بِسۡمِ اللّٰہِ الرَّحۡمٰنِ الرَّحِیۡمِ

(In the Name of Allah, the Most Merciful, the Most Compassionate.)

PHYSICS 10

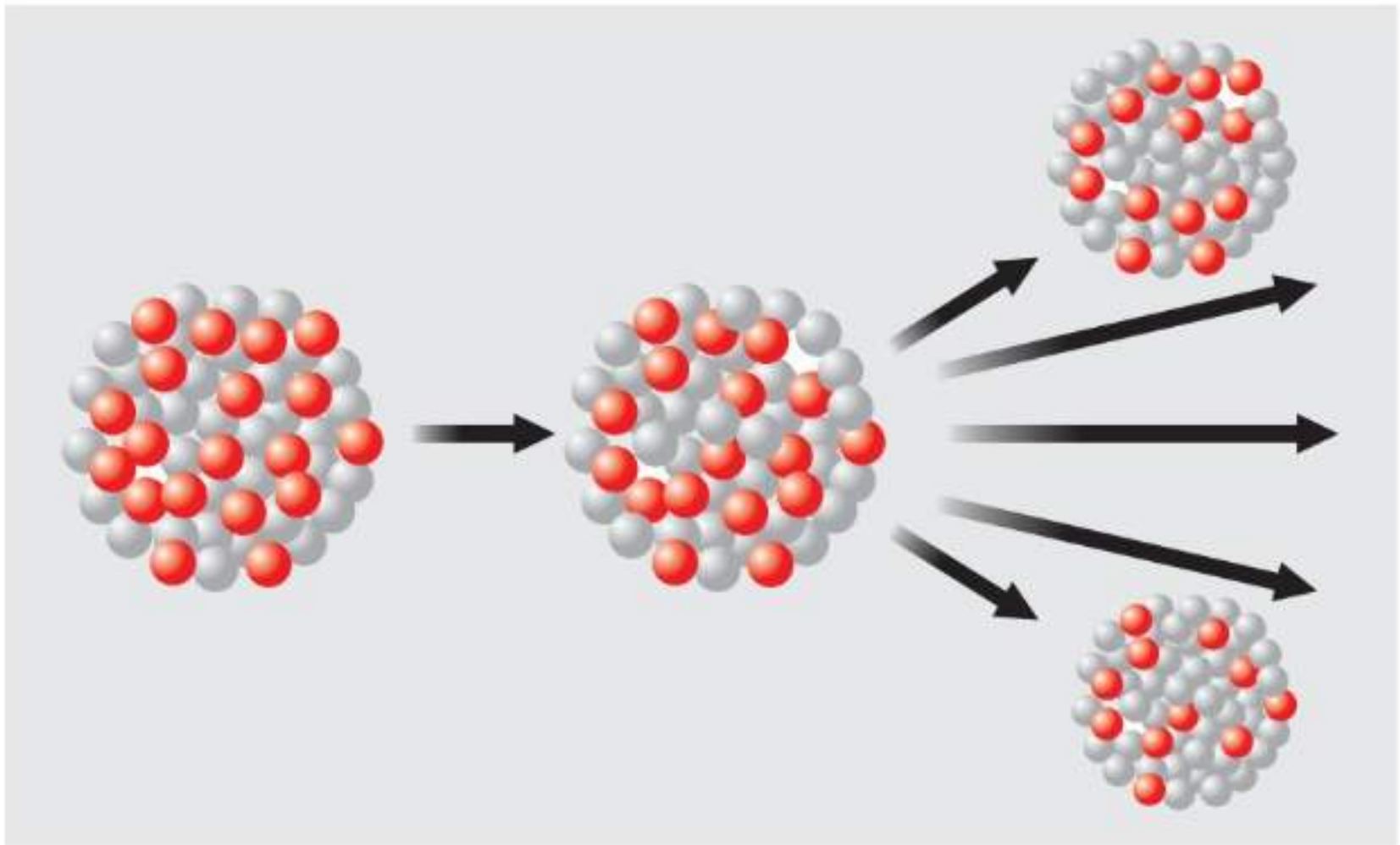

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Table of Contents

Chapter	Description	Page No.
10	Thermal Physics	1
11	Transfer of Thermal Energy	19
12	Waves	32
13	Sound	46
14	Light	62
15	Electrostatics	88
16	Electricity	104
17	Electromagnetism	126
18	Electromagnetic Induction and Electromagnetic Waves	138
19	Electronics	153
20	Atomic and Nuclear Physics	166
21	Space and Environment	186
•	Pairing Scheme and Model Paper	i-iv

CHAPTER 10

THERMAL PHYSICS

Student's learning outcomes (SLOs)

After studying this unit, student will be able to:

- describe qualitatively the thermal expansion of solids (linear and volumetric expansion).
- explain the thermal expansion of liquids (real and apparent expansion) and gases.
- discuss the pressure and the changes in pressure of a gas in terms of particles [the forces exerted by particles colliding with surfaces, creating a force per unit area.]
- discuss the applications and consequences of thermal expansion in real life.
- define and calculate specific heat for solids and liquids.
- discuss everyday effects due to the large specific heat of water.
- use the terms for the changes in state between solids, liquids and gases (This includes stating the relative order of magnitudes of the expansion of solids, liquids and gases.)
- describe evaporation in terms of particles [in terms of the escape of more energetic particles from the surface of a liquid].
- discuss how temperature, humidity, surface area and air movement over a surface affect evaporation.
- explain how evaporation causes cooling.
- describe the use of cooling caused by evaporation in the refrigeration process without using harmful CFCs.
- define latent heat of fusion and latent heat of vaporization of ice and water. How these can be determined Experimentally? [including illustrating the analysis of data by sketching temperature-time graph on heating ice.]

- describe superconductivity [as when atoms are in this state, their kinetic energy is low, so there is little (or no) resistance to the flow of electrons.
- state that certain materials, when cooled to near absolute zero, can exhibit superconductivity.

Heat and temperature play a vital role in our daily life, from feeling the warmth of the Sun to enjoying a cold drink on a hot day. Thermal physics helps us to understand how heat flows, how the temperature of substances change , and how heat energy is transferred. This field explains important concepts such as temperature, heat transfer, specific heat capacity, phase changes, latent heat and evaporation. Understanding these principles helps us to understand how everyday objects like refrigerators, heat engines, and even Earth's climate function. Thermal physics is not just about daily life, it also helps scientists to explore space, develop efficient energy systems, and emendate modern technology.

10.1 Thermal Expansion

Thermal expansion is the change in length, area, or volume of a substance when it is heated. As the temperature rises, the particles within a substance gain more kinetic energy. This causes them to move faster and spread out, leading to expansion of the material (Fig. 10.1-b).

Conversely, when a substance is cooled, its particles lose energy and move closer together, causing the material to contract (Fig. 10.1-a). This phenomenon is known as thermal contraction.

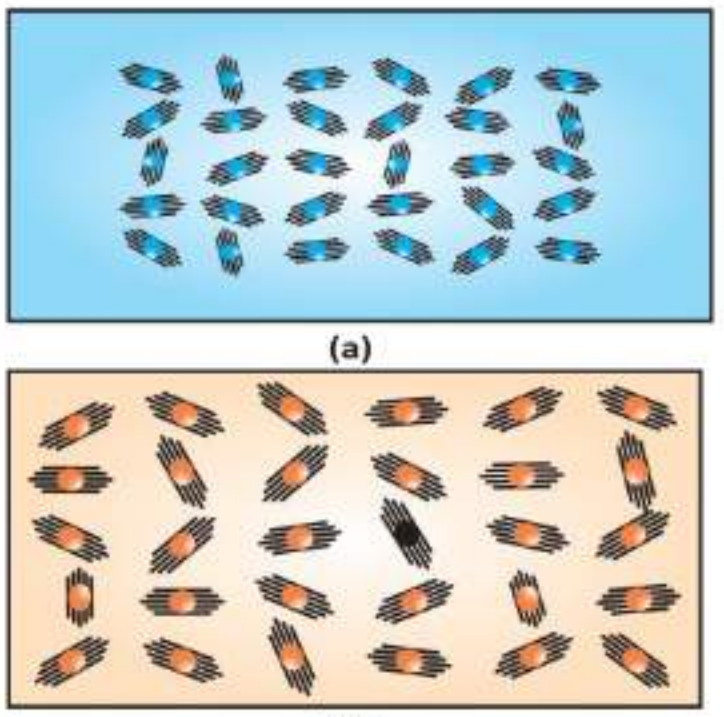


Fig. 10.1: Molecules of an object moving with (a) smaller amplitude at low temperature (b) larger amplitude at higher temperature

Thermal Expansion in Solids

When solids are heated, they expand, and this expansion remains almost consistent over a broad temperature range. Change in temperature may cause respective change in length or volume of the solids. If length of a solid changes upon heating, then it is called linear thermal expansion. For example, consider a metal rod in Fig. 10.2 with an initial length L_o at a temperature T_o. When heated to a

temperature T, its new length becomes L. Thus, the increase in length of the rod is:

$$\Delta L = L - L_o$$

and the rise in temperature is:

$$\Delta T = T - T_o$$

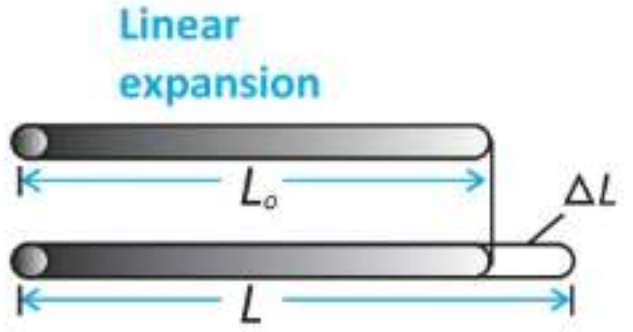


Fig. 10.2: Linear expansion in a metal rod

It has been observed that the change in length ΔL of a solid is directly proportional to its original length L_o and the temperature change ΔT. Thus,

$$\Delta L \propto L_o \Delta T$$

or $$\Delta L = \alpha L_o \Delta T$$

$$\alpha = \Delta L / L_o \Delta T$$

or $$L - L_o = \alpha L_o \Delta T$$

or $$L = L_o (1 + \alpha \Delta T) \text{ .....(10.1)}$$

Here α is called the coefficient of linear expansion of the material. Table 10.1 shows the value of 'α' of different solid materials.

The volume of a solid also increases when its temperature rises. This is known as volume thermal expansion. Suppose a solid has an initial volume V_o at a temperature T_o. When heated to a temperature T, its new volume becomes; $\Delta V = V - V_o$.

and the rise in temperature is: $\Delta T = T - T_o$

Similar to linear expansion, the increase in volume ΔV is directly proportional to its original volume V_o and the temperature change ΔT, thus

$$\Delta V \propto V_o \Delta T$$

or $$\Delta V = \beta V_o \Delta T$$

Table 10.1: Values of some coefficient of linear expansion (α) of different solid materials

Substance	α (K^{-1})
Aluminium	**2.4×10^{-5}**
Brass	**1.9×10^{-5}**
Copper	**1.7×10^{-5}**
Steel	**1.2×10^{-5}**
Silver	**1.93×10^{-5}**
Gold	**1.3×10^{-5}**
Platinum	**8.6×10^{-5}**
Tungsten	**0.4×10^{-5}**
Glass (pyrex)	**0.4×10^{-5}**
Glass (Ordinary)	**0.9×10^{-5}**
Concrete	**1.2×10^{-5}**

or $V - V_o = \beta V_o \Delta T$

or $V = V_o (1 + \beta \Delta T)$ ..... (10.2)

Here β is called coefficient of volume expansion which determines how much a material expands with temperature. Different solids have different values of β, meaning some expand more than others when heated.

Mathematically,

$$\beta = \frac{\Delta V}{V_o \Delta T}$$

In solids, atoms are arranged in a tight, regular pattern. As the temperature rises, each atom pushes slightly harder against its neighbours due to increased vibration. Since there is no room to move inwards, the structure expands outward instead.

Thermal Expansion in Liquids

When a liquid is heated, its volume increases. This happens because the heat energy makes the liquid molecules move faster, causing them to spread apart and take up more space. Unlike solids, which have a fixed shape and expand in a limited way, liquids do not have a definite shape, so they expand freely in all directions when their temperature rises.

The degree to which a liquid expands depends on its specific coefficient of volumetric expansion, a property unique to each substance. This expansion is quantified by the formula:

$\Delta V = \beta V_o \Delta T$ ..... (10.3)

where ΔV is the change in volume, β is the volume expansion coefficient, V_o is the original volume, and ΔT is the temperature change.

A common example of thermal expansion in liquid as seen in flask (Fig 10.3). When the flask is heated, the glass expands leading to decrease in liquid level from A to B which is known as expansion of flask (AB). As the liquid heats up, it expands

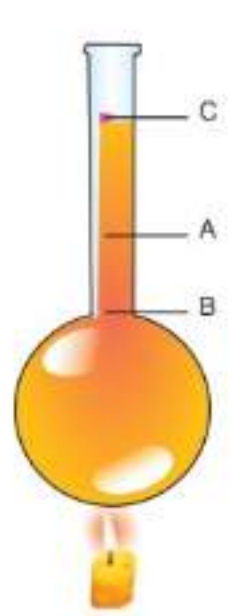


Fig. 10.3 : Thermal expansion of a liquid

and the level rises from B to C which is known as real expansion (BC). Where AC is an apparent expansion. Remember that real expansion is always greater than apparent expansion.

$$BC = AC + AB$$

Tidbit

Liquids do not have a fixed shape, so they expand more freely than solids. That is why we should not fill a bottle of water to the top before freezing it, it might crack.

Thermal Expansion in Gases

When temperature of a gas increases, its volume increases as long as the pressure remains same. This is called thermal expansion of the gas. As the temperature of a gas increases, the kinetic energy of its particles also increases. This causes the gas molecules to move faster and collide more frequently and forcefully with the walls of the container. Thus, collisions exert pressure, on the container walls.

If a gas is in a non flexible container, the increased collisions lead to a rise in pressure. However, in a flexible container, the volume can expand instead, allowing pressure to remain constant. This behaviour aligns with Charles' law, which states that the volume of a gas is directly proportional to its temperature at constant pressure.

The expansion of gases plays an important role in daily life and various industries. For example, in a hot air balloon, the air inside is heated, causing it to expand and become lighter than the cooler air outside. This makes the balloon to rise (Fig. 10.4). Similarly, in car engines, fuel burns and produces hot gases that expand quickly, pushing the pistons and making the vehicle move. In weather patterns, warm air expands and rises, affecting air pressure and causing winds and weather changes. However, the uncontrolled expansion of gases can be dangerous. For instance, aerosol cans and gas cylinders can explode if exposed to high temperatures because the gas inside expands beyond what the container can withstand.

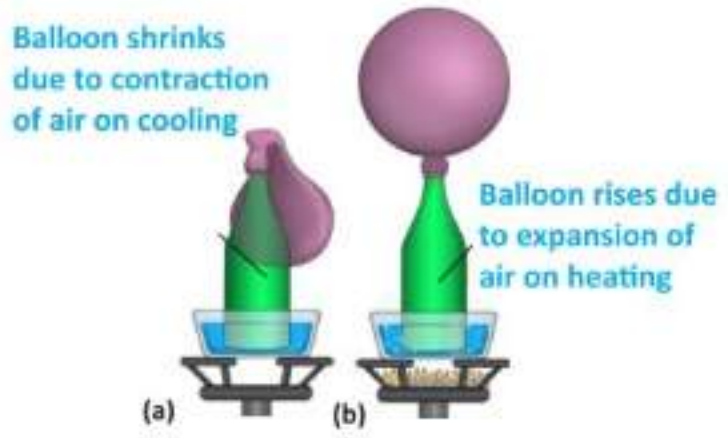


Fig. 10.4: Thermal expansion of gas in a balloon (a) Before heating (b) After heating

Consequences of Thermal Expansion in Real Life

When materials expand or contract due to temperature changes, it can lead to structural, mechanical, and functional consequences. Thermal expansion is commonly used in our daily life such as:

1. **Thermometers:** In thermometers, thermal expansion in a narrow tube helps in the measurement of temperature.

2. **Gaps in Railway Tracks:** Steel tracks of the rails expand on hot days. Without room to expand, the tracks may bend or twist a phenomenon called "sun kinks" which can cause train derailments. Small gaps are left between railway tracks to allow them to expand in summer, preventing them from bending (Fig. 10.5-a).

3. **Bridges:** Bridges have small gaps called expansion joints that allow them to expand in hot weather and contract in cold weather without breaking (Fig. 10.5-b).

4. **Metal Lids on Jars:** When a metal lid is stuck on a glass jar, running warm water over it makes the lid expand slightly, making it easier to open.

Fig.10.5: (a) Expansion gaps in railway tracks (b) Expansion joints in bridges

5. **Gas Containers (like aerosols or propane tanks):** Gases expand significantly when heated. If containers are exposed to heat (like being left in the Sun), pressure can build up inside and causes explosions. Warning labels advise users to store these containers away from heat, and pressure relief valves are often included.

6. **Pipes and Plumbing:** Water pipes can expand and contract, especially with hot water. This may lead to pipe bursts or joint leaks if not properly accounted for. Flexible joints and loops are used in piping systems to absorb movement.

7. Hot Air Balloon: The expansion of heated air is intentionally used to make the balloon rise. Heating the air inside causes it to expand, reducing its density so it lifts the balloon (Fig.10.6).

Fig. 10.6: When hot air balloon is heated, air inside the balloon expands and becomes less dense, causing the balloon to rise

Brain Teaser

Why do not train tracks buckle in winter but do in summer even though the metal is the same?

Example 10.1: A metal rod of length 1.5 m expands by 0.025 m when heated from 30 °C to 180 °C. Calculate its coefficient of linear expansion.

Solution:

Given that;

L_o = Initial length = 1.5 m

ΔL = Change in length = 0.025 m

ΔT = Change in temperature = 180 °C - 30 °C

= 150 °C or 150 K

To find; α = Coefficient of linear expansion = ?

The formula for linear expansion is:

$$\Delta L = \alpha L_o \Delta T$$

or $$\alpha = \Delta L / L_o \Delta T$$

Substituting the values

$$\alpha = 0.025 \text{ m} / 1.5 \text{ m} \times 150 \text{ K}$$

$$\alpha = \frac{0.025}{225} = 1.11 \times 10^{-4} \text{ K}^{-1}$$

10.2 Specific Heat Capacity

The energy required to heat a material depends on three factors:

1. Mass of the substance
2. Change of temperature
3. Nature of the material

Some substances absorb heat more easily than others. For example, heating 1 kg of water by 1 °C requires more energy than heating 1 kg of alcohol by the same amount. This relationship is expressed using the formula:

$$Q = m\,c\,\Delta T \quad \text{.....(10.4)}$$

where

Q = heat energy
m = mass of the substance
ΔT = change in temperature
c = specific heat capacity

Specific heat capacity (c) is the amount of heat energy needed to increase the temperature of 1 kg of a substance by 1 °C (or 1 K). The SI unit of specific heat capacity is $J\,kg^{-1}\,K^{-1}$.

For Your Information

Metal heats up quickly due to its low specific heat capacity, while wood stays normal because of its higher specific heat capacity.

Specific Heat Capacity of Solids

The specific heat capacity of solids is the heat energy needed to raise the temperature of 1 kg of a solid by 1 °C. Materials with a high specific heat capacity, such as wood and rubber require more heat to increase their temperature, making them useful in applications like cooking utensils and thermal insulation. On the other hand, metals like steel and copper have low specific heat capacities, i.e; they heat up and cool down quickly, so they are used in making cooking items, kettles, radiators, and heat engines.

