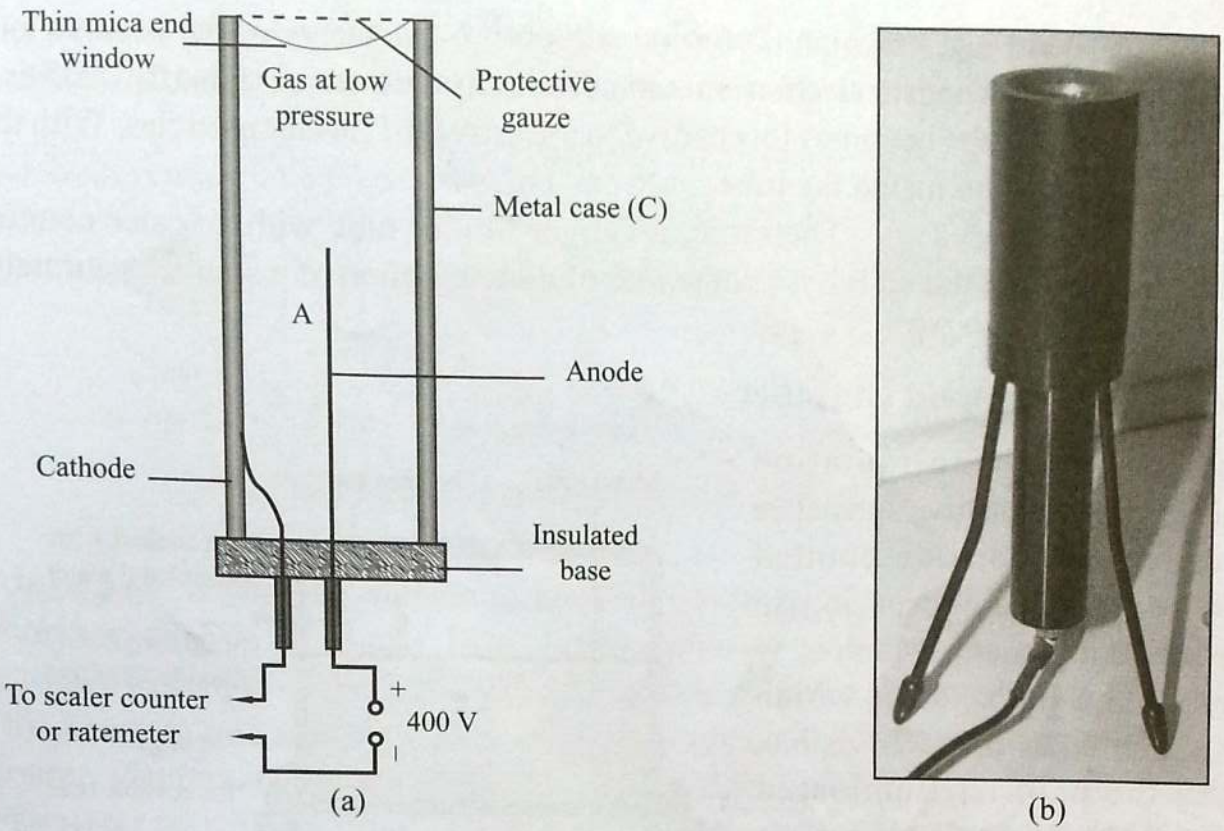


Fig. 14.9: The Geiger-Müller tube

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.

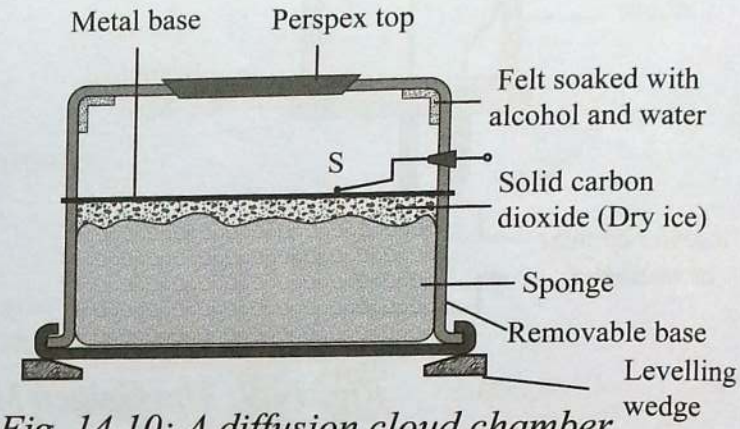


Fig. 14.10: A diffusion cloud chamber

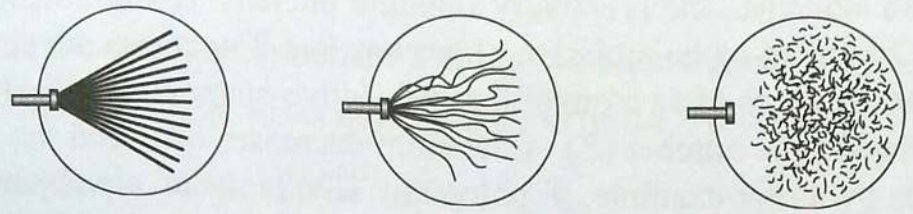
The cloud chamber enables photographs to be obtained on the paths of the ionising particles. Fig. 14.10 illustrates the basic design of a diffusion cloud chamber.