Do You Know?

Why does metal feel colder than wood when touched, if they are both at the same temperature?

Metal is a conductor, wood is an insulator. The metal conducts the heat away from our hands, the wood does not conduct the heat away from our hands as well as the metal, so the wood feels warmer than the metal.

Specific Heat Capacity of Liquids

The specific heat capacity of a liquid is the amount of heat energy needed to raise the temperature of 1 kg of the liquid by 1 °C or 1 K. Different liquids have different specific heat capacities based on their molecular structure and ability to store heat. One of the most important liquids in this regard is water, which has a high

specific heat capacity of 4,200 J kg^{-1} K^{-1}. This means water can absorb and store a large amount of heat with only a small temperature increase. Because of this property, water is widely used in cooling systems, heating systems, and as a natural temperature stabilizer. Other liquids, such as alcohol and mercury, have lower specific heat capacities, meaning they heat up and cool down more quickly than water.

Effects of Large Specific Heat Capacity of Water

Large water bodies like oceans and lakes absorb heat during the day and release it slowly at night, preventing drastic temperature changes. This is why coastal areas have milder climates compared to inland regions. Since water has a specific heat capacity of 4200 J kg^{-1} K^{-1}, while dry soil has only 810 J $kg^{-1}K^{-1}$, soil heats up five times faster than the same mass of water under the same heat. As a result, land temperatures rise and fall more quickly than sea temperatures, making seasonal temperature changes less extreme in coastal areas.

Water's high specific heat capacity also makes it useful for storing and transferring heat. In an automobile engine, the cooling system uses water to absorb and carry away the heat produced during the engine operation. The pump circulates water through jackets around the engine cylinders, where it absorbs heat (Fig. 10.7). This heated water then flows through the thermostat, which regulates its movement based on temperature. If the water is too hot, the thermostat opens, allowing it to enter the radiator. In the radiator, a fan draws in outside air, which cools the water passing through it. The cooled water then returns to the engine to absorb more heat, and this cycle is repeated. A pressure release cap ensures that the system remains safe by releasing excess pressure. This property helps water to carry away engine heat efficiently, preventing overheating and ensuring smooth engine performance.

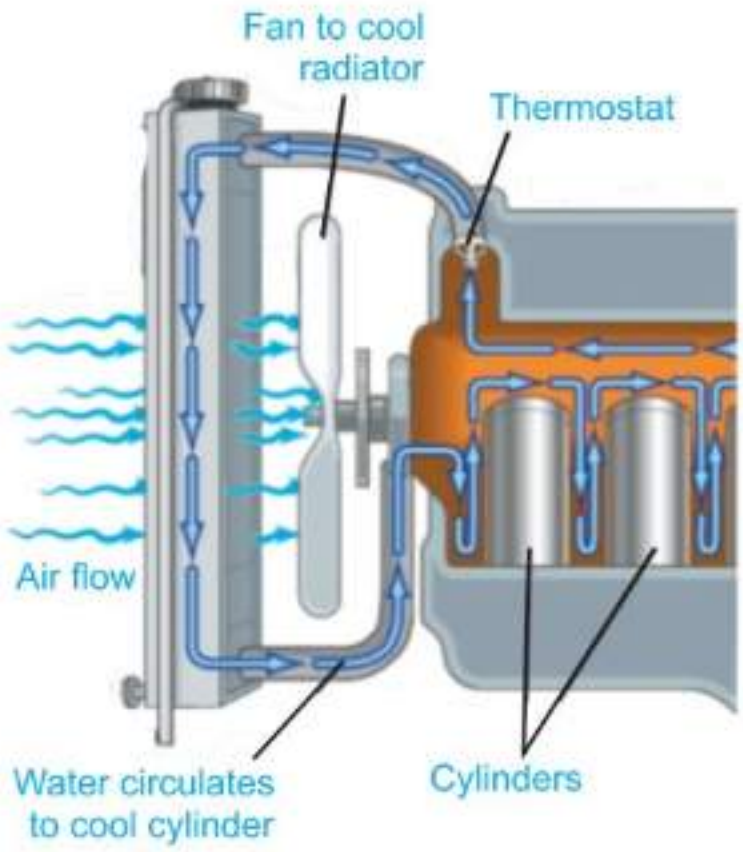


Fig. 10.7: Cooling system of automobile

10.3 Change in State

By absorbing or losing energy, the *K.E.* of the atoms or molecules of a substance changes that can lead to change in the state of a matter. Change in states of matter occurs when matter loses or absorbs energy.

Change in State of a Substance

When a substance absorbs energy, the atoms and molecules move more rapidly and hence need more space and separation between atoms or molecules. It may lead to turn a solid to liquid, called melting and liquid to gas, known as boiling. By losing energy, the atoms and molecules will slow down and hence there is less space and separation between them. It may lead to turn a gas to liquid, called condensation and a liquid to solid, known as solidification. Keep in mind that intermolecular forces are the strongest in solids due to least separation and weakest in the gases, as the molecules are far apart as compared to liquids and solids. This is the reason that the gases exhibit the greatest relative thermal expansion while solids have the least expansion.

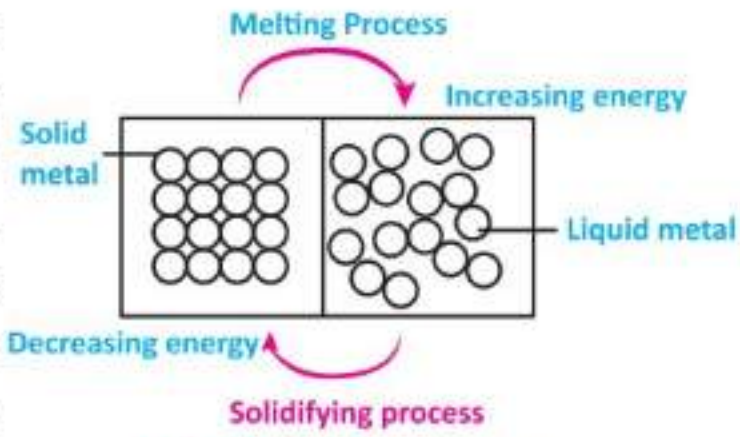


Fig. 10.8: Phase changes

10.4 Evaporation

Evaporation is a natural process by which a liquid changes into a gas at its surface without boiling.

It occurs at all temperatures but is faster at higher temperatures. This change occurs at the surface of the liquid, where some of the particles have enough energy to escape into the air as vapour. Evaporation does not require the entire liquid to be heated, it can occur at room temperature. For instance, when water is spilled on the floor, it gradually disappears as it turns into water vapour. This process plays a key role in everyday life and in nature. It helps in drying wet clothes, and

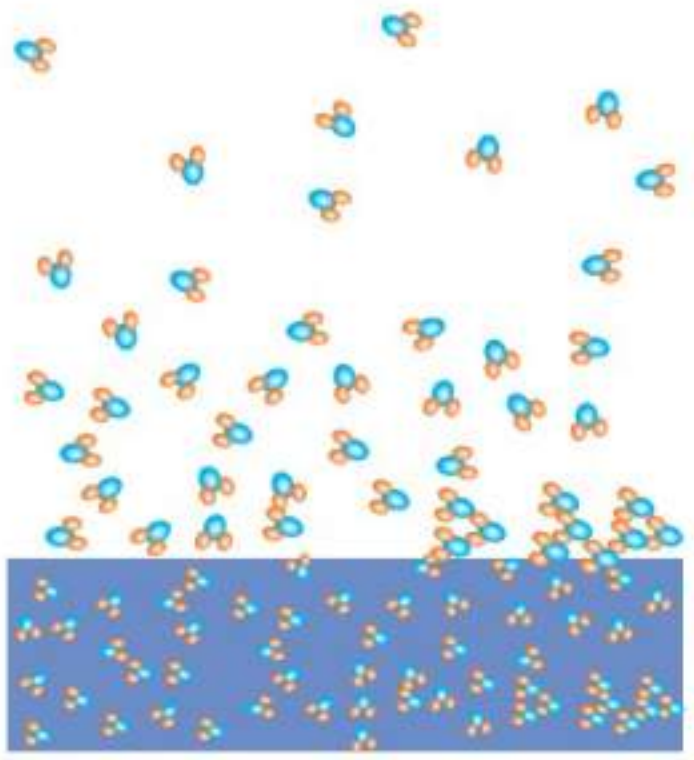


Fig. 10.9: Evaporation process (molecules at the surface of a liquid gain enough energy to escape into the air as vapour, leading to evaporation)

cooling our bodies through sweating. Several key factors influence how quickly or slowly this takes place:

1. **Temperature:** The higher the temperature, the faster evaporation occurs. When heat is added, the molecules in the liquid move more energetically, increasing the chances of them escaping into the air as vapour.

Tidbit

Evaporation from our skin takes away body heat, keeping us cool. That is our body's natural way of managing temperature.

2. **Surface Area:** A larger surface area allows more liquid to be exposed to the air, which speeds up evaporation. For example, water in a wide, shallow dish will evaporate quicker than the same amount in a tall, narrow container.
3. **Air Movement (Wind Speed):** Wind or air movement helps to carry away the vapour molecules from the surface of the liquid. This prevents saturation of the air above the liquid and allows more molecules to evaporate (Fig. 10.9).
4. **Humidity of the Surrounding Air:** If the air is already full of moisture (high humidity), evaporation slows down. But in dry air, the process occurs more rapidly because the air can absorb more water vapour.
5. **Nature of the Liquid:** Different liquids evaporate at different rates based on their molecular structure. For instance, alcohol evaporates faster than water because its molecules require less energy to escape into the air.
6. **Pressure:** Lower atmospheric pressure can enhance evaporation since there is less force pushing down on the liquid surface, making it easier for molecules to escape.

Cooling Caused by Evaporation

During evaporation, the molecules that evaporate take away heat from the remaining liquid. This process cools the liquid down because the higher-energy molecules leave, leaving behind cooler molecules.

For example, when we sweat, the sweat on our skin evaporates, taking heat away from our body and making us feel cooler. Similarly, wet clothes dry faster on a hot day because

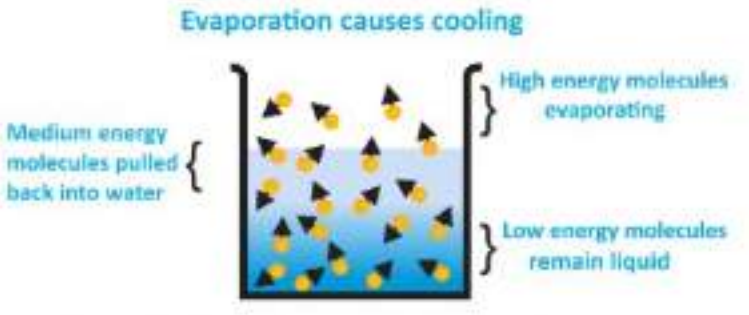


Fig. 10.10: High-energy molecules escape from the liquid surface as vapour, leaving behind lower-energy particles

water evaporates quickly, cooling the clothes as it evaporates.

This cooling effect due to evaporation is important in everyday life and in nature, helping to regulate temperatures and keep things cool (Fig. 10.10).

Brain Teaser

If evaporation produces cooling, why does not boiling water feel cold?

Refrigeration without Chlorofluorocarbons (CFCs)

In modern refrigeration systems, the cooling effect caused by evaporation plays an important role in lowering temperatures without relying on harmful CFCs (chlorofluorocarbons). These systems use environmentally friendly refrigerants that evaporate at low temperatures inside the cooling coils. As the refrigerant evaporates, it absorbs a large amount of heat from the surrounding area (such as inside a refrigerator), causing the temperature to drop. This absorbed heat is then carried away as the vapour is compressed and condensed back into a liquid outside the cooling compartment (Fig. 10.11). This cycle of evaporation and condensation enables continuous cooling, while avoiding the environmental damage once caused by ozone-depleting CFCs.

Tidbit

Refrigerators use an amazing trick: they cool by letting special liquids evaporate inside coils. No harmful CFCs needed today, modern coolants are more eco-friendly.

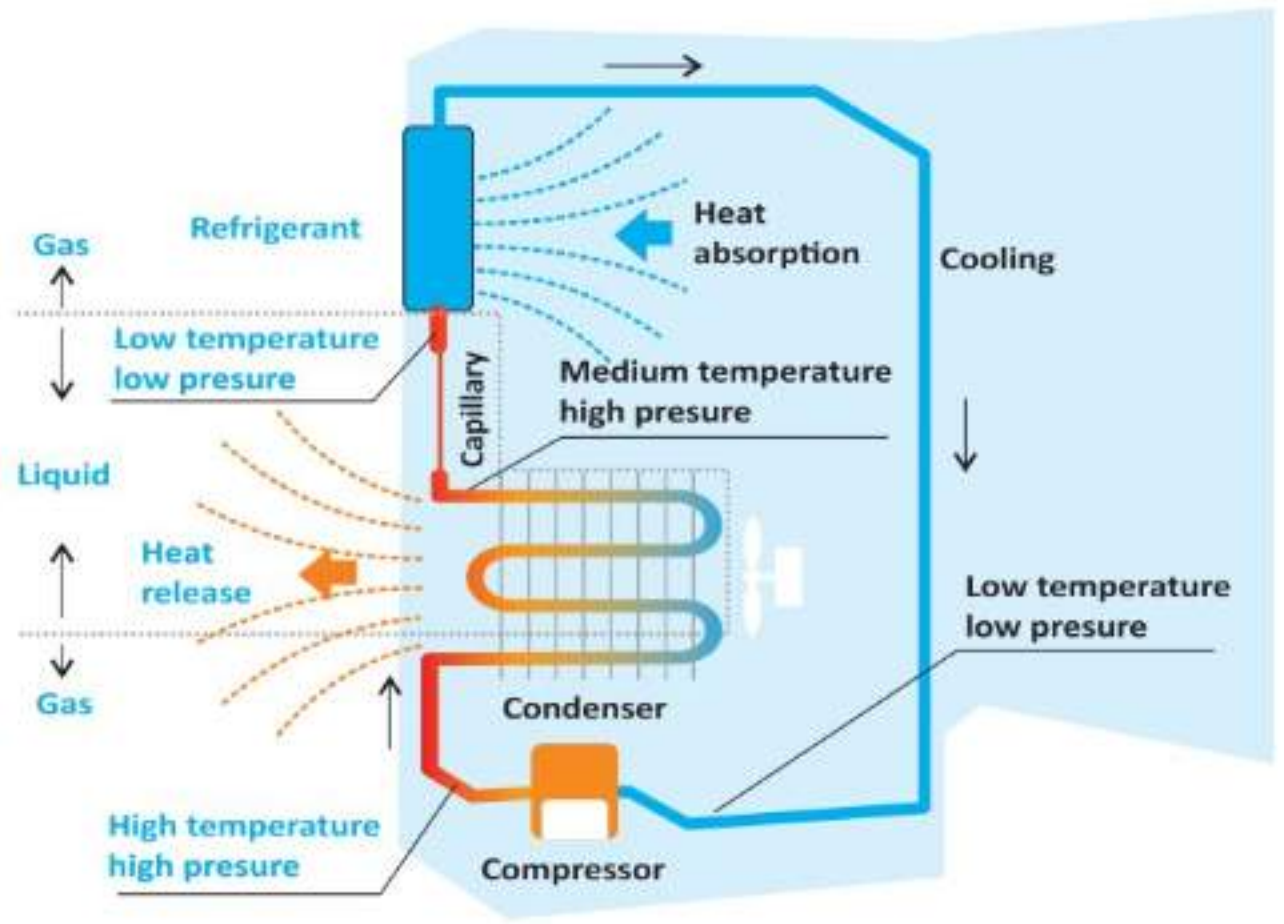


Fig. 10.11: Block diagram of refrigerator

10.5 Latent Heat

Latent heat is the heat energy required to change the state of a substance without changing its temperature.

This heat is used to break or form bonds between particles instead of increasing their movement.

Latent Heat of Fusion

Latent heat of fusion is the heat energy required to convert 1 kg of a solid into a liquid at its melting point while keeping the temperature constant. When a solid melts into a liquid, it absorbs heat without rise in temperature. This heat is used to break the strong bonds between solid particles, allowing them to move more freely as a liquid. The temperature remains constant until the entire solid has melted. The latent heat of fusion is calculated using the formula:

Tidbit

When ice melts or water boils, energy is working hard behind the scenes to break bonds between molecules but the thermometer does not show any rise in temperature.

$$Q = m L_f \quad \text{.....(10.5)}$$

where

L_f = Latent heat of fusion

Q = Heat energy

m = Mass of the substance

Example: Ice at 0 °C absorbs heat but remains at 0 °C until it completely melts into water.

The latent heat of fusion of ice is 3.36×10^5 J kg^{-1}, meaning 3.36×10^5 joules of heat is needed to melt 1 kg of ice into water at 0 °C.

Example 10.2: How much heat is required to melt 600 g of ice at 0 °C into water at 0 °C? Latent heat of fusion of ice is 3.36×10^5 J kg^{-1}.

Solution:

Given that;

Mass of ice m = 600 g

= 0.600 kg

Latent heat of fusion of ice $L_f = 3.36 \times 10^5$ J kg^{-1}

To find;

Heat required $Q = ?$

Using the formula $Q = m \times L_f$

Substituting the values $Q = 0.600 \text{ kg} \times 3.36 \times 10^5 \text{ J kg}^{-1}$

$Q = 201{,}600$ J

or $Q = 201.6$ kJ

Experiment 1: This involves placing small ice pieces in a beaker over a stand, suspending a thermometer to measure temperature. Heating the beaker causes the ice to melt, keeping the mixture at 0 °C until all ice melts. Note the time taken for complete melting. Further heating causes water temperature to rise from 0 °C to 100 °C. Record the time for this increase. Plot a temperature-time graph (Fig. 10.12) and calculate the latent heat of fusion of ice using collected data.

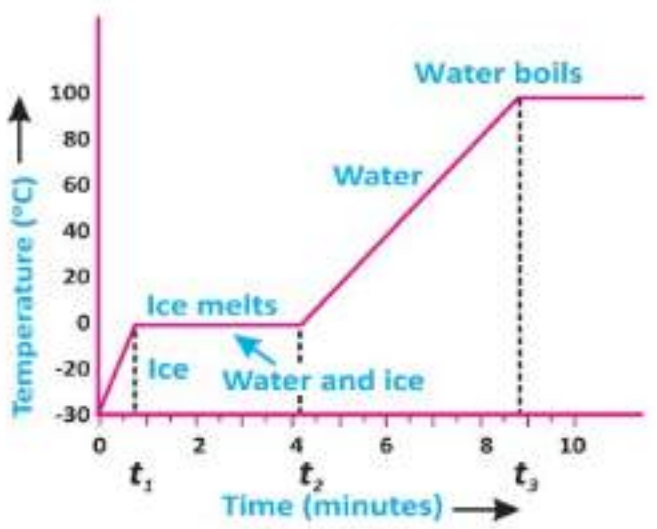


Fig. 10.12: Temperature-time graph as ice changes into water that boils as heating continues

Latent Heat of Vaporization

Latent heat of vaporization is the heat energy needed to change 1 kg of a liquid into gas at its boiling point without changing the temperature.

When a liquid changes into gas, it absorbs heat, but its temperature remains constant until the entire liquid has evaporated. This heat is used to break the bonds between liquid molecules, allowing them to escape as gas. The latent heat of vaporization of water is 2.26×10^6 J kg^{-1}. This means 2.26×10^6 J of heat energy is needed to convert 1 kg of water into steam at 100 °C. The latent heat of

vaporization is expressed as:

$$Q = m\,L_V \quad \ldots\ldots\ldots\ldots \quad (10.6)$$

where L_V is Latent heat of vaporization, Q is heat energy and m is the mass of the substance

Table 10.2 shows the melting point, boiling point, latent heat of fusion, and latent heat of vaporization of some common substances.

Experiment 2: At the end of experiment 1, the beaker contains boiling water. Continue heating water until all the water changes into steam. Note the time which the water in the beaker takes to change completely into steam at its boiling point 100 °C.

Table 10.2: Melting point, boiling point, latent heat of fusion, and latent heat of vaporization of some common substances

Substance	Melting point (°C)	Boiling point (°C)	Heat of fusion ($J\,g^{-1}$)	Heat of vaporization ($J\,g^{-1}$)
Aluminium	660	2250	39.7	10500
Copper	1083	2595	205.0	4810
Gold	1063	2660	64.0	1580
Helium	-270	-269	5.5	21
Lead	327	1750	23.0	858
Mercury	-39	357	11.7	270
Nitrogen	-210	-196	25.5	200
Oxygen	-219	-183	13.8	210
Water	0	100	336.0	2260

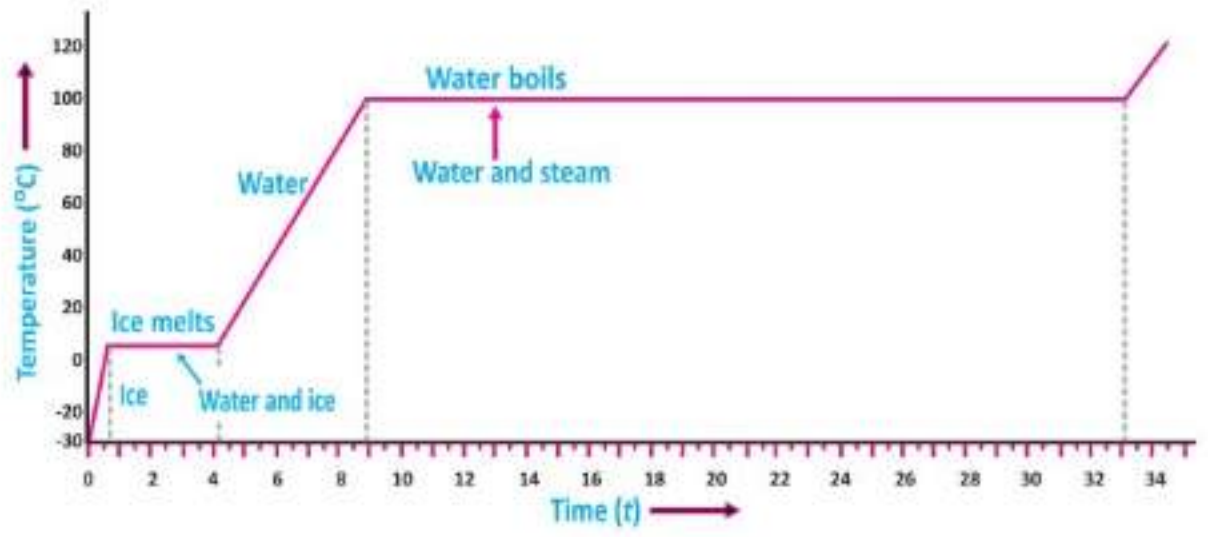


Fig. 10.13: Temperature-time graph as ice changes into water and water into steam on heating

Extend the temperature-time graph as shown in Fig. 10.13. Calculate the latent heat of fusion of ice from the data.

10.6 Superconductivity

Superconductivity is a special property of some materials where they have zero electrical resistance when cooled below a certain temperature, called the critical temperature. In this state, electricity flows without any energy loss, making superconductors very efficient.

How does Superconductivity Work ?

Since there are no collisions, electric current flows without facing any resistance as supercunductors have zero electrical resistance. Figure 10.14 shows the variation of electrical resistivity with temperature for a superconductor and a normal metal. The resistivity of a superconductor drops to zero below the critical temperature (T_c), whereas a normal metal shows a gradual decrease in resistivity.

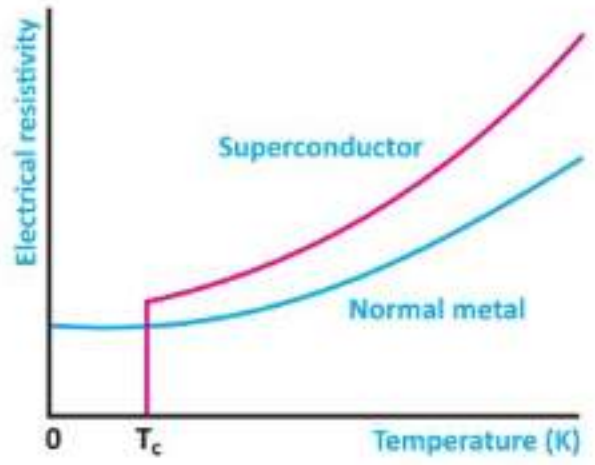


Fig. 10.14: Variation of electrical resistivity with temperature for a superconductor and a normal metal

Materials That Show Superconductivity

Some metals and ceramics become superconductors at extremely low temperatures.

1. Mercury – Becomes superconducting below 4.2 K.

2. Lead – Becomes superconducting below 7.2 K.

3. High-temperature superconductors (ceramics) work at higher temperatures, such as 135 K.

Brain Teaser

Why do superconductors need extreme cold temperature to work?

Uses of Superconductors

Superconductors are used in advanced technologies, including:

1. MRI Machines : To generate strong magnetic fields for medical imaging.

2. Maglev Trains : Use of superconductors to float the train above tracks, reducing friction.

3. Particle Accelerators: Help scientists to study fundamental particles.

Superconductors are important for future technologies, making electrical systems more efficient and powerful.

EXERCISE

A. Multiple Choice Questions

Tick (✓) the correct answer.

10.1 When the temperature of a rod of copper is increased, its length:
(a) remains the same (b) increases (c) decreases (d) becomes double

10.2 The amount by which unit length of a material increases when the temperature is raised to 1°C, is called the coefficient of:
(a) cubic expansion (b) volume expansion
(c) linear expansion (d) none of these

10.3 What does a liquid turn into once it is evaporated?
(a) Gas (b) Water vapours (c) Air (d) Both (a) and (b)

10.4 Which property determines how much heat a solid can absorb before its temperature changes significantly?
(a) Density (b) Specific heat capacity (c) Colour (d) Hardness

10.5 High-temperature superconductors typically involve which typle of material?
(a) Pure metals (b) Organic compounds
(c) Ceramics (d) Liquid crystals

B. Short Answer Questions

10.1 What factors influence the thermal expansion of solids?

10.2 What is latent heat of fusion?

10.3 How do different materials exhibit varying thermal expansion behaviours?

10.4 How does evaporation contribute to cooling processes in everyday life?

10.5 What is latent heat of vaporization, and how is it calculated?

C. Constructed Response Questions

10.1 Why do bridges need expansion joints but glass jars with metal lids do not, even though both experience temperature changes? Discuss in terms of the nature of thermal expansion.

10.2 If two liquids are heated under same conditions, but one of them heats up faster, what does this indicate about the specific heat capacity?

10.3 Why does a liquid evaporate faster when the air is dry?

10.4 When a piece of ice melts, the temperature does not increase even though heat is supplied. Where does the energy go, and why is this important in phase change?

10.5 Why do electric transmission wires sag in summer and tighten in winter?

D. Comprehensive Questions

10.1 How does thermal expansion differ between solids, liquids, and gases? Provide examples to illustrate these differences.

10.2 What are some practical consequences of thermal expansion in everyday life, such as in construction materials or household appliances?

10.3 What is latent heat, and why is it important in phase transitions like melting and vaporization?

10.4 Why do solids, liquids, and gases expand when heated? Explain with examples.

10.5 If we have an equal amount of water in a wide, shallow dish and a tall, narrow container kept at the same temperature, in which container will evaporation occur faster? Explain the reason scientifically.

E. Numerical Problems

10.1 A metal rod of length 1 m expands by 0.02 m when heated from 20 °C to 120 °C. Calculate its coefficient of linear expansion. **[Ans: 2.0×10^{-4} K^{-1}]**

10.2 A container holds 1 litre of water at 20 °C. What will be its volume at 80 °C, assuming water's coefficient of volume expansion is 2.1×10^{-4} per °C?
[Ans: 1012.6 cm^3]

10.3 A steel rod initially measures 2 m at 20 °C. If its coefficient of linear expansion is 1.2×10^{-5} $°C^{-1}$, what will be its length at 100 °C?
[Ans: 2.002 m]

10.4 A steel bridge expands by 5 cm on a hot summer day. If the bridge originally spanned 100 m, what is the temperature change?
[Ans: 41.67 °C]

10.5 How much heat is required to raise the temperature of a 2 kg iron bar from 20 °C to 100 °C, given that the specific heat capacity of iron is 450 J kg^{-1} K^{-1}?
[Ans: 72 kJ]

10.6 How much heat is required to melt 500 g of ice at 0 °C into water at 0 °C? (Latent heat of fusion of ice = 3.36×10^5 J kg^{-1}) **[Ans: 168 kJ]**

10.7 Calculate the heat required to completely vaporize 1 kg of water at 100 °C. (Latent heat of vaporization of water = 2.26×10^6 J kg^{-1})
[Ans: 2.26 M J]

CHAPTER 11

TRANSFER OF THERMAL ENERGY

Student's learning outcomes (SLOs)

After studying this chapter, students will be able to:

- explain thermal conduction in all solids (in terms of atomic or molecular lattice vibrations and also in terms of the movement of free (delocalized) electrons in metallic conductors).
- analyze everyday applications of conduction, convection, and radiation. (a) Heating objects such as kitchen pans (b) Heating a room by convection (c) Measuring temperature using an infrared thermometer (d) Using thermal insulation to maintain the temperature of a liquid and to reduce thermal energy transfer in buildings (e) The mechanism of a household hot-water system.
- explain convection in liquids and gases [in terms of density changes]. Justify experiments to illustrate convection.
- explain convection in seawater to support marine life.
- describe the role of land breezes and sea breezes in maintaining moderate coastal climates.
- explain how birds are able to fly for hours without flapping their wings and gliders are able to rise by riding on thermal currents.
- describe the process of thermal energy transfer by radiation [and know that it does not require a medium].
- describe the effect of surface colour and texture on the emission, absorption, and reflection of infrared radiation.
- justify qualitatively how the rate of emission of radiation depends on the surface temperature and surface area of an object.
- analyze the consequence of heat radiation in the greenhouse effect and its effect on global warming.

Heat is an important form of energy that is essential for life. It plays a pivotal role in cooking, maintaining our body temperature, and supporting various industrial processes. Understanding how heat flow is important for protecting ourselves from extreme temperatures. In this chapter, we will look into the different methods of heat transfer. When two objects with different temperatures come into contact, thermal energy flows from the hotter object to the cooler one, a process known as heat transfer. This is a natural occurrence that continues as long as there is a temperature difference between the objects. Thermal energy constantly transfers from one object to another until thermal equilibrium is reached. Whether it is the Sun warming the Earth, a hot cup of coffee, or a metal rod heating when placed in a flame, heat transfer is a fundamental part of daily life. This chapter focuses on the three primary types of heat transfer conduction, convection, and radiation. Understanding of these processes is important not just in nature, but also in the fields like engineering, meteorology, and technology.

11.1 Conduction

Conduction is the process by which heat is transferred through direct contact between particles in a material, without any actual movement of the material. It happens when fast-moving (hotter) particles collide with slow-moving (cooler) particles, transferring their kinetic energy (Fig. 11.1). This method of heat transfer is most efficient in solids, especially in metals, as their particles are densely packed, and freely moving electrons facilitate the quick transfer of energy.

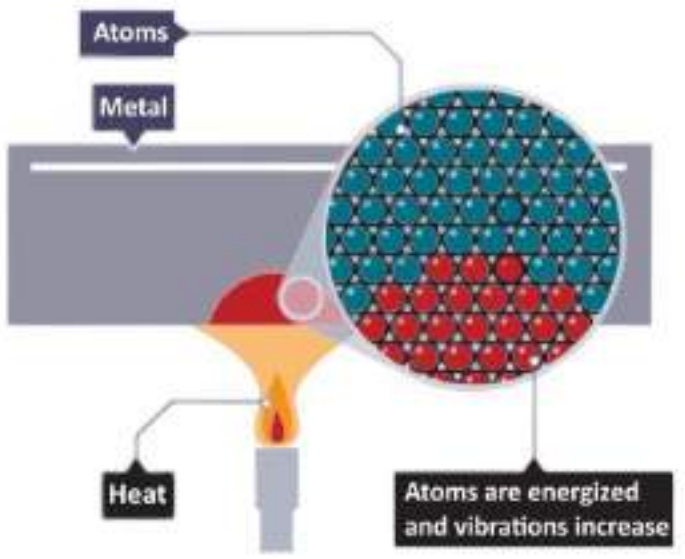


Fig. 11.1: Heat transfer in metals through conduction

Thermal Conduction in Solids

When the handle of a metal spoon is placed in hot water, it quickly becomes warm, whereas the handle of a wooden spoon does not heat up. This difference highlights how materials transfer heat in different ways. Both metals and non-metals can conduct heat, but metals are typically much better at it. In solids, the atoms and molecules are tightly packed and constantly vibrate around their mean positions as shown in Fig. 11.1. When one end of the solid is heated, the particles at that end

begin to vibrate more vigorously. These vibrating particles collide with nearby atoms or molecules, transferring some of their energy. This process causes the neighbouring particles to vibrate more rapidly and, in turn, pass some of their energy to other surrounding particles. Gradually, heat spreads throughout the solid, but the transfer is slow, with only a small amount of heat moving from the hotter to the cooler parts. In conduction, heat transfers through a solid medium due to a temperature difference.

why does heat travel more quickly in metals than in non-metals?

Metals have free electrons that can move freely within the material. These fast-moving electrons carry energy quickly from the hot areas to the cooler areas of the metal. This is why heat moves more rapidly through metals than non-metals.

Tidbit

Diamonds are the best heat conductors, far better than metals. A high quality diamond can conduct heat 4-5 times better than copper.

Do You Know?

Heat is transferred to an object, for example, how the stove "heats" the pot.

11.2 Convection in liquids and Gases

Liquids and gases are not very efficient in conducting heat. However, heat can still be transferred through these fluids (liquids or gases) by a process called convection.

When a liquid or gas is heated, it becomes less dense (lighter) and expands. The heated liquid or gas rises above the heat source, and cooler fluid from the surrounding area moves in to take its place. This colder fluid then gets heated as well. In this way, heat is transferred through fluids by the movement of heated molecules from the hotter parts to the colder parts of the fluid.

Convection is the transfer of heat through the actual movement of molecules from a hot area to a cold area.

Experiment: (For Liquid Convection)

Fill a beaker two-thirds with water and heat it by placing a burner underneath. Now drop two or three potassium permanganate crystals into the water. We will notice coloured streaks moving upward above the flame, then flowing downward along

the sides, as shown in Fig. 11.2. These coloured streaks reveal the movement of currents within the liquid. But why do these currents stop when the burner is removed? As the water at the bottom of the beaker heats up, it expands, becoming lighter and rising. Meanwhile, the cooler, denser water sinks to replace it.

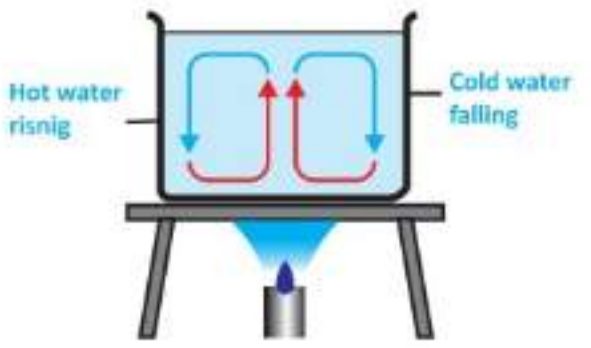


Fig. 11.2: Convection currents circulate heat as hot water rises and cold water sinks

Convection Currents in Air

When gases get heated, they expand, and this creates convection currents due to the differences in air density at various points in the atmosphere. This can be demonstrated with a simple experiment, as shown in Fig. 11.3. Can you explain the process?

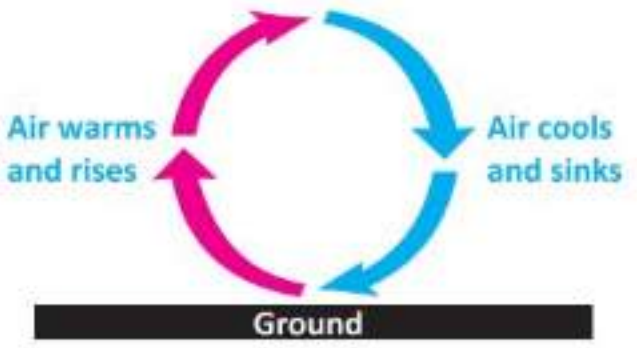


Fig. 11.3: Convection currents drive air circulation as warm air rises and cool air sinks

This process begins when the Sun heats the Earth's surface, warming the air close to the ground. As the air warms up, it becomes lighter and less dense, causing it to rise. As it rises, it cools down, becomes denser, and sinks back toward the surface. The cooler air then gets heated, and the cycle repeats. This movement of air creates convection currents, which are responsible for various natural phenomena such as winds, sea breezes, and weather patterns. These currents help to distribute heat throughout the atmosphere, playing a vital role in regulating Earth's climate and weather.

Applications of Convection Currents

Convection currents created by electric, gas, or coal heaters are used to warm our homes and offices. Central heating systems also rely on convection to distribute heat throughout the buildings. On a larger scale, convection currents occur naturally in the environment. The daily changes in temperature in the atmosphere are caused by the movement of warm or cool air. Land and sea breezes are examples of convection currents in nature.

Land and Sea Breezes

Why does a sea breeze blow during the day, and why does a land breeze occur at night?

Land and sea breezes are caused by convection. During the day, the land heats up faster than the sea due to the land's lower specific heat capacity. The warm air above the land rises, and cooler air from the sea moves in to replace it, creating a sea breeze, as shown in Fig.11.4.

Fig. 11.4: Sea breeze blows from sea to land as warm air rises over heated land (day time)

At night, the land cools down more quickly than the sea. As a result, the air above the sea becomes warmer and rises, while cooler air from the land moves towards the sea, creating a land breeze, as illustrated in Fig. 11.5.

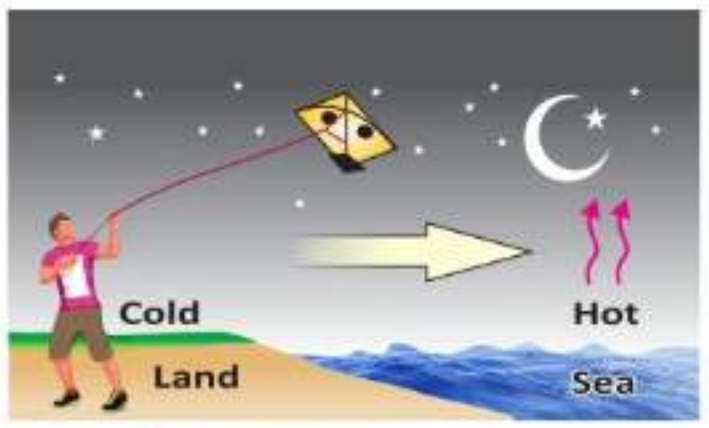


Fig. 11.5: Land breeze blows from land to sea as warm air rises over heated water (night time)

Gliding

What keeps a glider in the air?