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 $^{-}50^{\circ}$ 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. 14.11 (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 14.11: Appearance of α, β and γ ray tracks

Alpha particles having maximum ionising power produce straight thick tracks of short length (Fig. 14.11 (a)). Beta particles give rise to thin broken erratic tortuous tracks. The length of the tracks are greater than those of alpha particles (Fig. 14.11 (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. 14.11 (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

This is 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.

14.7 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: ${}^{4}_{2}He$ or ${}^{4}_{2}\alpha$. Hence,

$$ \square\ {}^{210}_{84}Po \longrightarrow {}^{4}_{2}He + Pb $$

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 ${}^{0}_{-1}e$ or ${}^{0}_{-1}\beta$. 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, ${}^{14}_{6}C$, emits a beta particle, the reaction produces a beta particle and a nitrogen nucleus. The reaction can be written as:

$$^{14}_{6}C \longrightarrow \beta - \text{particle} + \text{Nitrogen}$$

$$^{14}_{6}C \longrightarrow e + N$$

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

Gammar 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 gammar emission of cobalt – 60 is

$$^{60}_{27}Co \longrightarrow {}^{60}_{27}Co + {}^{0}_{0}\gamma$$

The general equation for v – emission is

$$^{A}_{Z}X \longrightarrow {}^{A}_{Z}X + {}^{0}_{0}\gamma.$$

Example 14.6

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 14.7

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 14.8

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) $c + 0 = 209$

$c = 209$

$d + (-1) = 82$

$d = 82 + 1$

$d = 83$

(c) since a = 4, b = 2 then, ${}^{4}_{2}A$ is helium nucleus.

Exercise 14.2

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**, **y** and **z** in the equation.

$$^{14}_{6}C \longrightarrow ^{x}_{7}N + ^{z}_{y}\beta + \text{Energy}$$

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.

14.8 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 14.11 shows some of the naturally radioactive elements.

Table 14.11

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 14.12 show some artificial radioactive isotopes and their half-lives.

Table 14.12

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.

14.9 Nuclear fission and nuclear fusion

(a) Nucleus 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. 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 sun produces its light and heat through hydrogen fussion to form helium. This process has not yet been exploited and is under research.

14.10 Hazards of radioactivity and precaution

All radioactive substances are dangerous because the radiation they emit can ionise the medium through which they travel. The radiation can cause different chemical changes in living cells. Since the body absorbs the radiation energy, ions produced can change or destroy living cells. Widespread damage of cells may cause death.

Apart from the immediate effect like skin burns, vomiting, diarrhoea, there are also possible delayed effect of radiation like loss of hair, cancer, leukaemia and genetic damage. The leakage of radioactive materials to the ground or atmosphere can lead to disasters and the damage done to the environment is extensive.

Radioactive waste, produced in the nuclear reactors, are dangerous to health and continue to be dangerous for a long time. Many people died when a nuclear reactor exploded in Chernobyl (Russia) in 1986. The atomic bombs dropped in Hiroshima and Nagasaki (Japan) in 1945 not only killed many thousands of people, but the survivors of the explosion also suffered from serious mental depression and genetic damage.

Precautions

When outside the human body, alpha particles do not penetrate far into the body and therefore the risk is small; but when they come inside the body, the risk is high. They ionise living cells leading to dehydration.

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. 14.12).

Fig. 14.12: 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.

14.11 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 centuries ago.

(d) Uses in industries

Leakages in underground water pipes can be located using a gamma ray source of short half-life (Fig. 14.13).

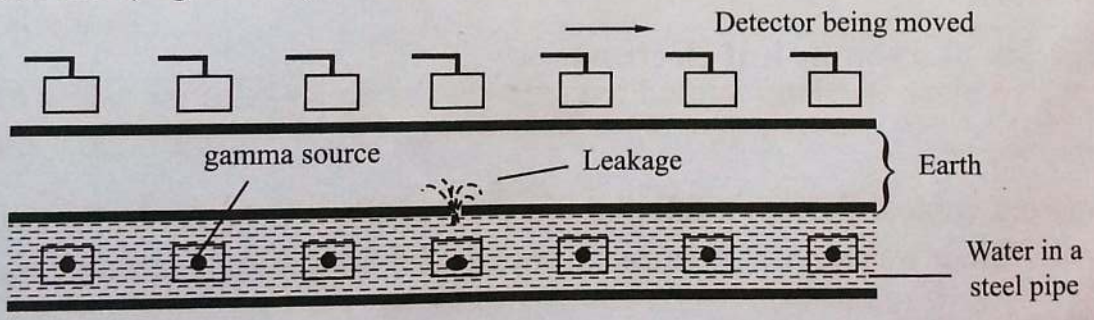


Fig. 14.13: Leakage in underground pipe

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

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.

Exercise 14.3

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.14.14 shows the construction of a leaf electroscope and Fig. 14.15 shows an assembled leaf electroscope.