A glider, which is like a small plane without an engine, relies on the upward movement of warm air currents, or thermals, created by convection (Fig. 11.6).

Fig. 11.6: A glider

Gliders take advantage of these rising currents of warm air to stay in the air for extended periods. Similarly, birds use thermals to stay aloft for hours without flapping their wings. They stretch their wings and circle in the thermals, allowing them to gain altitude as the warm air rises. Birds such as eagles, hawks, and vultures are especially skilled at using thermals to glide over long distances with little effort, barely needing to flap their wings (Fig. 11.7).

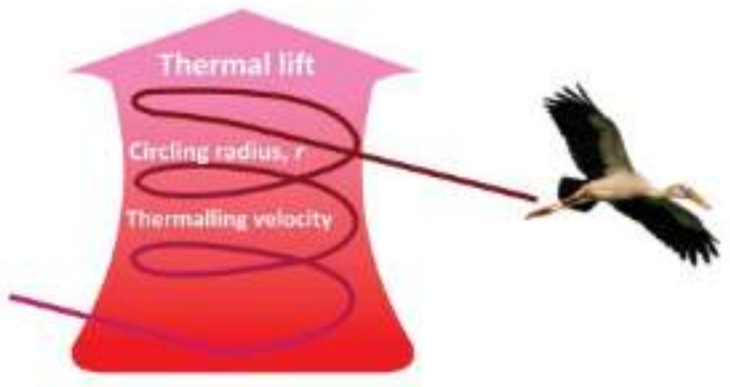


Fig. 11.7: Birds flying taking the advantage of thermal air currents

Convection in Seawater and Marine Life

Convection plays an important role in seawater and is important for supporting

marine life. When sunlight heats the surface of the ocean, the warm water becomes lighter and stays at the top, while the cooler, denser water sinks to the bottom. This difference in temperature causes convection currents in the ocean. These currents continuously move water up and down, helping to mix oxygen from the surface into deeper layers and bringing nutrients from the ocean floor to the surface. This process is very important for the survival of marine animals and plants because it ensures that there is enough oxygen and food available at different depths. Without convection, the deep ocean would lack oxygen, and surface waters would lack nutrients, making it difficult for marine ecosystems to thrive.

Brain Teaser

Why do we feel a nice breeze coming from the sea during the day time at the beach?

Brain Teaser

How can birds fly for hours without moving their wings much in sunny weather?

Heating and cooling of Rooms by Convection

In winter, gas heaters are often used to warm rooms (Fig. 11.8). When the heater is turned on, it warms the air near it. This warm air becomes lighter (less dense) and rises toward the ceiling. As the hot air moves up, cooler, heavier air moves down to take its place near the heater. This process is called a convection current. Similar effect is applied during summer when air conditioning is used to cool the room. It keeps the air moving and helps in spreading the heat evenly throughout the room. That is why, rooms gradually become warmer without needing fans.

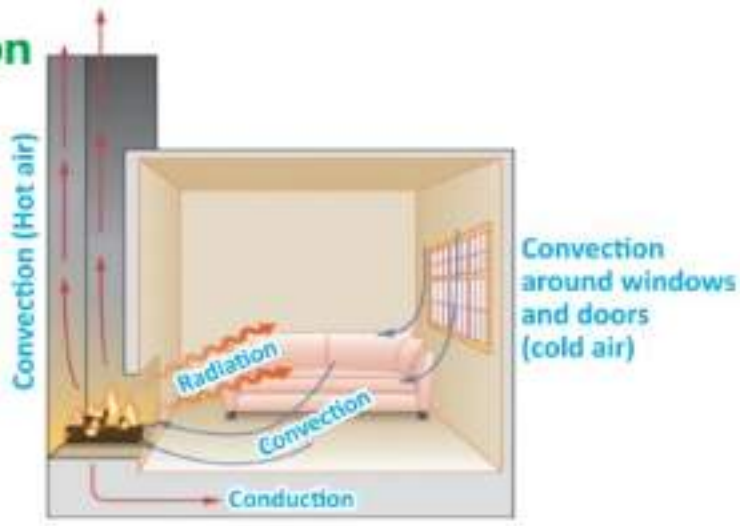


Fig. 11.8: Heating room by convection

The Mechanism of a Household Hot-Water System

In most homes, hot water is provided using a storage tank water heater. The system works by bringing cold water into the house through pipes, where it splits into two lines: one for cold water use and one that goes into the water heater. Inside the water heater, the cold water is heated using an electric heating element or a gas burner, depending on the type of system. As the water heats up, it becomes less dense and rises naturally to the top of the tank, while the cooler,

denser water stays at the bottom. When someone turns on a hot water tap, the hot water from the top of the tank flows out easily, and new cold water enters from below to be heated. A thermostat inside the tank controls the heating element or gas burner, ensuring that the water stays at a set temperature (Fig. 11.9). This system ensures a steady supply of hot water.

Fig. 11.9: Household hot-water system

11.3 Heat Transfer through Radiation

The Sun serves as the main source of heat for our planet. However, this heat does not reach the Earth through conduction or convection, as there is no medium between the Sun and Earth's atmosphere. Instead, heat is transferred via radiation, a process in which energy travels across space in the form of electromagnetic waves. This is the mechanism through which the Sun's heat reaches the Earth.

In radiation, heat transfer occurs through electromagnetic waves without requiring a medium.

Radiation from a Fireplace

How does heat travel from a fireplace to us (Fig. 11.10)?

Heat does not reach us via conduction through the air because air neither conducts heat efficiently nor transfers heat but radiation emitted is influenced by various factors, including:

- the colour and texture of the surface
- the temperature of the surface
- the surface area

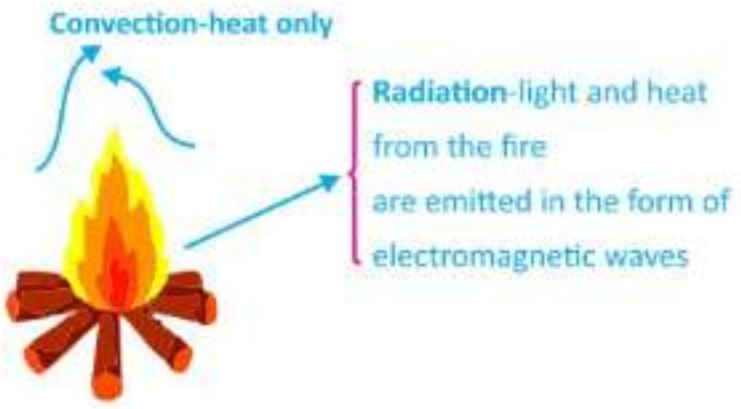


Fig. 11.10: Thermal radiations transform in form of E.M waves

Why Objects Cool or Warm Over Time?

Why does a hot cup of tea cool down over time, and why does a cold glass of water warm up? All objects in a room, including the walls, ceiling, and floor radiate heat while simultaneously absorbing it. If temperature of an object is higher than that of its

Do You Know?

- Convection is when liquid or gases get heated.
- Conduction is when something is hot and it touches another object and it becomes hot.
- Radiation is when energy travels through E.M. waves to heat something up.

surroundings, it radiates more heat than it absorbs. Consequently, its temperature decreases until it matches the temperature of the surrounding environment. On the other hand, if the temperature of the object is lower than its surroundings, it absorbs more heat than it radiates, causing its temperature to rise until it reaches equilibrium with the environment. The rate at which different surfaces emit heat depends on their characteristics. This phenomenon can be illustrated with Leslie's cube (Fig. 11.11).

Leslie's Cube – Emission and Absorption of Radiation

Leslie's cube is a metal box with faces of different materials, such as:

- a shiny silver surface
- a dull black surface
- a white surface
- a coloured surface

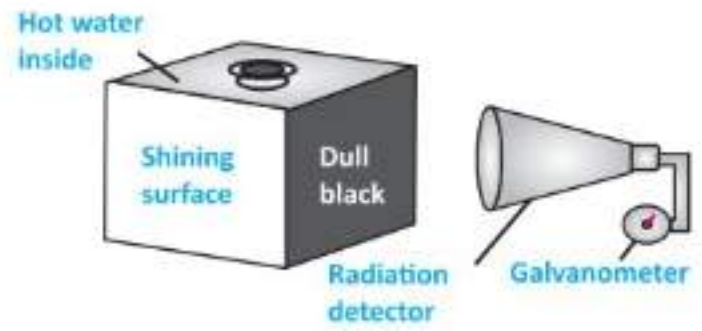


Fig. 11.11: Radiations from Leslie's cube

When the cube is filled with hot water and one face is directed towards a radiation detector, it is found that the dull black surface is the most effective emitter of heat (Fig. 11.11). The rate at which different surfaces absorb heat also varies based on their nature. For example, when comparing a dull black surface with a polished silver one, the dull black surface absorbs heat more rapidly, causing its temperature to rise quickly, while the polished silver surface absorbs heat more slowly and warms up at a much slower rate. These observations are recorded and compared for clarity (Fig.11.12).

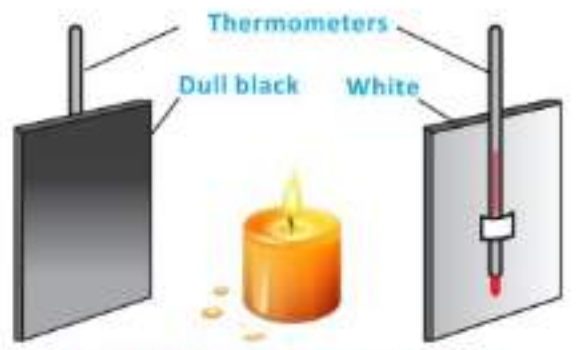


Fig. 11.12: A comparison of absorption of radiations

Effect of Surface Colour and Texture on Infrared Radiation

The colour and texture of a surface have a strong effect on how it emits, absorbs, and reflects infrared radiation. Dull and dark-coloured surfaces are very good at absorbing and emitting infrared radiation. That is why a dull black surface heats up quickly and cools down faster by giving off more heat. On the other hand, shiny and light-coloured surfaces are poor absorbers and emitters of radiation. Instead, they reflect most of the infrared radiation away. This is why shiny surfaces, like polished metals, stay cooler under the Sun compared to dark surfaces. The texture also

matters. Rough surfaces absorb and emit radiation better, while smooth surfaces tend to reflect more radiation.

Impact of Surface Temperature and Surface Area on Heat Transfer

The rate of radiation emitted by an object depends greatly on two important factors: the surface temperature and the surface area. When the surface temperature of an object increases, it radiates more energy because hotter objects emit more heat compared to cooler ones. For example, a hot iron rod glows and emits more heat than a warm one.

Tidbit

Heat from the Sun reaches us through radiation, no air needed, just pure energy travelling across space.

Similarly, the surface area also plays a major role. If an object has a larger surface area, it can emit or absorb more heat at a faster rate. This is why radiators used for heating rooms are made with lots of thin slots or fins to increase the surface area without taking up too much space. A larger area means more radiation can happen at the same time, making heat transfer more efficient. Thus, both a higher surface temperature and a larger surface area help an object emit thermal energy more quickly through radiation.

Do You Know?

Dull black surfaces absorb and emit more heat than shiny surfaces that is why solar panels are black.

Measuring Temperature Using an Infrared Thermometer

An infrared thermometer (Fig. 11.13). measures the temperature of objects without touching them. It detects the heat (infrared radiation) emitted by the object. During the COVID-19 pandemic, these thermometers were used widely to check body temperatures safely. They are also useful for checking the heat of ovens, machines, or even dangerous radioactive materials. To use it, we point the thermometer at the object, press the trigger, and read the temperature on the screen.

Fig. 11.13: Infrared thermometer

Applications of Heat Transfer

1. Heating Objects such as Kitchen Pans

One everyday application of heat transfer is when we cook food using kitchen pans. When a pan is placed on a stove, heat from the flame or heating element transfers to the pan mainly by conduction. The metal of the pan, being a good conductor, quickly absorbs the heat and passes it through the surface. This causes the entire pan to become hot, allowing food placed inside to cook evenly (Fig.11.14).

Fig. 11.14: Heat transfer through conduction in a boiling pan

2. Using Thermal Insulation to Maintain the Temperature of a Liquid

Thermal insulation helps to keep hot things hot and cold things cold. For example, a thermos flask (vacuum flask) has double walls with a vacuum between them (Fig. 11.15). The vacuum stops heat transfer by conduction and convection because there is no air or material to move heat. The inside walls of the flask are coated with a reflective layer (silvered coating) that bounces back radiation to keep the liquid warm. The outer casing and lid are made of insulating materials like plastic or stainless steel to prevent heat loss. This smart design helps liquids like tea, coffee, or soup to stay at the right temperature for many hours.

Fig. 11.15: Thermos flask

Tidbit

The handle of a cooking pan stays cool because it is made of poor conductors like wood or plastic.

3. Reducing Thermal Energy Transfer in Buildings

Thermal insulation in buildings helps to keep them warm in winter and cool in summer. By adding things like thick curtains, foam in the walls, double-glazed windows (Fig. 11.16-a), or false ceilings (Fig. 11.16-b). We can reduce heat loss through conduction, convection, and radiation. In cold weather, insulation stops warm indoor air from escaping. In hot weather, it prevents heat from entering from outside. This reduces the need for heaters and air conditioners, saving energy and lowering costs. Even simple ideas like using proper shading outside the windows or ensuring good ventilation can make a big difference in

(a) Doubled-glazed window (b) False cieling

Fig. 11.16: Reducing thermal energy transfer

11.4 Greenhouse Effect

The greenhouse effect refers to the process by which the Earth's atmosphere traps some of the Sun's heat, maintaining a temperature that is suitable for life.

Without this effect, the planet would be too cold to support life as we know it.

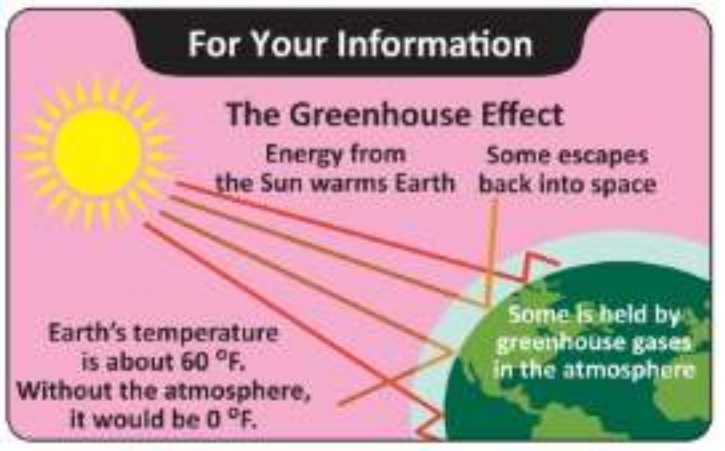
Temperature Regulation in a Greenhouse

How is the temperature controlled inside a greenhouse? The Sun emits both short-wavelength light and ultraviolet radiations and long-wavelength thermal radiations (infrared). Transparent materials such as glass and plastic allow short-wavelength radiations to pass through but block long-wavelength infrared radiation. This creates a heat trap inside the greenhouse. The rays from the Sun warm the objects inside the greenhouse, and these objects emit radiations with longer wavelengths. However, the glass or plastic sheets prevent this longer-wavelength radiations from escaping, reflecting it back into the greenhouse and maintaining a warm environment that benefits plant growth.

Greenhouse Effect on Earth

The Earth's atmosphere functions in a similar way to a greenhouse, trapping heat from the Sun with gases such as carbon dioxide and water vapours (Fig. 11.17). This helps to maintain the Earth's temperature. In recent years, the amount of carbon dioxide in the atmosphere has increased significantly, strengthening the greenhouse effect. As a result, more heat is trapped, leading to a rise in the Earth's average temperature, a phenomenon known as global warming. This increase in temperature has serious implications for global climate patterns.

For Your Information



Tidbit

The public has been led to believe that increased carbon dioxide from human activities in causing a green house effect that is heating the planet. But carbon dioxide comprises only 0.035% of our atmosphere and is a very week green-house gas.

Do You Know?

- **Greenhouse gases absorb solar energy and trap it in the atmosphere.**
- **Without greenhouse gases creating what is known as the "Greenhouse Effect" the Earth would not be warm enough for human to live.**

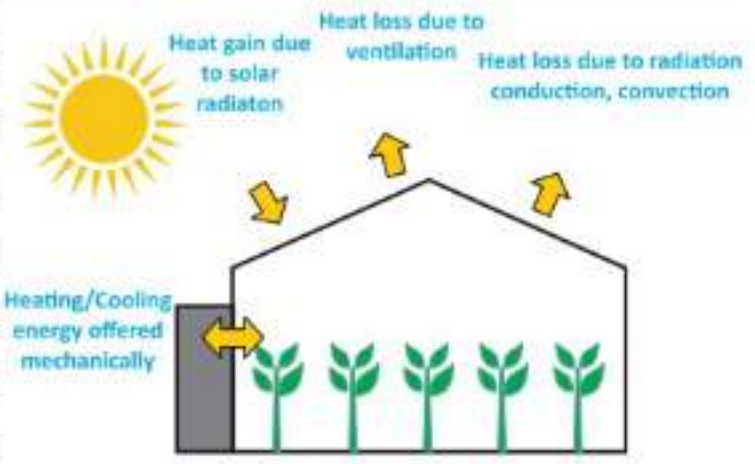


Fig. 11.17: Heat transfer mechanisms in a greenhouse

EXERCISE

A. Multiple Choice Questions

Tick (✓) the correct answer.

11.1 Which method of heat transfer requires direct contact between particles?
(a) Convection
(b) Radiation
(c) Conduction
(d) Evaporation

11.2 What causes convection currents in liquids and gases?
(a) The continuous movement of particles in all directions
(b) The rising of warm regions and sinking of cooler regions
(c) The conduction of heat through the medium
(d) The reflection of heat waves

11.3 The natural phenomenon caused by convection currents is:
(a) earthquakes
(b) land and sea breezes
(c) magnetic fields
(d) solar eclipses

11.4 How does heat transfer occur through radiation?
(a) Through direct contact between objects
(b) Through the movement of heated fluid
(c) Through electromagnetic waves without needing a medium
(d) Through the absorption of water molecules

11.5 The surface which absorbs and emits the most radiation is:
(a) smooth and shiny surfaces
(b) dark and rough surfaces
(c) transparent and thin surfaces
(d) polished and white surfaces

11.6 What is the role of the greenhouse effect in Earth's temperature regulation?
(a) It allows all heat to escape into space
(b) It blocks heat from entering the atmosphere
(c) It traps heat to maintain a stable temperature
(d) It causes immediate cooling of Earth's surface

11.7 The Sun's heat reaches the Earth:
(a) through conduction between air particles
(b) through convection in space
(c) through radiation via electromagnetic waves
(d) through reflection by the moon

B. Short Answer Questions

11.1 What are the three primary types of heat transfer?
11.2 Why does heat travel faster in metals compared to non-metals?
11.3 How does convection transfer heat in liquids and gases?
11.4 What natural phenomenon causes land and sea breezes?
11.5 How do birds and gliders take advantage of convection currents?
11.6 What is radiation, and how does it transfer heat?
11.7 Why does a dull black surface emit and absorb more radiation than a shiny silver surface?
11.8 How does the greenhouse effect help regulate Earth's temperature?