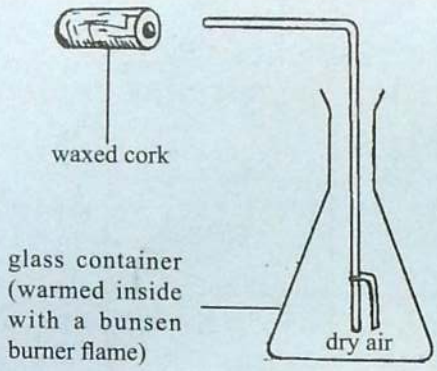


Fig.14.14: Construction of leaf electroscope

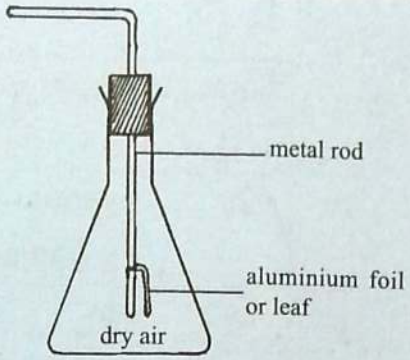


Fig. 14.15: Assembled leaf electroscope

Unit 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_1 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 14.13 below compares the charge, mass, range in air, ionising power, penetrating power and source of alpha, beta particles or gamma rays.

Table 14.13

	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.

Unit Test 14

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) $^{2}_{1}H + - H \longrightarrow ^{4}_{2}He + ^{1}_{0}n$

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) $^{210}Po \longrightarrow ^{4}He + _{82}Pb$

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 14.14.

Table 14.14

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. 14.16 and the results obtained given as shown in Table14.15.

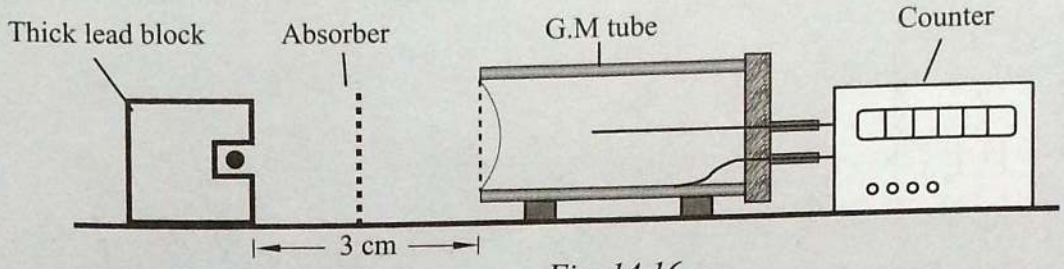


Fig. 14.16

Table 14.15

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.

PHYSICS, MODEL EXAMINATION PAPER

PAPER 1 (100 MARKS)

2HRS

1. (a) Mention two uses of liquid pressure. (2 marks)

   (b) Figure 1 is a hydraulic system being used to raise a load. A force of 50N is applied on piston A_1.

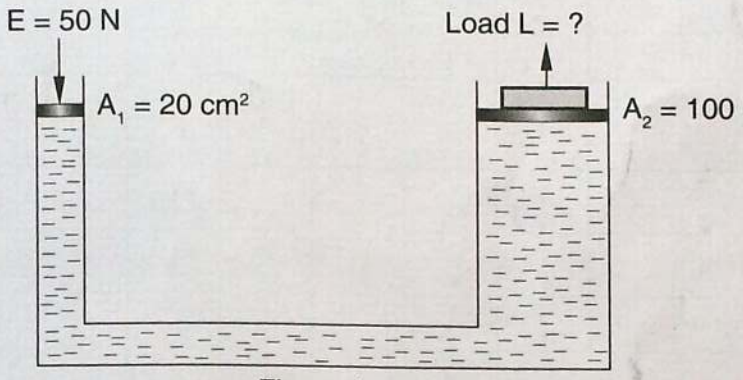


Figure 1

   (i) Calculate the pressure pistonA_1 exerts on the liquid. (3 marks)

   (ii) How much pressure does the liquid exert on piston A_2?

   (iii) Calculate the value of the output force labeled F in the diagram in Figure 1. (3mks)

   (iv) Explain why the hydraulic system in figure 1 is a force multiplier. (3mks)

   (c) Derive a formula to show that the pressure of a liquid depends on its density and depth. (4 marks)

2. (a) (i) Explain why mass is a scalar quantity while momentum is a vector quantity (1 mk)

   (ii) An object is pulled by two forces whose magnitudes are 250 N and 320N. The angle between the two forces is 60°. Draw a scale diagram to show the size of the resultant force. (3mks)

   (b) (i) State Newton's second law of motion (3mks)

   (ii) A car weighing 500kg moves from rest and reaches a speed of 15m/s in 5 seconds.

Calculate:

(i) the acceleration of the car. (2 mks)

(ii) the force exerted by the car's engine (2 mks)

(c) A cyclist starts from rest and accelerates uniformly at $1m/s^2$ for 20 seconds. He then travels at a constant speed for 1 minute and finally decelerates uniformly at $2m/s^2$ until he stops. Draw a velocity time graph on the graph paper in figure 2 to represent the motion of the cyclist.