C. Constructed Response Questions

11.1 During the Leslie's Cube experiment, why does the dull black surface radiate more heat than the shiny silver one, even though they are at the same temperature?
11.2 How does the size (surface area) of a radiator affect the amount of heat it emits through radiation? Explain using a real-world example.
11.3 Why is convection not possible in solids, and how do convection currents in liquids and gases compensate for their poor thermal conductivity?
11.4 How do birds like eagles and gliders manage to stay aloft without flapping their wings for hours? Explain the scientific principle involved.
11.5 Why does a hot metal object placed in a cooler room eventually cool down? Explain using the concepts of radiation and thermal equilibrium.

D. Comprehensive Questions

11.1 Describe how convection occurs in fluids. How do convection currents contribute to natural phenomena such as sea breezes and wind patterns?
11.2 How does radiation differ from conduction and convection in terms of heat transfer? Give examples of radiation in everyday life and explain how different surfaces affect radiation absorption and emission.
11.3 Discuss the role of the greenhouse effect in regulating Earth's temperature. What are the potential consequences of an enhanced greenhouse effect due to human activities?
11.4 Compare the absorption and emission of heat by different surfaces. How does the colour and texture of a surface affect its ability to absorb and emit heat?
11.5 Analyze how uneven heating of Earth's surface leads to the formation of convection currents and influence with patterns.

CHAPTER 12

WAVES

Student's learning outcomes (SLOs)

After studying this chapter, students will be able to:

- prove that waves transfer energy without transferring matter.
- describe what is meant by wave motion [as illustrated by vibrations in ropes and springs and by experiments using water waves].
- state the types of waves:
  - (i) transverse waves
  - (ii) longitudinal waves
- describe the features of a wave [in terms of wave front, wavelength, frequency, time period, crest (peak), trough, compression, rarefaction, amplitude and wave speed].
- define the terms frequency, wavelength and amplitude.
- recall and apply the equation wave speed = frequency × wavelength; $v = f \lambda$
- illustrate that for a transverse wave the direction of vibration is at right angles to the direction of the energy transfer [including giving examples such as electromagnetic radiation, waves on the surface of water, and seismic waves].
- illustrate that for a longitudinal wave, the direction of vibration is parallel to the direction of the energy transfer [including giving examples such as sound waves and seismic P-waves (primary)].
- describe how waves can undergo reflection, refraction and diffraction (using ripple tank).
- describe how wavelength affects diffraction at an edge.
- describe how wavelength and slit size affect diffraction through a slit.
- analyze the phenomenon of tsunamis generated under the surface of water [in terms of underwater earthquakes/volcanic activity generating waves that increase in frequency and amplitude as they encounter increasingly shallow water].

The concept of waves demonstrates the transfer of energy from one place to another without the transfer of the matter. Waves play a vital role in understanding various phenomena of our everyday life. Waves are all around us from small ripples on a quiet lake to the loud sound of thunder in the sky. In this chapter, we will explore various types of waves, their properties, and the principles that govern their behaviour. We will uncover the main concepts such as amplitude, wavelength, frequency, and speed of waves. Through experiments and real life examples, we will also see how waves influence our daily lives and contribute to various fields, including communication, medicine, and technology.

12.1 Waves and Nature of Waves

As waves travel through a medium, they cause the particles within it to vibrate. These vibrations allow energy to be transferred from one particle to the next, as shown in Fig. 12.1. However, the particles themselves do not move along with the wave. They simply oscillate around their original positions. For example, when a twig is dropped into still water, ripples spread across the surface, as shown in Fig. 12.2. These ripples carry energy outward, yet the water and the twig remain mostly in place.

A similar effect occurs with sound waves. When a guitar string is plucked, it creates vibrations that travel through the air as sound waves (Fig. 12.3). The air particles do not move toward our ears; instead, they vibrate in place to pass the energy forward.

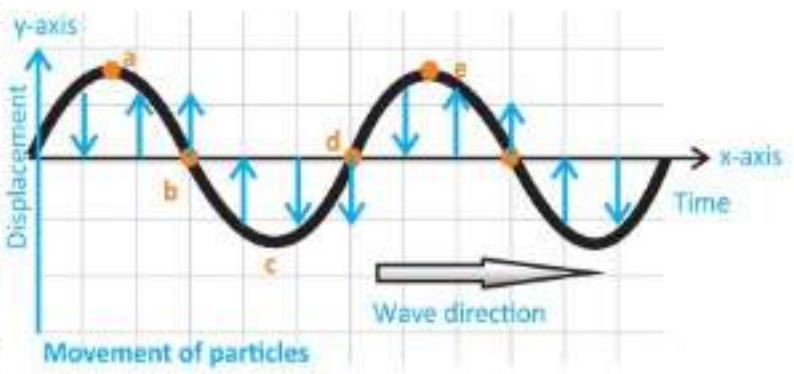


Fig 12.1: Vibration of particles in a wave perpendicular to the wave direction

Fig 12.2: Ripples in water showing energy transfer without transfer of matter

Waves can transfer energy from one place to another without transferring matter.

The same principle is illustrated by vibrations in a spring. When one end of a stretched spring is pushed and released, longitudinal waves move through the spring. As shown in

Fig. 12.4, the spring develops regions of compression (where the coils are close together) and rarefaction (where the coils are spread out). These compressions and rarefactions travel along the spring, showing how energy is transmitted without the entire spring moving forward. This experiment visually demonstrates wave motion and how longitudinal waves (such as sound) travel through matter.

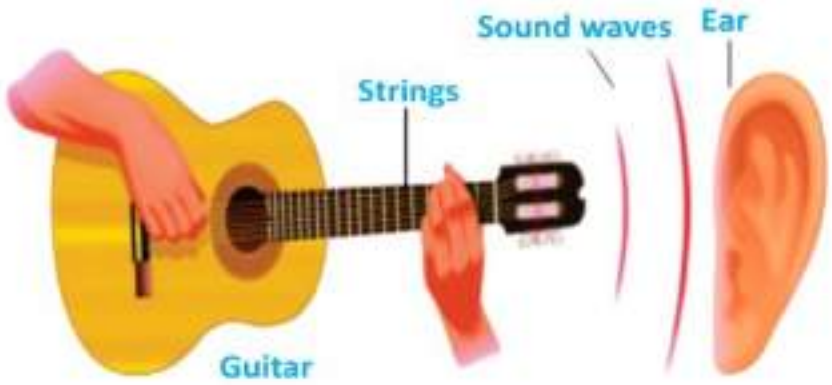


Fig 12.3: Vibrations from a guitar string producing sound waves that transfer energy through air to the ear

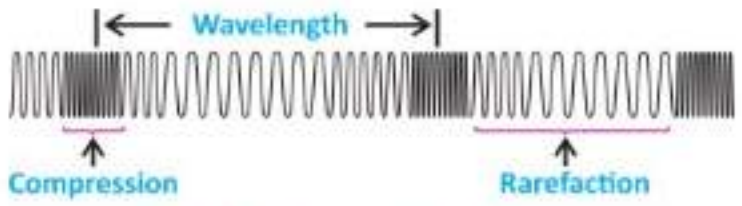


Fig 12.4: Longitudinal wave (Stretched spring)

Water Wave Experiment to Demonstrate Wave Motion

A simple and effective way to understand wave motion is through an experiment using a ripple tank, as shown in Fig. 12.5. In this setup, a shallow tray is filled with water to a uniform depth. A bar, connected to a motor, vibrates up and down gently on the water's surface. This disturbance generates ripples or wave crests that spread outward across the water surface.

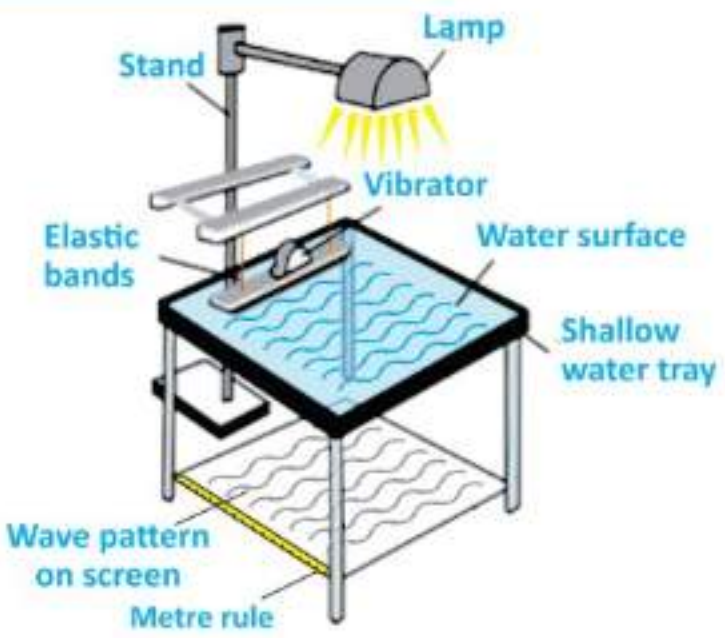


Fig. 12.5: Ripple tank

12.2 Types of Waves

There are two main types of waves:

1. Mechanical Waves

Mechanical waves are waves that require a material medium such as air, water, or a solid material to travel. These waves cannot pass through vacuum because they rely on the vibration of particles in the medium to transfer energy. The particles of the medium vibrate

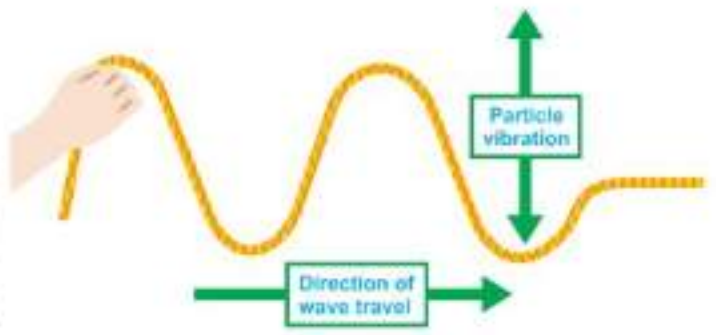


Fig. 12.6: A transverse wave on a rope showing particle vibration perpendicular to the direction of wave travel

and pass the energy along, even though the particles themselves do not move with the wave.

Tidbit

Waves carry energy across oceans, air, and even empty space without dragging particles along with them.

A simple way to observe this is by moving one end of a rope up and down. The wave travels along the rope, but each part of the rope only moves vertically while the wave itself moves forward, as shown in Fig. 12.6.

Examples of mechanical waves include sound waves, water waves, vibrations on a rope or spring, and seismic waves produced by earthquakes.

2. Electromagnetic Waves

Electromagnetic waves are different from mechanical waves because they do not require a material medium to travel. These waves can move through empty space (vacuum), that is why sunlight and other types of radiation from the Sun are able to reach the Earth through space.

Examples of electromagnetic waves include radiowaves, microwaves, infrared rays, visible light, ultraviolet rays, X-rays, and gamma rays. These waves differ in their wavelengths and frequencies, but they all travel at the same speed in vacuum approximately 3,00,000 km per second (3×10^8 m s^{-1}), known as the speed of light.

Do You Know?

Radiowaves are electromagnetic waves that travel at the speed of 3,00,000 kilometre per second through air.

Tidbit

Infra means below; infrared waves have a lower frequency than red waves. Warm objects radiate light in the infrared region of the spectrum.

The range of all these electromagnetic waves is called the electromagnetic spectrum, as illustrated in Fig. 12.7.

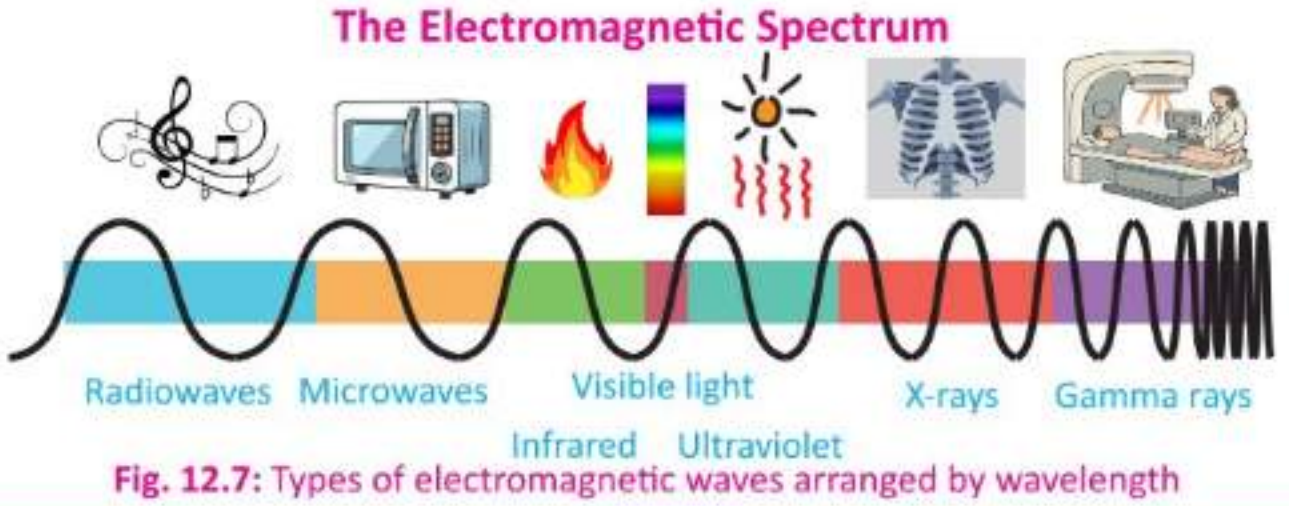


Fig. 12.7: Types of electromagnetic waves arranged by wavelength

Types of Mechanical Waves

Mechanical waves are divided into two main types, depending on how the particles of the medium vibrate in relation to the direction the wave travels. These are:

1. Transverse Waves

2. Longitudinal Waves

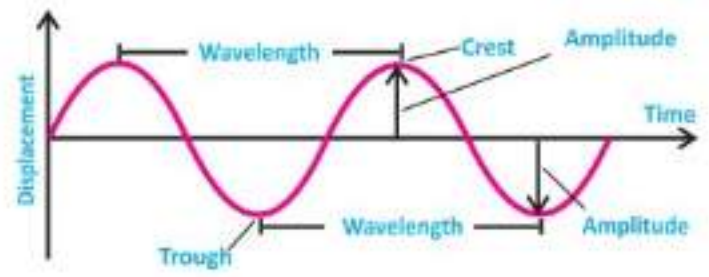


Fig. 12.8: A transverse wave labelled with crest, trough, wavelength, and amplitude

Transverse Waves

In transverse waves, the particles of the medium vibrate at right angles to the direction in which the wave is travelling. This perpendicular vibration causes the energy to transfer through the medium without any significant forward movement of the particles themselves. A simple way to observe a transverse wave is by holding one end of a rope and moving it up and down. While the wave travels horizontally along the rope, the rope segments move vertically. This motion results in the formation of the highest points known as crests and the lowest points called troughs, as shown in Fig. 12.8.

Brain Teaser

When we shake a stretched slinky spring side-to-side and then push it back and forth. What two types of waves did we just create?

An excellent example of a transverse wave is a water wave. As the wave moves forward across the water surface, the water molecules move up and down rather than along with the wave. Another important example is electromagnetic radiation (such as light, radiowaves, and X-rays), where the electric and magnetic fields oscillate perpendicular to the direction of energy propagation.

Longitudinal Waves

In longitudinal waves, the particles of the medium vibrate parallel to the direction in which the wave is travelling. Instead of moving up and down like in transverse waves, where the particles move back and forth along the same path as the energy flow. This creates regions where particles are close together, known as compressions, and regions where particles are spread apart, known as rarefactions (Fig. 12.9).

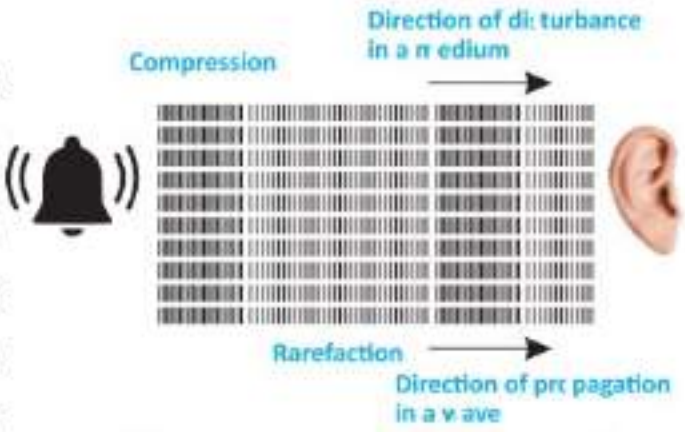


Fig. 12.9: A longitudinal sound wave showing compressions and rarefactions

A common and important example of a longitudinal wave is a sound wave. When a

sound is produced, such as when someone claps his hands, the air molecules near the hands are first pushed together, forming a compression. Immediately after, they spread apart into a rarefaction as the wave continues to move forward through the air. This sequence of compressions and rarefactions allows sound to travel to our ears without the air itself moving permanently from the source to the listener.

12.3 Terms and Parameters of Waves

A transverse wave is shown in Fig. 12.8, labelled with crest, trough, wavelength, and amplitude. The definitions of these key terms are given below:

Tidbit

Frequency tells us how many waves pass a point in one second. That is why FM radio station is called "88.0 MHz". It is sending 88 million wave cycles per second.

Crest

The crest is the region of a transverse wave, above the mean position.
It is the upper part of a wave.

Trough

The trough is the region of a transverse wave, below the mean position.
It is the lower part of a wave.

Compression

A compression is a region in a longitudinal wave where the particles of the medium are close together, resulting in high pressure.

Rarefaction

A rarefaction is a region in a longitudinal wave where the particles are spread apart, resulting in low pressure.

Amplitude

The amplitude of a wave is the maximum displacement of a point on the wave from its undisturbed (rest) position. It indicates the energy carried by the wave.

Tidbit

The time period tells how long one complete wave takes to pass a point like the rhythm heartbeat of the wave.

Wavelength (λ)

The wavelength is the distance between two corresponding points on adjacent waves (e.g., crest to crest or trough to trough in transverse waves, or compression to compression in longitudinal waves).
Its SI unit is metre (m).

Brain Teaser

Two waves travel at the same speed, but one has a higher frequency. Which has the shorter wavelength?

Frequency (f)

The frequency of a wave is the number of complete wave cycles that pass a fixed point in one second.

It is measured in hertz (Hz), where; 1 Hz = 1 wave per second

Wave Period (T)

Time required to complete one wave to pass a fixed point is called wave period.

It is the inverse of frequency.

i.e; $T = 1 / f$

It is measured in seconds (s).

Wave Front

A wave front is an imaginary surface on which all the points have same phase of vibration (i.e., have the same displacement and direction of motion).

It represents the leading edge of the wave as it travels through a medium.

Wave Speed (v) / Wave Equation

The wave speed is the rate at which the wave propagates through a medium.

As, Speed = Distance travelled / Time taken

Let us consider a wave:

Distance travelled = λ (wavelength)

Time taken = T (time period)

Then $v = S / t$

Since $S = \lambda$ *and* $t = T$

Substitute into the formula:

Now $v = \lambda / T$ ..... (12.1)

$1 / T = f$ (where f is frequency)

So $v = f \times \lambda$ ..... (12.2)

where v is the wave speed (in metres per second), f is the frequency (in hertz), and λ is the wavelength (in metres).

Equation (12.2) is known as wave equation. This is used to calculate wave speed.

Example: A wave takes 5 seconds to complete 10 cycles. If the wavelength of the wave is 1.2 metres, calculate:

(a) frequency of the wave (b) speed of the wave

Solution:

Given that; Number of cycles = 10

Time t = 5 seconds

Wavelength λ = 1.2 m

To find;	(a) Frequency f =?
	(b) Speed of wave v = ?
We know that;	f = Number of cycles / Time
	$f = 10 / 5 = 2$ Hz
As	$v = f \times \lambda$
Substituting the values	$v = 2 \times 1.2 = 2.4\ m\ s^{-1}$

12.4 Properties of Waves

One of the most fascinating aspects of waves is how they behave when they encounter obstacles or pass from one medium into another. These behaviours include reflection, refraction, and diffraction. Such properties can be observed clearly using a ripple tank, a shallow glass container filled with water, often used in classrooms to study wave motion.

Reflection of Waves

Reflection occurs when waves strike a surface and bounce back into the same medium. This behaviour can be clearly observed using a ripple tank, as shown in Fig. 12.10. In this setup, when straight water waves generated by a vibrating bar move across the tank and strike a barrier, they reflect from the surface (Fig. 12.11).

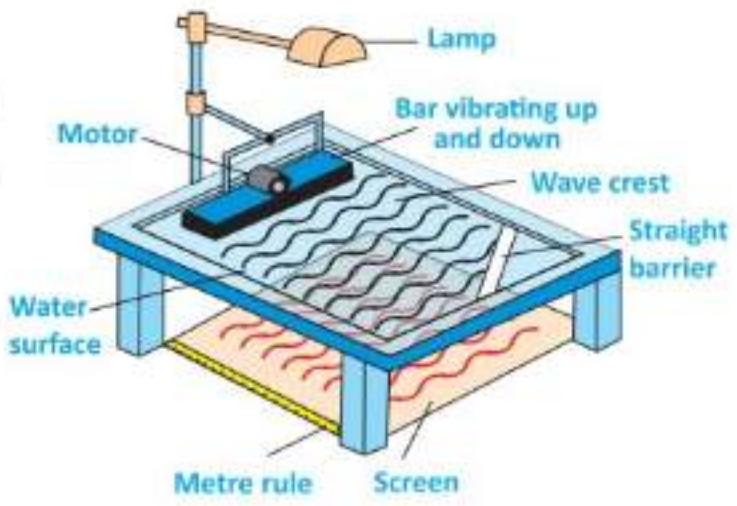


Fig. 12.10: Ripple tank setup showing water waves

The angle at which the waves approach the barrier is called the angle of incidence, and the angle at which they reflect is called the angle of reflection. These two angles are always equal. This is called law of reflection.

Angle of incidence = Angle of reflection

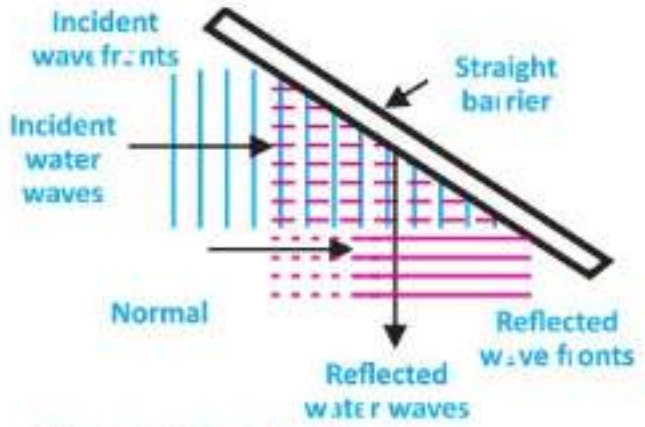


Fig. 12.11: Reflection of water waves

Reflection is the bouncing back of waves into the same medium after striking the surface of another medium.

This property is common to all types of waves, including water waves, sound waves (such as echoes), and light waves (as seen in mirrors).

Refraction of Waves

Refraction occurs when waves pass from one medium into another and change direction due to change in speed.

As the water waves cross into this shallow region, they slow down and bend, demonstrating the refraction of waves. Although the speed and wavelength of the waves change during this process, their frequency remains the same. This bending occurs because waves travel faster in deeper water and slower in shallow water, creating a noticeable change in direction.

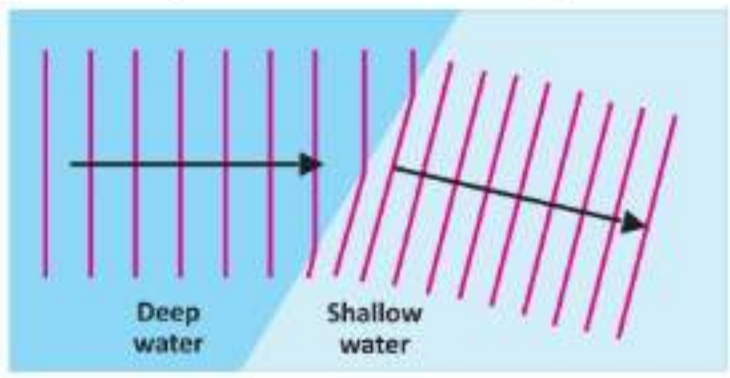


Fig. 12.12: Refraction of waves

This change in wave behaviour is also illustrated in Fig. 12.12, where wave fronts are shown bending as they pass from deep water into shallow water, with a shorter wavelength in the shallow region. The bending clearly shows how the direction and spacing of the waves are affected by the depth of the water.

When a wave passes from one medium into another at an angle, its wavelength and speed change, causing the wave to change direction. This process is called refraction.

Diffraction of Waves

Diffraction is the bending and spreading of waves as they pass through a narrow slit or move around an obstacle. This behaviour can be easily observed in water waves when they encounter openings of different sizes.

1. When the size of slit is wider than the wavelength, the waves pass mostly straight through with only slight bending at the edges (Fig. 12.13-a).

(a) Size of slit is larger than the wavelength of the water waves

(b) Size of slit is the same as the wavelength of the water waves

(c) Size of slit is smaller than the wavelength of the water waves

Fig. 12.13: Diffraction of water waves

2. If the slit size is nearly equal to the wavelength, the waves spread out more and appear almost circular beyond the slit (Fig. 12.13-b).

3. When the size of slit is smaller than the wavelength, the waves show maximum diffraction, forming strong circular patterns (Fig. 12.13-c).

This shows that the amount of diffraction increases when the size of slit is closer to or smaller than the wavelength of the waves.

The spreading of waves when they pass through a slit or move around an obstacle is called diffraction.

A common example is how we can still hear someone speaking even when he is behind a wall. This happens because sound waves, which have relatively long wavelengths, diffract around corners and obstacles, allowing the sound to reach us even without a direct line of sight.

12.5 Seismic and Tsunami Waves

Seismic and tsunami waves are natural waves produced by disturbances in the Earth's crust and ocean. Understanding them is important for safety and readiness since they have the potential to do a great deal of harm.

Seismic Waves

Seismic waves are those that pass through the Earth and are typically created by earthquakes, volcanic eruptions, or explosions. Seismometers detect these waves, which aid scientists in their investigations of the Earth's insides.

Primary Waves (P-Waves)

These are the fastest seismic waves and the first to be detected during an earthquake. P-waves can travel through solids, liquids, and gases. They move by compressing and expanding the material in the same direction as the wave travels, similar to a slinky toy being pushed and pulled. This compressional movement is shown in Fig. 12.14, where alternating regions of high and low density represent compressions and rarefactions.

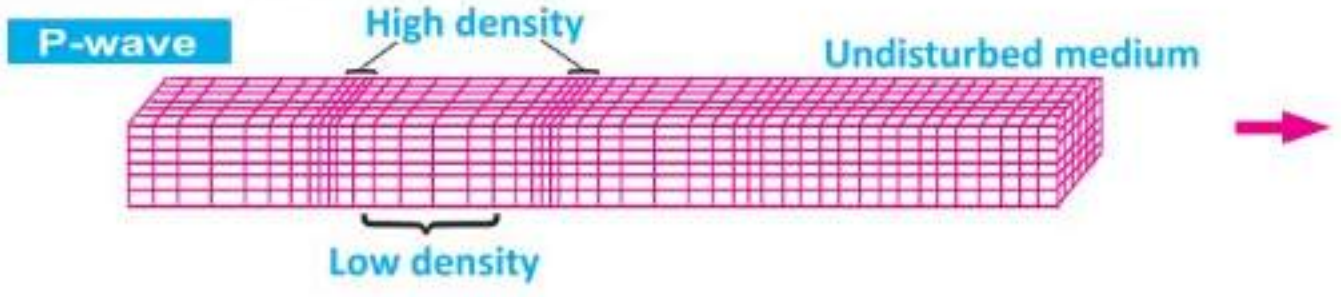


Fig. 12.14: P-wave showing longitudinal motion

Tsunami Waves

Tsunamis are extremely large and powerful ocean waves caused by sudden disturbances under the sea. These disturbances may include underwater earthquakes, volcanic eruptions, or landslides. When such events occur, they can cause a sudden shift in the ocean floor, which pushes a huge volume of water upward. This disturbance creates energy that spreads across the ocean as long, fast-moving waves, as shown in Fig. 12.15.

Fig. 12.15: A large ocean wave formed during a tsunami

Characteristics of Tsunami Waves

In the deep ocean, tsunami waves travel at very high speeds, often reaching up to 800 kilometres per hour. However, in deep water, these waves are often just a few centimetres in height and go unnoticed by ships or people.

As tsunami waves approach shallow coastal areas, their behaviour changes dramatically due to their interaction with the sea floor:

1. Wave speed decreases: As the water becomes shallower, the bottom of the wave touches the ocean floor, slowing the wave down.

2. Wavelength shortens: The distance between wave crests becomes smaller.

3. Frequency increases: More waves arrive at the shore in a shorter period of time.

4. Amplitude increases: As the energy gets compressed into a smaller space, the wave height increases significantly.

5. This transformation can result in towering waves, sometimes reaching heights of 30 metres (100 feet) or more, causing severe coastal flooding, destruction of buildings, and loss of life.

6. A tragic real-life example is the 2004

Tidbit

Though often called tidal waves, tsunamis are not caused by tides they are the result of undersea earthquakes; landslides, or volcanic eruptions.

Brain Teaser

If waves do not carry matter, how does a tsunami destroy buildings when it hits the shore?

Do You Know?

Out at sea, a tsunami is only about 1 m high, and could pass a boat without being noticed, as it approaches the shore. Its sudden deceleration from about 250 m s^{-1} to 15 m s^{-1} creates the enormous waves.

Indian Ocean tsunami, caused by a massive undersea earthquake near Sumatra. The earthquake displaced a huge section of the ocean floor, triggering tsunami waves that travelled across thousands of kilometres. These waves struck the coastlines of countries such as Indonesia, Sri Lanka, India, and Thailand, reaching heights of over 15 metres in some areas and causing massive devastation and loss of more than 2,30,000 lives.

EXERCISE

A. Multiple Choice Questions

Tick (✓) the correct answer.

12.1 The direction of vibration in a longitudinal wave is:
(a) at right angles to the wave direction
(b) in circular motion
(c) opposite to the wave direction
(d) in the same direction as the wave travels

12.2 Which part of a transverse wave carry the lowest point?
(a) Crest (b) Compression
(c) Rarefaction (d) Trough

12.3 Which of the following wave type requires a medium to travel?
(a) X-rays (b) Light waves
(c) Radiowaves (d) Sound waves

12.4 The property of a wave which indicates how much energy it carries is:
(a) crest (b) amplitude
(c) wavelength (d) speed

12.5 A wave front is:
(a) the distance between two crests
(b) a region of high pressure in a wave
(c) a line joining points that vibrate in phase
(d) the outer edge of a wave medium

12.6 The wave phenomenon which occurs when waves change direction due to a change in speed is:
(a) diffraction (b) reflection
(c) absorption (d) refraction

12.7 What happens to wave speed and wavelength when a tsunami approaches shallow water?
(a) Speed increases, wavelength increases
(b) Speed decreases, wavelength shortens
(c) Speed remains the same, wavelength shortens
(d) Speed increases, wavelength stays constant

12.8 Which wave behaviour explains how sound is heard around a corner?
(a) Reflection
(b) Refraction
(c) Interference
(d) Diffraction

B. Shorts Answer Questions

12.1 What do waves transfer from one place to another?
12.2 Name any two examples of mechanical waves.
12.3 Which type of wave can travel through vacuum?
12.4 What is the difference between transverse and longitudinal waves?
12.5 What is meant by wavelength?
12.6 Write the definition of frequency.
12.7 What causes a tsunami in the ocean?

C. Constructed Response Questions

12.1 Why sound cannot travel through space, but light can? Explain using the concept of wave types.
12.2 A student shakes one end of a rope and observes waves move along it. What kind of wave is this, and how do the particles move?
12.3 How does the amplitude of a wave relate to the energy it carries? Give an example to support your answer.
12.4 Why do we still hear a person talking even if he is behind a wall? Explain using the concept of diffraction.
12.5 If size of slit, a wave passes through is much smaller than the wavelength, what will happen to the wave after passing through the slit? Explain briefly.

D. Comprehensive Questions

12.1 Explain how waves transfer energy without transferring matter. Give examples from daily life.
12.2 Describe the difference between mechanical and electromagnetic waves with suitable examples.
12.3 What are transverse and longitudinal waves? Explain each with the help of diagrams and examples.
12.4 Discuss the properties of waves; such as reflection, refraction, and diffraction. Support your answer with examples.

12.5 What is diffraction? How do wavelength and slit size affect the diffraction of waves?

E. Numerical Problems

12.1 The wavelength of a wave is 2 metres and its frequency is 5 Hz. What is the speed of the wave? **[Ans: 10 m s^{-1}]**

12.2 A wave travels at a speed of 300 m s^{-1} and has a wavelength of 3 metres. Calculate its frequency. **[Ans: 100 Hz]**

12.3 A sound wave has a frequency of 250 Hz and a speed of 340 m s^{-1}. Find its wavelength. **[Ans: 1.36 m]**

12.4 A wave has a frequency of 50 Hz. How much time does it take to complete one wave? **[Ans: 0.02 s]**

12.5 A wave has a wavelength of 0.5 m and frequency of 200 Hz. Calculate the speed of the wave. **[Ans: 100 m s^{-1}]**

12.6 The time period of a wave is 0.02 seconds. Calculate the frequency of the wave. **[50 Hz]**

CHAPTER 13

SOUND

Student's learning outcomes (SLOs)

After studying this chapter, students will be able to:

- describe the production of sound.
- describe the longitudinal nature of sound waves.
- state the approximate range of frequencies audible to humans as 20 Hz to 20,000 Hz.
- justify why sound waves cannot travel in vacuum (including experiments to demonstrate this).
- describe how changes in amplitude and frequency affect the loudness and pitch of sound waves.
- describe how different sound sources produce sound waves with different quality (including making reference to the shape of the traces on an oscilloscope).
- describe an echo as the reflection of sound waves.
- justify simple experiments to show the reflection of sound waves.
- illustrate a method involving a measurement of distance and time for determining the speed of sound in air.
- state that the speed of sound in air is approximately 330-350 $m\ s^{-1}$.
- describe that, in general, sound travels faster in solids than in liquids and faster in liquids than in gases.
- define ultrasound as sound with a frequency higher than 20 kHz.
- illustrate and analyze the uses of ultrasound (in cleaning, parental and other medical scanning, and in sonar, including calculation of depth or distance from time and wave speed).
- illustrate the use of infrasound (e.g., by elephants in communication and in the study of seismic activity).
- analyze the effects of noise pollution on the environment.
- justify the importance of acoustic protection.
- describe how knowledge of the properties of sound waves is applied in the design of buildings with respect to acoustics.
- explain the use of soft materials to reduce echo sounding (such as in classroom studies and other public gathering buildings).
- explain, with examples, how sound can reflect, refract, and diffract.

Sound waves are simple to generate. When we speak, our vocal cords vibrate, producing sound waves. Any object that vibrates in the air causes nearby air layers to vibrate as well, which in turn affects adjacent layers. This continuous vibration pushes and pulls the air, creating waves of compression and rarefaction. When these waves reach our ears, they cause our eardrums to vibrate, allowing us to perceive sound. As these vibrations move through the air, they form sound waves. These waves are longitudinal, meaning air particles oscillate back and forth in the same direction as the wave's energy transfer. The speed at which sound waves travel through the air is approximatly 330-350 $m\ s^{-1}$. In this chapter, we will explore the fascinating world of sound, how it moves, reflects, bends, and helps us understand both nature and technology.

13.1 Production and Propagation of sound

Production of Sound

Sound is produced by vibrating objects. When an object vibrates, it makes the air around it to vibrate as well. These air vibrations travel to our ears and create the sensation of sound.

For example, in a guitar, the sound is produced when its strings vibrate (Fig. 13.1). Similarly, our voice is produced by the vibrations of our vocal cords. The human heart and other organs like the lungs also create sound waves when they vibrate. Doctors use a stethoscope to listen to these sounds.

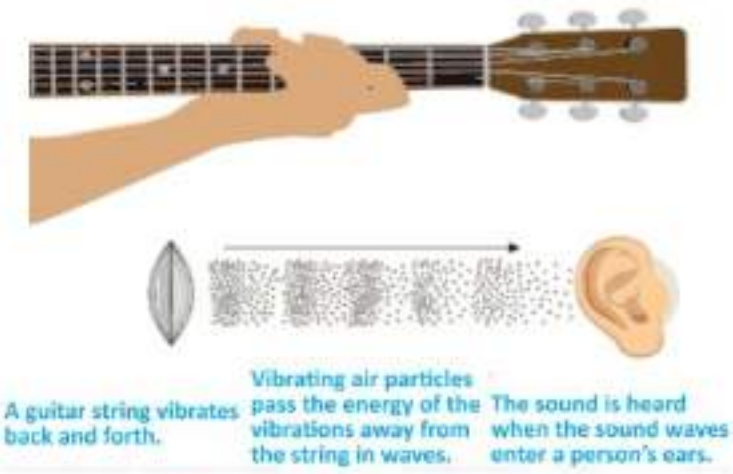


Fig. 13.1: Vibrations of guitar strings produce sound waves

Tidbit

Sound needs a medium (like air, water, or solids) to travel through. In vacuum, there are no particles to vibrate, which is why sound cannot travel there.

Activity 13.1: In school laboratories, tuning fork is used to produce a specific sound. When a rubber hammer is struck with the tuning fork, it begins to vibrate (Fig. 13.2). By bringing it close to our ear, we can hear the sound produced by these vibrations.

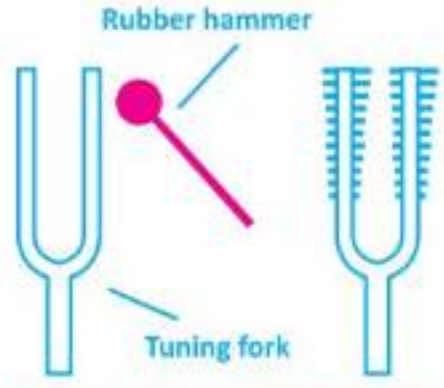


Fig. 13.2: Strike a rubber hammer on a tuning fork to produce vibrations

We can also observe the vibrations of a tuning fork by bringing one of its prongs in contact with a small table tennis ball hanging from a thread (Fig. 13.3). When the vibrating prong touches the ball, the ball moves, showing the presence of vibrations. Similarly, if we place the vibrating tuning fork into a glass of water, we will notice water splashing. But what causes this splash? This simple activity demonstrates that vibrations are responsible for producing sound.