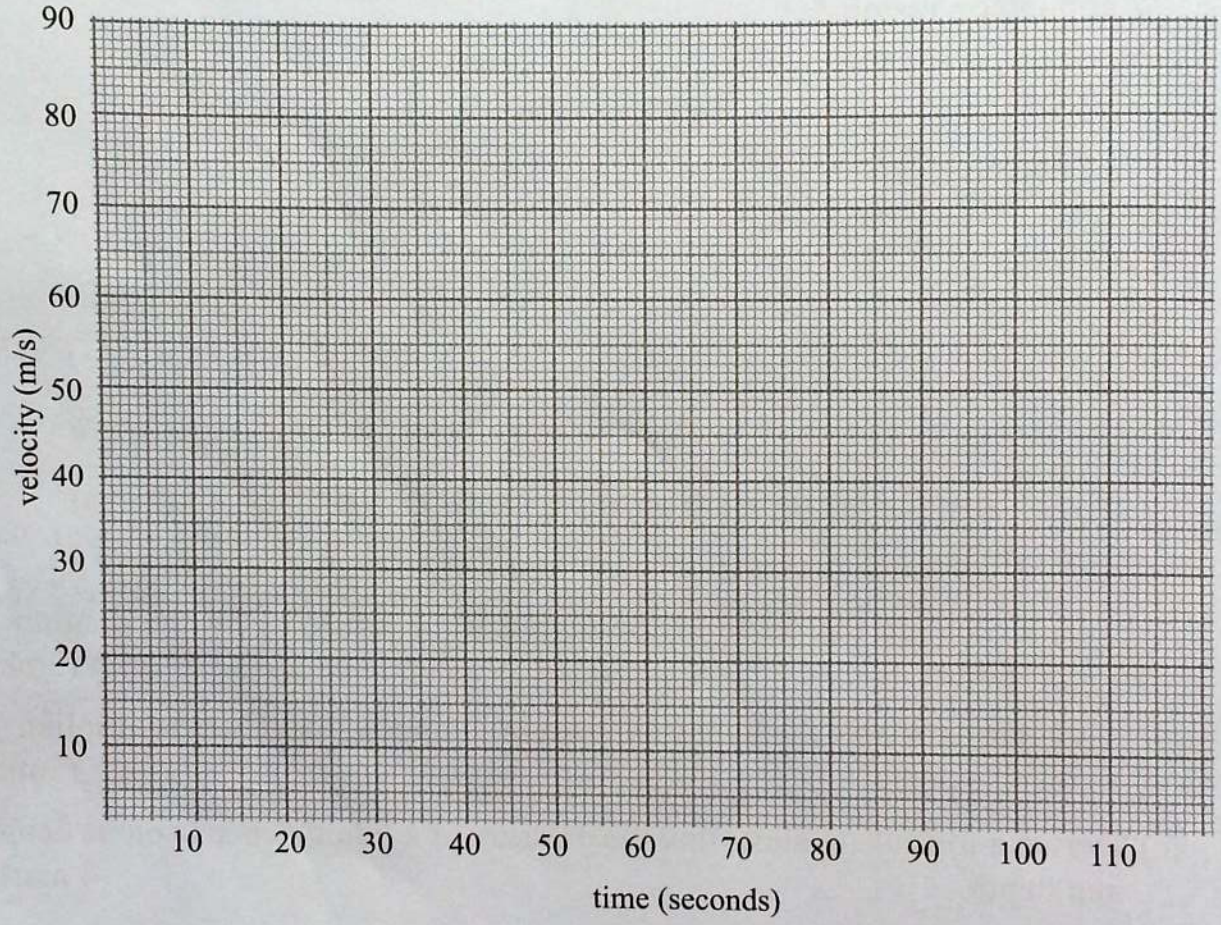


Figure 2 (6 mks)

3. (a) Explain each of the following:

(i) A transformer will not work on direct current (D.C). (2 mks)

(ii) If a transformer increases voltage, it reduces current. (2 mks)

(b) Figure 3 is a diagram of a transformer.

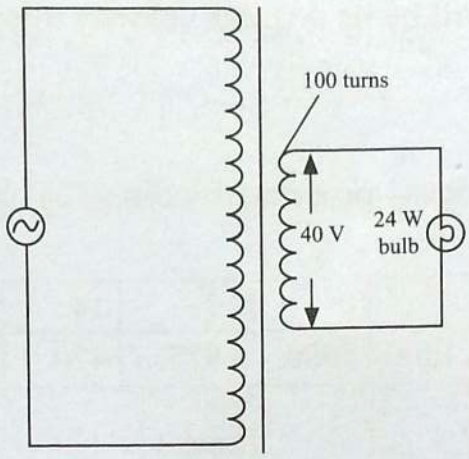


Figure 3

(i) Explain the reason why this transformer can never be practically 100% efficient. (2mks)

(ii) Assuming this transformer is 100% efficient, calculate the current through the input coil. (3mk)

4. (a) Define the following terms as applied in thin lenses:

(i) Principal focus. (1mk)

(ii) Focal length (1mk)

b) An object 2 cm high is 4 cm in front of a converging lens of focal length 5cm.

(i) Draw a ray diagram and find the position of the image formed. (Use a scale of 1cm:2 cm on the vertical and horizontal axes). (3mks)

(ii) Describe the nature of the image formed.