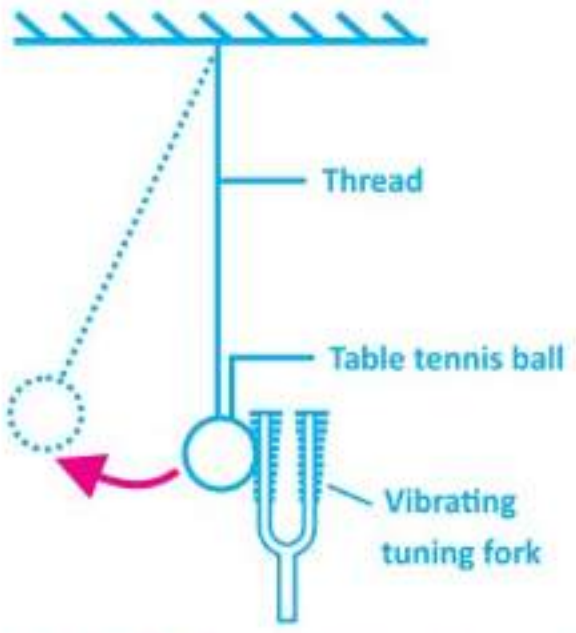


Fig. 13.3: The production of sound waves from a vibrating tuning fork

Propagation of Sound

Sound needs a medium, such as air, water, or a solid, to travel from one place to another. When a tuning fork vibrates, it creates compressions (high pressure) and rarefactions (low pressure) in the air, allowing sound to travel. As the prong moves forward, it pushes air molecules together, forming a compression that moves outward. When it moves back, it creates a rarefaction, where air molecules spread apart. This continuous cycle of compressions and rarefactions propagates sound as a longitudinal wave, meaning air molecules move in the same direction as the wave (Fig. 13.4). The wavelength of a sound wave is the distance between two successive compressions or rarefactions.

Do You Know?

Sound is a
MECHANICAL WAVE

- Sound requires a medium
- Sound can travel in a solid, liquid or gas

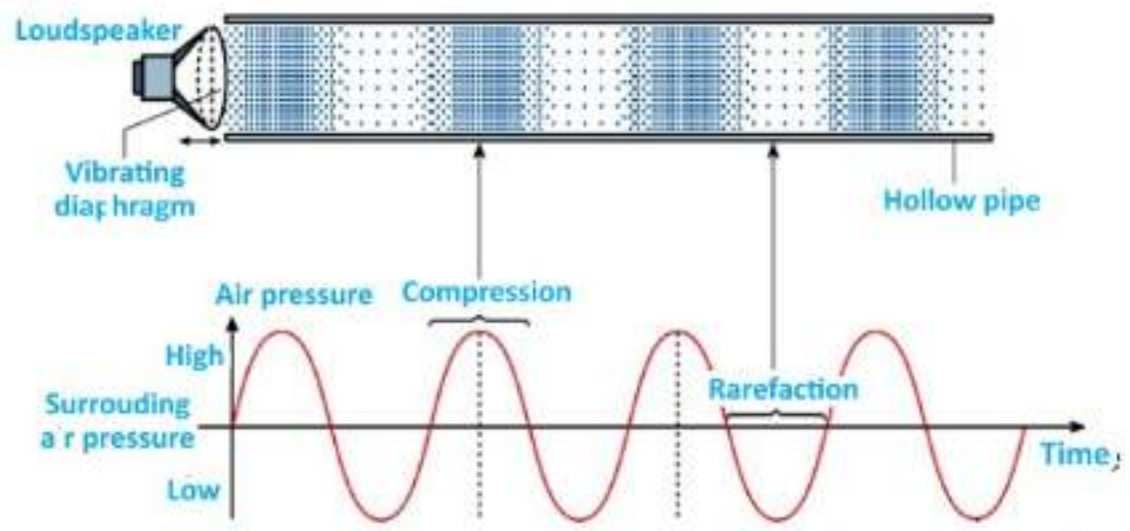


Fig. 13.4: Longitudinal waves showing compression and rarefaction in sound propagation

Activity 13.2: Unlike light waves, which are electromagnetic and can travel through vacuum, sound waves need a material medium to propagate. This can be demonstrated using a bell jar setup (Fig. 13.5). The bell jar is placed on the base of a vacuum pump, with an electric bell suspended inside using two wires connected to a power supply. When the power supply is turned ON, the electric bell rings, and we can hear the sound. Next, air is pumped out of the jar using the vacuum pump. As the air is removed, the sound of the bell becomes weaker and eventually fades, even though the bell continues ringing. When air is reintroduced into the jar, the sound becomes audible again. This demonstrates that sound waves require a medium, such as air, to propagate.

Brain Teaser

If sound is created by vibrations, how do particles move when sound waves pass through the air?

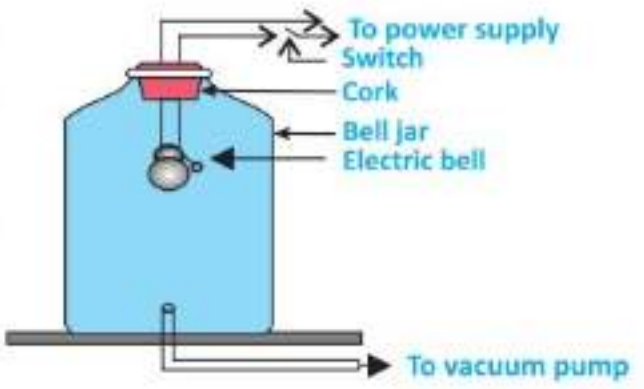


Fig.13.5: Bell jar apparatus

Longitudinal Nature of Sound Waves

The propagation of sound waves can be understood through the example of a slinky (Fig. 13.6). Sound travels in the form of a longitudinal wave. This means the particles of air move back and forth in the same direction as the sound wave. If we push and pull one end of the slinky, we will see some parts where the coils come close together (called compression) and some parts where they spread apart (called rarefaction).In the same way, when sound moves in air, it creates compressions (where air particles are closer) and rarefactions (where particles are far apart).The distance between two compressions or two rarefactions is called the wavelength. So, just like the slinky, sound moves by making compressions and rarefactions, showing that it is a longitudinal wave.

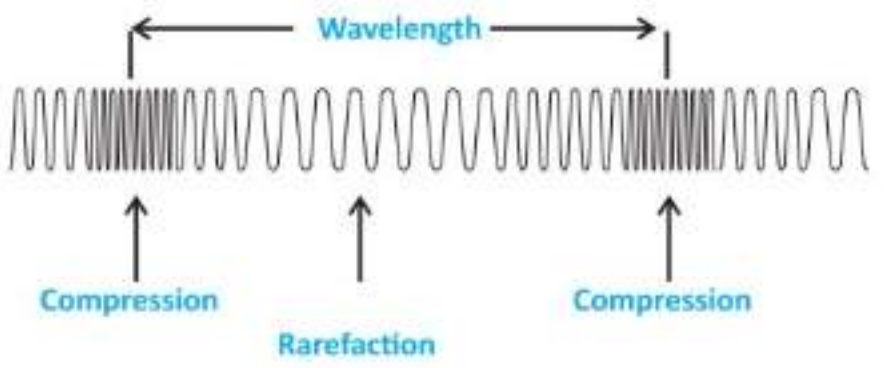


Fig. 13.6: Propagation of longitudinal sound waves in a slinky, showing compressions and rarefactions

13.2 Speed of Sound

Sound waves require a medium with vibrating particles to travel and cannot propagate through vacuum. The speed of sound varies with the type of medium. It moves 5 times faster in liquids and 15 times faster in solids than in gases. In air, factors like temperature, and humidity affect its speed. At room temperature (21°C), sound travels at 343 m s^{-1} in air, increasing with higher temperature and humidity. Since solids and liquids transmit sound faster than gases, the material of the medium plays a key role in determining sound speed. The speed of sound *v* is calculated using a specific equation:

$$v = f\lambda \quad \ldots\ldots\ldots (13.1)$$

where *v* is the speed of sound, *f* is the frequency, and λ is the wavelength of the sound wave. The speed of sound in various media is shown in

Example 13.1: Calculate the frequency of a sound wave of speed 340 m s^{-1} and wavelength 2.0 m.

Solution:

Given that;

Speed of wave v = 340 m s^{-1}

Wavelength λ = 2.0 m

To find; f =?

Using the formula; $v = f\lambda$ or $f = v/\lambda$

Substituting the values

f = 340 m s^{-1}/2 m = 170 Hz

Table 13.1: Speed of sound in various media

Medium	Speed (m s^{-1})
Gases	
Air(0 °C)	330
Air (25 °C)	346
Air (100 °C)	391
Hydrogen (0 °C)	1290
Oxygen (0 °C)	317
Helium (0 °C)	972
Liquids at 25 °C	
Distilled water	1498
Sea water	1531
Solids at 25 °C	
wood	200
Aluminium	6420
Brass	4700
Nickel	6040
Iron	5950
Steel	5960
Flint Glass	3980

13.3 Characteristics of Sound

Sounds from different objects can be identified based on their distinct characteristics, as explained below:

Loudness

Loudness is a property of sound that allows us to differentiate between loud and faint sounds.

For example, when speaking with friends, our voice is soft, but while addressing a large audience, we speak louder. The loudness of a sound depends on several factors, which influence how we perceive its intensity. Some of these factors are discussed below:

Brain Teaser

Does the loudness of a sound affect the time it takes for an echo to return?

(a) Amplitude of the vibrating body

The loudness of sound depends on the amplitude of the vibrating object (Fig. 13.7). If we pluck the strings of a guitar with more force, the vibrations will have greater amplitude, producing a louder sound. Likewise, striking a drum harder causes its membrane to vibrate more intensely, resulting in a louder noise.

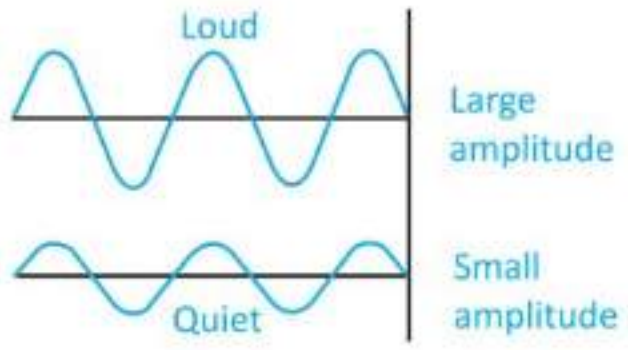


Fig. 13.7: Variation of loudness with amplitude

(b) Area of the vibrating body

The loudness of sound is also influenced by the size of the vibrating surface. A large drum produces a louder sound than a smaller one because its greater surface area allows more air to vibrate. Similarly, striking a tuning fork alone creates a faint sound, but placing it on a solid surface, like a bench, amplifies the sound. This demonstrates that a larger vibrating area increases loudness, while a smaller area produces a weaker sound.

(c) Distance from the vibrating source

The loudness of a sound decreases as the distance between the vibrating source and the listener increases. This occurs because the amplitude of the sound wave diminishes with distance. Additionally, the perception of loudness varies based on the listener's hearing ability. A person with sensitive ears perceives sound as louder compared to someone with hearing impairment. However, there is a physical characteristic of sound that remains independent of the listener's hearing ability. This is known as the intensity of sound, which is a measurable quantity and does not rely on human perception.

Pitch

Pitch is the characteristic of sound that allows us to differentiate between a shrill and a deep (grave) sound.

It is directly related to frequency, higher frequency results in higher pitch, while lower frequency produces lower pitch.

For example, the voices of women and children have a higher frequency, making them shrill and high-pitched, whereas the voices of men have a lower frequency, giving them a deeper and lower-pitched sound.

The relationship between pitch and frequency is represented in Fig. 13.8.

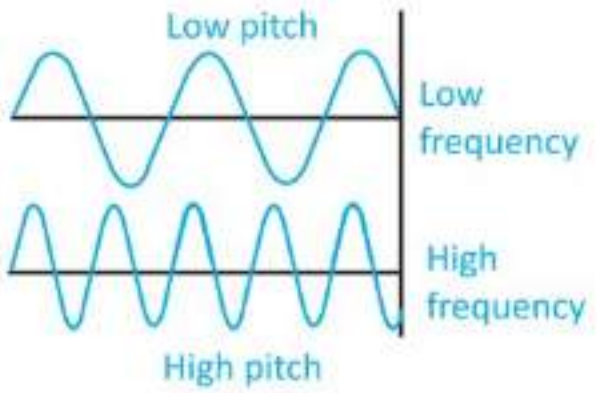


Fig 13.8: Variation of pitch with frequency

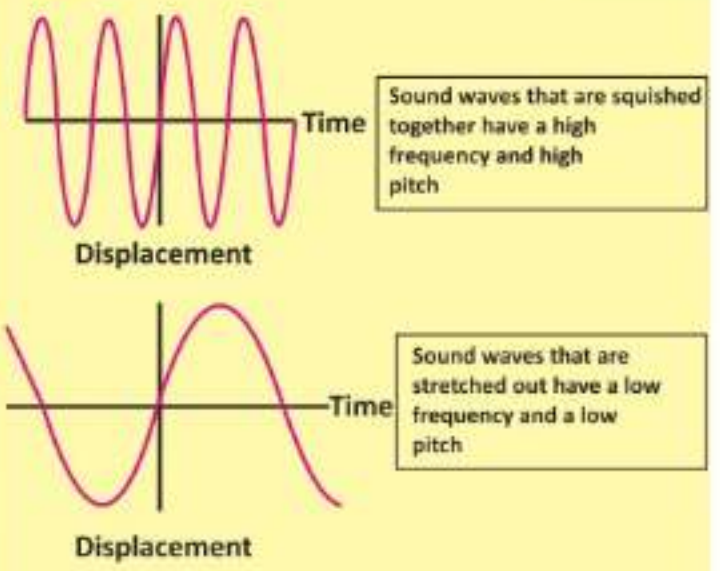
Quality of Sound

The quality of sound allows us to differentiate between two sounds having the same loudness and pitch.

This distinct quality arises due to the unique waveforms produced by each sound source.

For example, a violin, trumpet, flute, and oboe each generate a distinctive waveform. As illustrated in Fig. 13.9, the oscilloscope traces of these instruments show different shapes, with varying levels of complexity and harmonics. The violin has a rich, complex waveform, while the flute produces a simpler, more regular waveform. The trumpet and oboe each exhibit their own unique oscillation patterns, further demonstrating the diversity in sound production among instruments.

Do You Know?



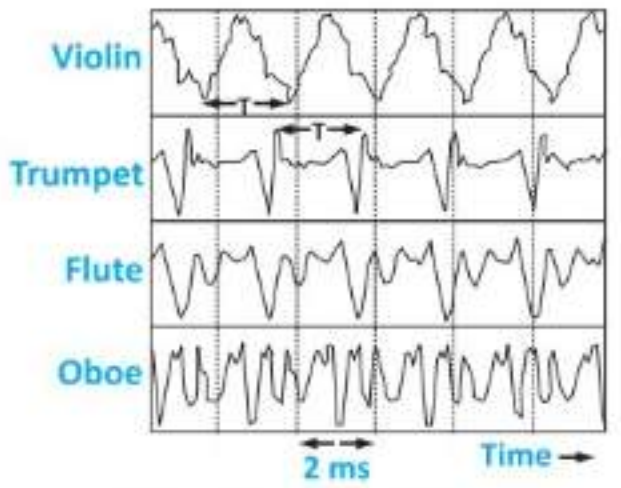


Fig. 13.9: Oscilloscope traces of different sound sources

Tidbit

The shape of a sound wave on an oscilloscope is affected by the instrument's unique construction and the way it produces vibrations.

The shape of these waveforms, when displayed on an oscilloscope, visually represents the timbre of each instrument. These differences in waveform structure are key to understanding how different sound sources can produce sound waves with varying qualities, despite having the same pitch and loudness.

Musical Sounds and Noise

In daily life, we hear sounds of different qualities. Musical instruments like the guitar, violin, recorder, and drum produce sounds with controlled pitch and quality, which are pleasant to hear. Such sounds are called musical sounds. However, some sounds, like traffic noise, door slamming, and machinery, are harsh and unpleasant. These are classified as noise. Noise results from irregular and sudden vibrations and is considered a form of pollution that affects both humans and animals.

Effects of Noise Pollution

Excessive noise from industrial machinery, vehicle horns, alarms, and construction work can lead to stress, lack of concentration, hearing loss, sleep disturbances, aggression, and hypertension.

Controlling Noise Pollution

The recommended safe noise level is 85 – 90 dB for a maximum of eight-hour workday. Noise pollution can be reduced by

1. using quieter, eco-friendly machinery.
2. installing sound barriers.
3. wearing hearing protection devices.
4. Tree plantation.

By controlling noise pollution, we can create a healthier environment.

13.4 Reflection of Sound (Echo)

When we clap or shout near a tall building or mountain, we hear the sound return after a brief delay (Fig. 13.10). This repeated sound is called an echo, caused by the reflection of sound waves from a surface.

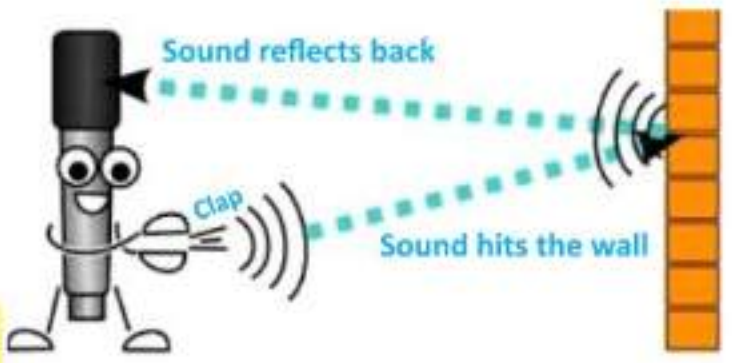


Fig. 13.10: Reflection of sound

When sound waves hit a surface and bounce back into the same medium, the phenomenon is called an echo or reflection of sound.

The human brain retains sound for about 0.1 seconds, so to hear a distinct echo, the reflected sound must reach us after at least 0.1 seconds. Given the speed of

sound in air (340 m s^{-1}), the minimum distance for an echo to form is 34 metres (total distance travelled by sound), meaning the reflecting surface must be at least 17 metres away. Echoes can also repeat multiple times due to successive reflections.

Activity 13.3: (Reflection of Sound)

Take two identical plastic tubes of appropriate length (or create them using chart paper) as shown in Fig. 13.11. Position the tubes on a table, ensuring they are near a wall. Place a clock close to the open end of one tube and listen for its sound through the other tube. Adjust the alignment of the tubes until the sound of the clock is distinctly heard. Measure the angles of incidence and reflection, then analyze their relationship. Gently raise the right tube slightly upward and observe any changes that occur.

Measuring Speed of Sound by Echo Method

Apparatus: Measuring tape, stopwatch, flat wall that can produce a good echo.

Procedure

1. Use a measuring tape to mark a 50 m distance from a wall.
2. Stand at this point and clap your hands, listening carefully for the echo from the wall. Ensure the echo is not reflecting from any other nearby structures. The time interval between the clap and its echo represents the time taken for sound to travel 100 m.
3. Begin clapping rhythmically and start a stopwatch with the first clap. Count each clap and stop both the clapping and the stopwatch upon hearing the echo of the 10 th clap.
4. Determine the average time for 10 claps. By calculating the time interval t between consecutive claps and applying the formula; $S=vt$, the speed of sound can be computed.

Do You Know?

How bats use echo to find food?