(c) Calculate the magnification of the image formed. (1mk)

(b) Explain how a magnifying glass works. (2mks)

5. (a) Define 'linear momentum.' (2mks)

(b) State the principle of conservation of momentum. (2mks)

(c) A perfectly elastic collision takes place between balls A and B with masses 4 kg and 2 kg respectively. The initial speed of A is 5 m/s while B is initially at rest. Given that the final speed of B is 2 m/s, determine the speed of A after collision. (4 mks)

6. (a) Define the following terms:

(i) Circular motion. (2mks)

(ii) Angular velocity. 2mks

(b) A wheel starts from rest and accelerates uniformly with an angular acceleration of 4 rad/s^2. What will be its angular velocity after 4 seconds? (3mks)

7. (a) Define 'half life'. (1mk)

(b) Table 1 shows the decay process of iodine-131

Time (days)	0	7	14	21	28	35
Activity (units per litre)	1600	875	470	260	140	77

Table 1

(i) Using the graph paper in figure 4, draw a graph of activity against time. 5mks

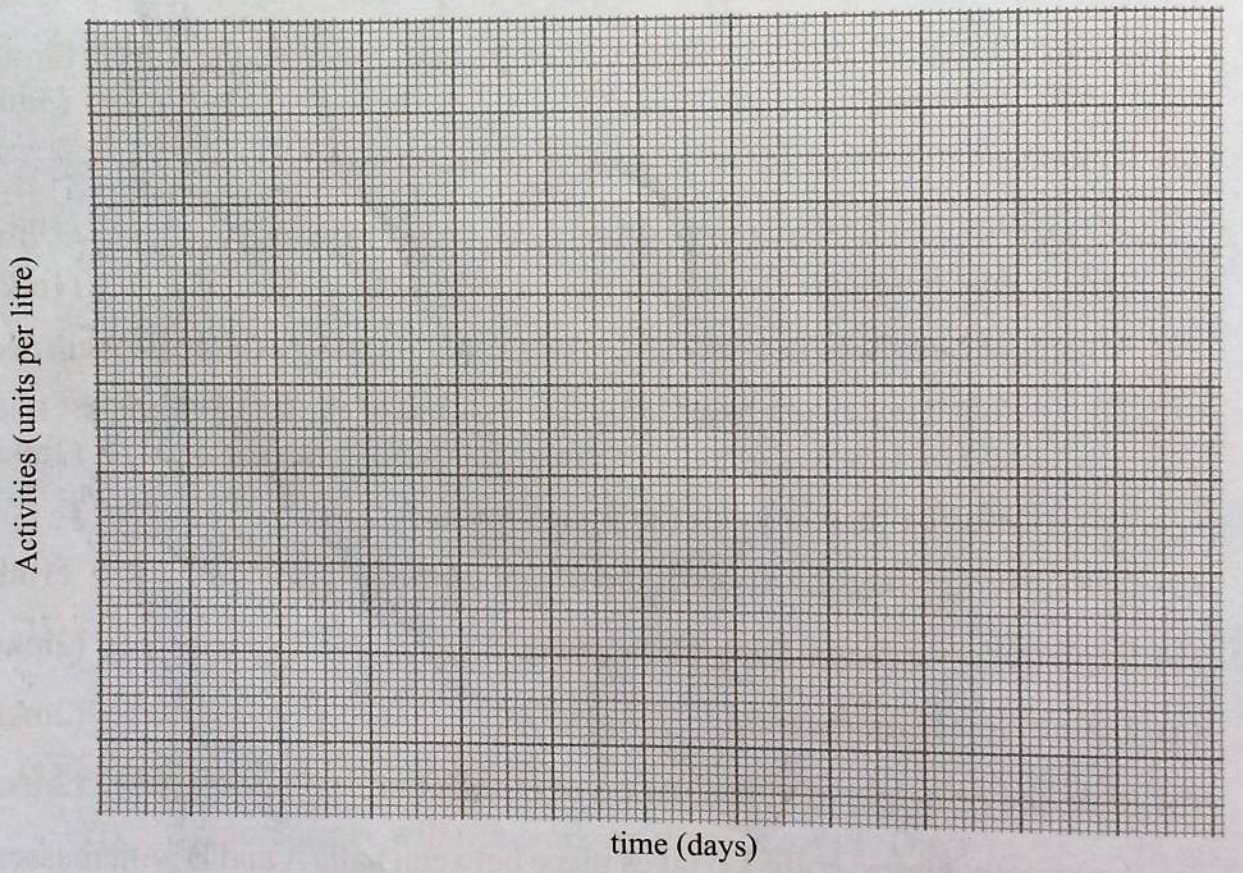


Figure 4

(ii) Estimate the half-life of iodine-131 and show on the graph how you arrived at the answer. (1mk)

(c) State any three safety precautions to be observed when using radioactive sources in a school laboratory. (3mks)

(b) Complete and balance the following nuclear equations.

(i) $____ + {}^{16}_{8}O \longrightarrow {}^{17}_{8}X$ (1mk)

(ii) ${}^{226}_{88}Ra \longrightarrow Rn + ____$ (1mk)

8. (a) Define "terminal velocity'. (2mks)

(b) Figure 5 shows a metal ball bearing falling in oil.

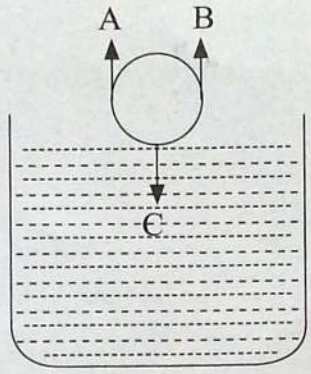


Figure 5

(i) Using forces A, B and C describe the motion of the ball bearing through the oil until it reaches the bottom of the container. (Assume the ball bearing reaches terminal velocity before reaching the bottom of the container). (8mks)

(ii) Mention two forces that affect terminal velocity (2mks)

(c) (i) What are semiconductors? (1mk)

(ii) Explain how raising the temperature of a semiconductor affects its electrical conductivity. (3mks)

(iii) With the aid of a diagram, explain how n-type semiconductors are made. (4mks)

PHYSICS, MODEL EXAMINATION PAPER

PAPER II

(50 MARKS) 2 HOURS

1. You are provided with a candle, a match box, a lens holder, convex lens, white screen and a meter ruler.

   (a) Arrange the candle, convex lens and screen as shown in Figure 1.

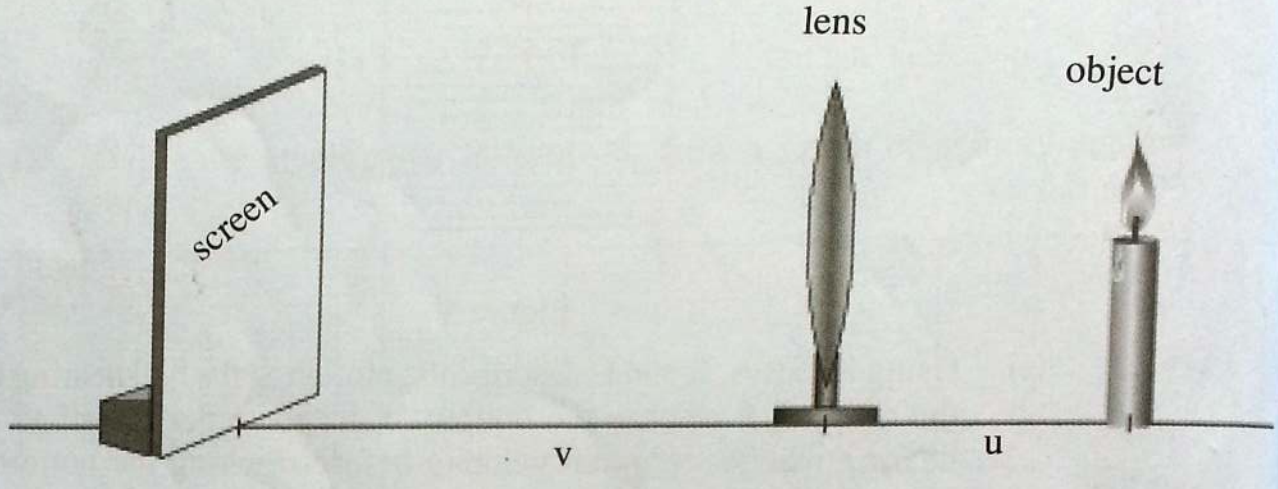


Figure 1

   (b) Light the candle.

   (c) With the candle at 20cm from the lens, produce a well-focused image of the flame on the screen.

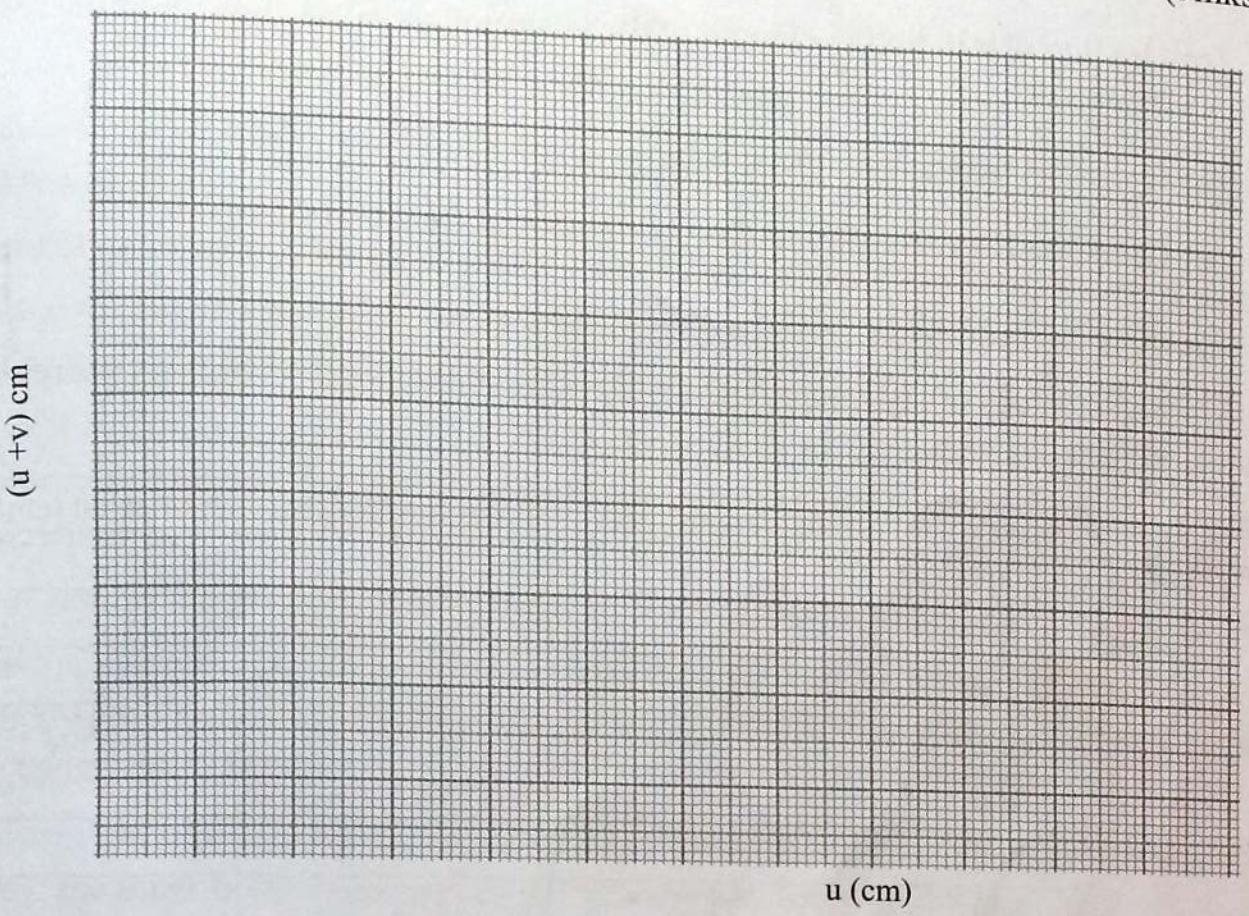
   (d) Measure and record the image distance in the table of results (Table 1)

   (e) Repeat steps (c) and (d) for object distance shown in Table 1.

Object distance, u(cm)	Image distance; v(cm)	u + v (cm)
20		
30		
40		
50		
60		

(f) Plot a graph of $u + v$ against u.

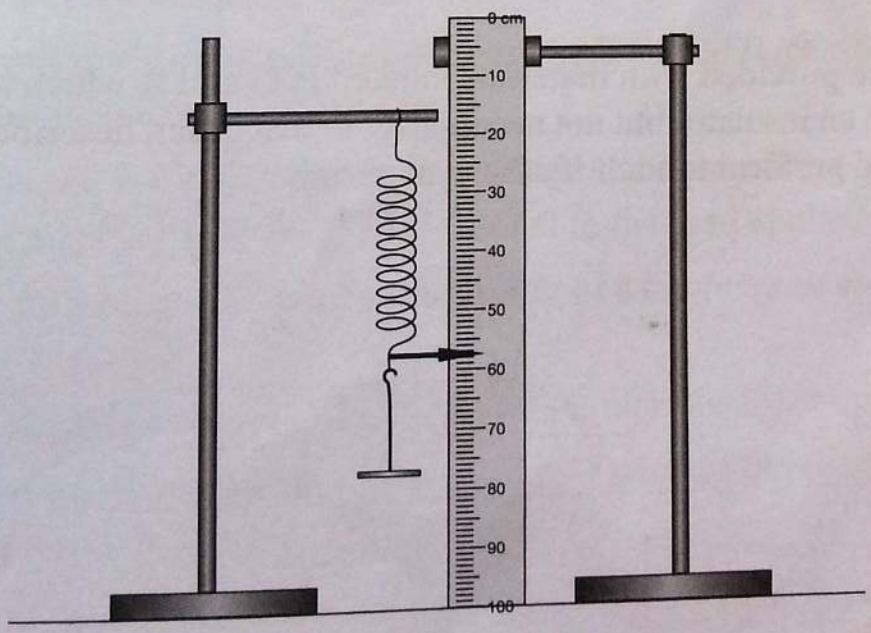
(5mks)



(g) From the graph, write down the coordinates of the minimum point. (1mk)

(h) Using the coordinates of minimum point, find the focal length of the lens (1mk)

2. You are provided with a clamp stand, a meter ruler, a spring and masses of 100g, 200g, 300g, 400g, 500g, 600g and 700g.



(a) Arrange the clamp stand and the spring as shown in figure 2

(b) Use the ruler to find the length of the unstretcher spring and record the result in table 2

(c) Hand a 100g mass on the spring.

(d) Calculate the extension in the spring caused by the 100g mass.

(e) Record the result in table 2.

(f) Repeat steps (c), (d) and (e) using the other masses and records all the results in table 2

Mass (g)	Initial length (cm)	Final length (cm)	Extension (cm)
0			
100			
200			
300			
400			
500			
600			
700			

4mks

3. With the aid of a well labeled diagram, explain how a manometer works to measure gas pressure
13mks

4. Suppose you are provided with materials labeled P, Q and R which are a diode, a conductor and an insulator but not necessarily in that order, describe an experiment you would perform to identify these materials

12mks

Glossary

Temperature: the degree of coldness or hotness of a body.

Heat: a form of energy, which passes from a body of high temperature to a body of low temperature.

Thermal expansion: change in size of a substance as a result of temperature change.

Inertia: the reluctance of a body to change its state of motion i.e. either to remain at rest or to continue moving in a straight line.

Newton's first law of motion: it states that a body continues in its state of rest or uniform motion in a straight line unless compelled by some external force to act otherwise.

Momentum: the product of the mass and the velocity of an object.

Newton's second law of motion: it states that the rate of change of momentum is directly proportional to the resultant force and it takes place in the direction in which the force acts.

Newton's third law of motion: it states that whenever a body exerts a force on another body; the other body exerts an equal but opposite force on the first body.

Elastic collision: a collision in which both K.E and momentum are conserved

Inelastic collision: a collision in which only momentum is conserved.

Frictional force: the force that opposes the relative motion of two surfaces in contact.

Coefficient of friction: the ration of frictional force (F) to the normal reaction (R).

Coefficient of static friction: the coefficient of frictional force when the two surfaces in contact are not sliding over each other.

Coefficient of kinetic friction: the coefficient of frictional force when the two surfaces in contact are sliding over each another.

Hooke's law: the law that states that provided the elastic limit is not exceeded, the extension of a spring is directly proportional to the load applied on the spring.

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

Angular velocity (ω): the rate of change of angular displacement.

Centripetal force: the force that pulls an object towards the center of the circle as it rotates, keeping it moving in a circular path.

Moment of a force: the product of the force and the perpendicular distance from the point to the line of action of the force.

Principle of moments: It states that, when a body is in equilibrium under the action of forces, the sum of clockwise moments about any point is equal to the sum of anticlockwise moments about the same point.

Couple: two equal and opposite parallel forces acting on a body at different points

Centre of mass of a body: is the point where the whole mass of the body appears to be concentrated.

Domain: a region in a magnetic material occupied by atomic magnets (dipoles).

Electromagnet: a metal core that is made into a magnet as electric current through a coil surrounding it.

Electromagnetic induction: the phenomena through which electric current is induced in a conductor inside a magnetic field when there is change in the magnetic flux linking the conductor.

Mutual inductance: the phenomena through which electric current is induced in a coil by the change in the current flowing through another coil.

Transformer: a device for stepping up/down voltage.

Semiconductors: materials whose electrical conductivity lies between that of good conductors and insulators.

Rectification: process of converting a.c to d.c.

Capacitor: a device that stores charge.

Photovoltaic cell: an electrical device that converts light energy directly to electric energy by photovoltaic effect.

Electromagnetic waves: waves that have both electric and magnetic fields.

Electromagnetic spectrum: arrangement of electromagnetic waves in order of their frequencies.

Global warming: the gradual increase in the temperature of the earth's atmosphere due to the greenhouse effect which is caused by increased levels of carbon dioxide, chlorofluorocarbons, and other pollutants.

Lens: a transparent medium bound between two surfaces of definite geometrical shape.

Principal focus: a point where all rays parallel to the principal axis converge after refraction by a convex lens, or appear to diverge from after refraction by a concave lens.

Myopia: short sightedness

Hypermetropia: long sightedness.

Atomic Number: Number of protons in an atom of an element.

Atomic mass: the total number of protons and neutrons in an atom of an element.

Isotopes: atoms of the same element with the same atomic number, but different mass numbers or are atoms of the same element with the same number of protons but different numbers of neutrons.

Radioactivity: the spontaneous and random disintegration of atoms emitting particles and/or radiations in order to attain a stable state.

Half-life: 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.

Alpha particle (α)**:** the nucleus of a helium atom with atomic number 2 and mass number 4.

Beta (β) *particles:* a fast moving electrons from the nucleus.

Gamma rays: a part of electromagnetic spectrum waves of very short wavelength.

Nuclear fission: the splitting of a heavy nucleus into lighter nuclei with the release of energy.

Nuclear fusion: is a process where energy is released when two lighter nuclei are fused together to form a heavier nucleus.

References

- Abbot A. F., (1977), *Ordinary Level Physics*, Heinemann Educational Publishers, 3rd Edition.
- Atikinson A., Sinuff H (1987), *New Complete Junior Physics*, Longhorn Publishers, Nairobi.
- Balarman K., Kariuki C (2004), *Longhorn Secondary Physics Form 3,* Longhorn Publishers , Nairobi.
- Balarman K., Kariuki C (2004), *Longhorn Secondary Physics Form 4,* Longhorn Publishers , Nairobi.
- Duncan T (1990), *Physics for Today and Tomorrow,* Trans-Atlantic Publications, Inc.; 2nd edition.
- Malawi Institute of Education (2013), *Malawi Junior Secondary Syllabus for Form 3 and 4 Physics,* Domasi
- Nelkon M (1990), *Principles of Physics*, Longman, 8th Edition
- *Apple Dictionary.*

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ISBN 999603845-9

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