Bats send out sound waves using their mouth or nose. When the sound hits an object, an echo comes back.
The bat can identify an object by the sound of the echo. They can even tell the size, shape and texture of a tiny insect from its echo.

Brain Teaser

Why can we hear our voice echoing back to us when we shout? How do the particles in the air play a role in this?

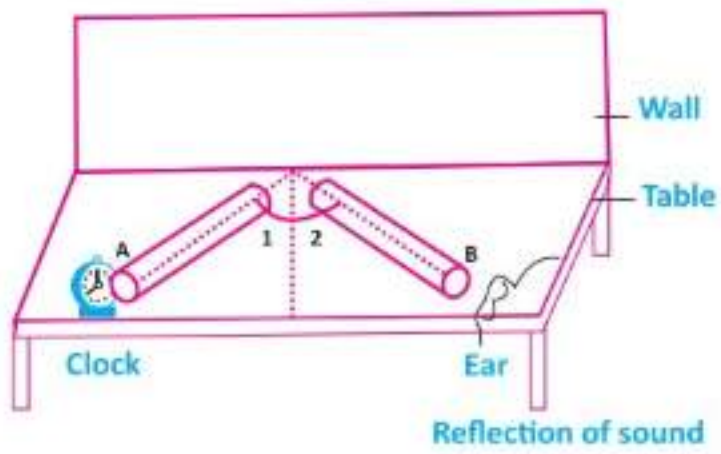


Fig.13.11: Reflection of sound using plastic tubes and a ticking clock

Brain Teaser

Can we hear someone scream if we are in space with him?

Example 13.2: Flash of lightning is seen 2 seconds earlier than the thunder. How far away is the cloud in which the flash has occurred? (Speed of sound = 332 m s^{-1})

Solution:

Given that;

Time t = 2 s

Speed of sound v = 332 m s^{-1}

To find;

Distance S = ?

As distance of the cloud; $S = vt$ = 332 m s^{-1} x 2s ; S = 664 m

13.5 Refraction and Diffraction of Sound

Sound waves, like other waves, exhibit various behaviours, including refraction and diffraction, in addition to reflection. Here is a closer look at these phenomena.

Refraction of Sound

Refraction occurs when sound waves change direction due to a variation in the medium's properties, such as density or temperature. This change occurs because the speed of sound differs in various mediums.

Example: When sound waves travel from air into water, they bend due to the difference in density, causing sound to move faster in water than in air. This is why a submerged person can clearly hear underwater sounds, while someone above the surface may struggle to hear them (Fig. 13.12).

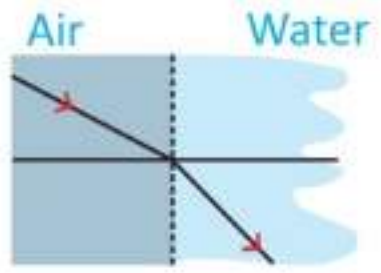


Fig.13.12: Refraction of sound

Diffraction of Sound

Diffraction occurs when sound waves bend around obstacles or spread out after passing through narrow slits (Fig. 13.13). This property allows sound to be heard even when the source is not in direct view.

Example: If someone is speaking from behind a wall, his voice can still be heard because the sound waves bend around the barrier. Similarly, sound can travel through

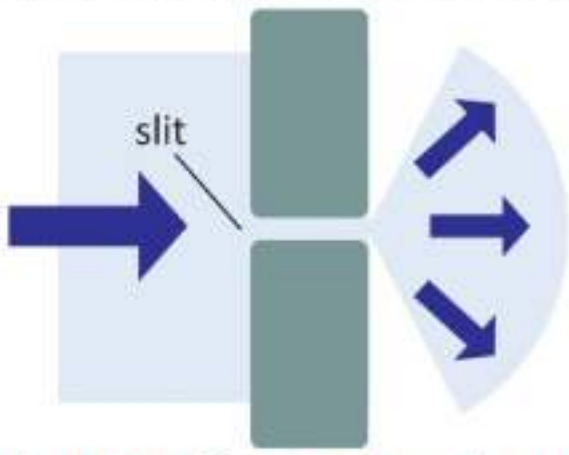


Fig.13.13: Diffraction of sound waves

an open doorway and spread into a room, allowing people inside to hear noises from the outside even if they cannot see the source.

We can hear someone speaking even if he is around a corner or behind a wall. This is because sound waves diffract around the obstacle and reach our ears.

Tidbit

Refraction of sound occurs when it travels through layers of air at different temperatures. That is why on a cool morning, sound may travel farther it bends back toward the ground due to slower speed in colder air. This is why distant train horns or bird calls sound clearer at dawn.

Diffraction is the bending of sound waves around obstacles or through slits. It allows sound to spread out and be heard even when the source is not directly visible.

13.6 Audible Frequency

The human ear can detect sounds within the 20 Hz to 20,000 Hz range, known as the audible frequency range.

Sounds below 20 Hz or above 20,000 Hz are inaudible to humans (Fig. 13.14). Hearing ability declines with age. Young children can hear up to 20,000 Hz, while older individuals may struggle with sounds above 15,000 Hz.

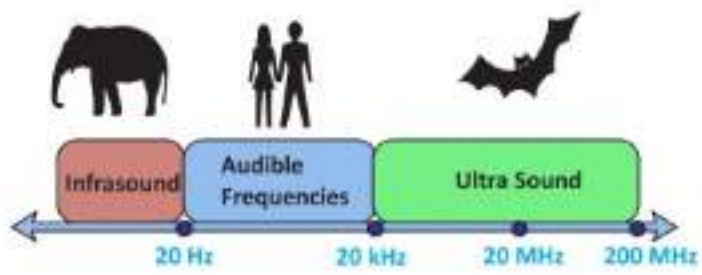


Fig.13.14: Frequency of sound

Infrasound

Infrasound refers to waves below 20 Hz, which humans cannot hear but may feel as vibrations.

Tidbit

Infrasound sensors are used to monitor volcanic eruptions, earthquakes, and even tsunamis before they strike. The low-frequency waves from these natural events travel great distances and help scientists issue early warnings!

Many animals, like elephants and whales, use infrasound for communication. It is produced by natural events (earthquakes, volcanoes), industrial processes, and human activities (machinery, explosions). Due to its ability to travel long distances, infrasound is used for monitoring natural disasters.

Uses of Infrasound

- **Elephant Communication:** Elephants use infrasound to communicate over

long distances. Their deep rumbles travel far through air and ground, helping them stay connected. They can sense these vibrations not just with their ears but also through their feet and trunks.

- **Earthquake Detection:** Scientists use infrasound to detect earthquakes before the strong shaking starts. These low-frequency waves act as an early warning system.
- **Volcano Monitoring:** When a volcano erupts, it creates unique infrasound waves. Scientists study these waves to predict eruptions and assess risks.
- **Nuclear Explosion Detection:** Special sensors track infrasound waves from nuclear explosions.

Do You Know?

Blue whales, the largest animals on the Earth, sing in infrasound that can travel across entire oceans! These deep calls help them communicate with others even when they are hundreds of kilometres apart.

Ultrasound

Sounds with frequencies above 20,000 Hz, which are inaudible to humans, are called ultrasound or ultrasonics.

Uses of Ultrasound

- **Medical Applications**

Ultrasound is widely used in medical diagnostics and treatments. When ultrasonic waves pass through the body, they reflect differently from various tissues and organs. These reflected waves are then captured and converted into images on a screen, a process known as ultrasonography. This helps in visualizing organs such as the heart, liver, and kidneys, as well as in monitoring pregnancies.

Do You Know?

Doctors use ultrasound waves to "see" inside the body without cutting it open! These waves are completely non-invasive and safe, making them ideal for monitoring babies during pregnancy or detecting organ problems.

For example, parental scanning uses ultrasound to observe the fetus inside the womb, assess its development, and detect any potential issues. Additionally, ultrasound aids in thyroid gland imaging for diagnosis, providing clear visual representations that help doctors evaluate thyroid health.

Underwater Exploration (SONAR)

Ultrasound is used to measure ocean depth and locate objects on the seabed. SONAR (Sound Navigation and Ranging) works by sending ultrasonic waves into water; the reflected waves help to determine the distance and shape of an object (Fig. 13.15).

Fig. 13.15: Illustration of sonar used by a ship

Calculating Distance in SONAR

The formula used to calculate distance (or depth) in sonar systems is:

Distance = (Speed of Sound in Water × Time) / 2 ..... (13.2)

where speed of sound in water is approximately 1500 m s^{-1} at room temperature. Time is the duration it takes for the ultrasound pulse to travel to the object and return to the source. The distance is divided by 2 because the pulse travels to the object and then returns to the source.

Industrial Applications

Ultrasound helps to detect cracks in machines like turbines, ship engines, and airplane parts. Ultrasound waves reflect from damaged areas, revealing hidden defects. It is also used to destroy bacteria in liquids through high-intensity waves.

Example 13.3: A sonar device on a ship sends out a sound pulse that returns after 3.2 seconds. If the speed of sound in water is 1600 m s^{-1}, what is the distance from the ship to the seafloor?

Solution:

Given that;

Time for the sound pulse to return $t = 3.2$ seconds

Speed of sound in water $v = 1600\ m\ s^{-1}$

To find; distance $d = ?$

The sound pulse travels to the seafloor and back, so the total distance covered is twice the distance from the ship to the seafloor.

Using the formula; $d = v \times t$

Substituting the values

$$d = 1600\ m\ s^{-1} \times 3.2\ s = 5120\ m$$

Since the distance covered is twice the actual distance to the seafloor, we divide by

2 to find the distance.

$d = 5120\ \text{m} / 2 = 2560\ \text{m}$

The distance from the ship to the seafloor is 2560 metres.

13.7 Acoustic protection of Buildings

Acoustic protection reduces unwanted sound using soft, porous materials like carpets and curtains, which absorb sound and minimize echoes. Hard, smooth surfaces reflect more sound, while excessive absorption can weaken audibility in classrooms and halls (Fig. 13.16-a). Multiple reflections, known as reverberation, can distort sound, so a balance between reflection and absorption is essential in auditoriums, lecture halls, and theatres. Reflective surfaces behind the stage help direct sound to the audience. Additionally, curved ceilings and sound boards are often used to ensure even sound distribution throughout the hall (Fig. 13.16-b).

Tidbit

In concert halls and theatres, curved ceilings and soft walls do not just look stylish. They are engineered to shape sound! While carpets and curtains absorb echoes, curved panels and reflectors bounce the music toward the audience so that even the person in the last row hears every note clearly. That is the science of acoustics protection—a perfect harmony of silence and sound!

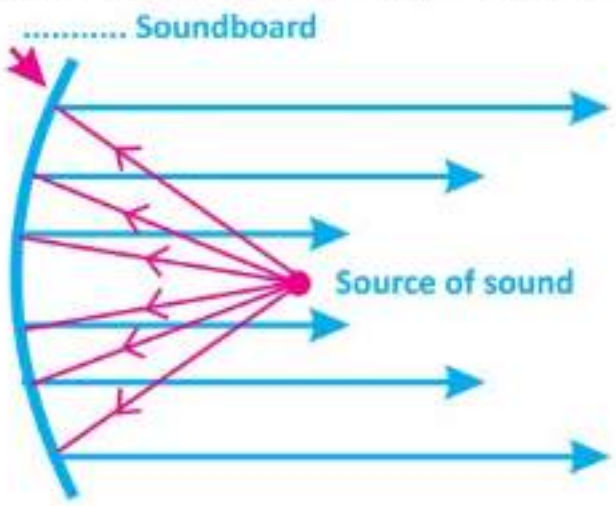


Fig. 13.16(a): Soundboard used in a big hall

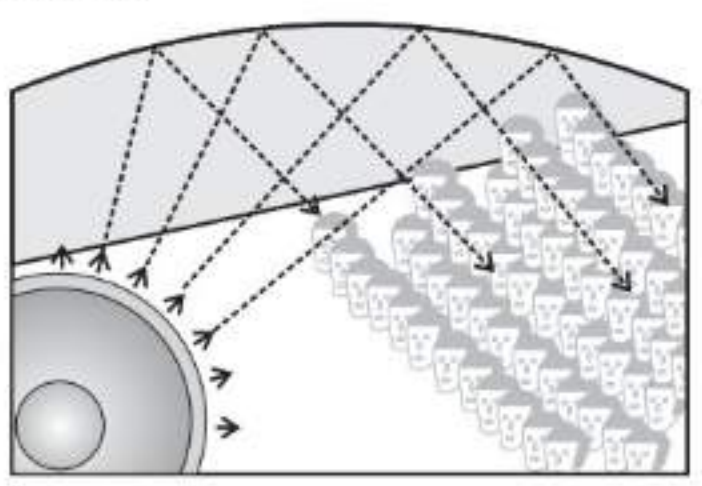


Fig. 13.16(b): Curved ceiling of a conference hall

EXERCISE

A. Multiple Choice Questions

Tick (✓) the correct answer.

13.1 What is required for the production of sound?
(a) A vacuum (b) Vibrations of a medium (c) Only air (d) Light waves

13.2 An echo is produced due to:
(a) refraction of sound waves (b) reflection of sound waves
(c) diffraction of sound waves (d) absorption of sound waves

13.3 An example of a longitudinal wave is:
(a) light wave (b) water wave (c) sound wave (d) radiowave

13.4 In which medium does sound travel the fastest?
(a) Gases (b) Liquids (c) Solids (d) Vacuum

13.5 What is the approximate speed of sound in air?
(a) 150 m s^{-1} (b) 330-350 m s^{-1} (c) 500 m s^{-1} (d) 1,000 m s^{-1}

13.6 Why is acoustic protection important in building design?
(a) To increase noise pollution (b) To reduce echo and improve sound quality
(c) To amplify sound (d) To increase the speed of sound

13.7 For a normal person, the audible frequency range for sound waves lies between:
(a) 10 Hz and 10 kHz (b) 20 Hz and 20 kHz
(c) 25 Hz and 25 kHz (d) 30 Hz and 30 kHz

B. Short Answer Questions

13.1 How does the medium affect the speed of sound?
13.2 Does sound waves show reflection?
13.3 What factors influence the loudness of sound?
13.4 Why do we hear an echo when we clap near a building?
13.5 What is ultrasound, how is it used in medicine?

C. Constructed Response Questions

13.1 Why does a tuning fork placed on a wooden table produce a louder sound than when held in the air? What does this tell us about the role of surface area in sound propagation?
13.2 If sound needs a medium to travel, how does the bell jar experiment prove this requirement? What happens when air is removed, and why?
13.3 A person hears his echo when shouting near a tall building. Why must the building be at least 17 metres away for the echo to be heard clearly?

13.4 Why do voices of men sound deeper than those of women or children, even when they are speaking at the same intensity? Explain using the relationship between frequency and pitch.

13.5 In what ways do soft materials like carpets or curtains improve the acoustics of a room? How do they affect echoes and sound quality?

13.6 When a person claps near a canyon and hears the echo after a few seconds, how can they calculate the distance to the canyon? What principle is used in this method?

D. Comprehensive Questions

13.1 What is the approximate speed of sound in air, and what factors affect it?

13.2 Why does sound travel faster in solids than in liquids and gases? Explain.

13.3 How do amplitude and frequency, affect the quality of sound? Explain.

13.4 How does echo occur? Explain.

13.5 How do reflection, refraction, and diffraction affect the behaviour of sound waves?

13.6 What are infrasound and ultrasound, and how are they used in different applications?

E. Numerical Problems

13.1 At a particular temperature, the speed of sound in air is 333 m s^{-1}. If the wavelength of a sound wave is 3 cm, calculate the frequency of the sound wave. Is this frequency in the audible range of the human ear?
[Ans: 11 kHz, yes audilble]

13.2 A clock chimes 48 times in 1 minute. Calculate the frequency and period of the chimes. **[Ans: 0.8 Hz, 1.25 s]**

13.3 A car horn emits a sound with a wavelength of 0.5 m. If the speed of sound in air is 340 m s^{-1}, calculate the frequency of the sound produced by the car's horn. **[Ans: 680 Hz]**

13.4 A wave travels with a speed of 500 m s^{-1} and has a wavelength of 2 metres. Calculate the time period of the wave. **[Ans: 0.004 s]**

13.5 A research boat sends a sound wave straight to the seabed and receives the echo 2 seconds later. The speed of sound in seawater is 1600 m s^{-1}. Find the depth of the sea at this position. **[Ans: 1600 m]**

13.6 A person claps his hands near a mountain and hears the echo after 6 seconds. If the speed of sound is 343 m s^{-1}, what is the distance of the mountain from the person? **[Ans: 1029 m]**

CHAPTER 14

LIGHT

Student's learning outcomes (SLOs)

After studying this chapter, students will be able to:

- define and use the terms normal, angle of incidence, and angle of reflection.
- describe an experiment to find the position and characteristics of an optical image formed by a plane mirror (same size, same distance from mirror as object, and virtual).
- use the law of reflection to solve simple optical problems.
- apply the qualitative principle that a wave refracts towards the normal when it slows down while entering a medium and that it refracts away from the normal if it speeds up when it enters a new medium (in the case the angle of incidence is zero, then the waves continue parallel to the normal).
- define and use the refractive index from vacuum to a medium for light as c/v.
- define refractive index n as; $n = \sin i / \sin r$. Apply Snell's law; $n = \sin i / \sin r$, to solve simple problems.
- describe an experiment to show refraction of light by transparent blocks of different shapes.
- define the terms critical angle C and total internal reflection.
- derive the equation; $n = 1 / \sin C$.
- apply the equation; $n = 1 / \sin C$ to solve simple problems.
- describe experiments to show internal reflection and total internal reflection.
- evaluate and illustrate the use of optical fibres, particularly in telecommunications, stating the advantages of their use in each context.
- analyze the action of thin converging and thin diverging lenses on a parallel beam of light.

- define and use the terms focal length, principal axis, and principal focus (focal point).
- draw ray diagrams to illustrate the formation of real and virtual images of an object by a converging lens.
- differentiate between real and virtual images.
- define and calculate linear magnification (as the ratio of image length to object length; state and use the equation; linear magnification = image length / object length).
- describe the use of a single convex lens as a magnifying glass.
- describe the use of a single convex lens in various optical device applications (specifically in the case of a magnifying glass, a camera, projector, and a photographic enlarger). This includes drawing ray diagrams to show how each forms an image.
- explain the dispersion of light by a prism [including the detection of non-visible spectra by a thermometer].
- draw ray diagrams to show the formation of images in the normal eye, a short-sighted eye, and a long-sighted eye.
- describe the use of converging and diverging lenses to correct long-sightedness and short-sightedness.
- state that extreme gravity from interstellar objects like black holes can cause light to bend (from the perspective of the observer) in a way that is analogous to a simple lens [This is called 'gravitational lensing].

Light is a form of energy that travels in the form of waves and allows us to see the world around us. In this chapter, we will explore how light reflects from mirrors, bends (refracts) when passing through different materials, and how lenses shape light to form images. Key topics include the angles of incidence, reflection, and refraction, as well as the difference between real and virtual images in everyday tools like cameras, microscopes, and eyeglasses. We will also learn how the human eye detects light and colour, and how lenses help to correct vision problems. In addition to this, the chapter will introduce advanced ideas such as gravitational lensing and how light is used in modern scientific and industrial technologies.

14.1 Reflection of Light

Reflection of light takes place when light hits a surface and bounces back instead of passing through it. This usually occurs on smooth and shiny surfaces, such as mirrors. The angle at which light strikes the surface (angle of incidence) is always equal to the angle at which it reflects (angle of reflection) (Fig. 14.1).

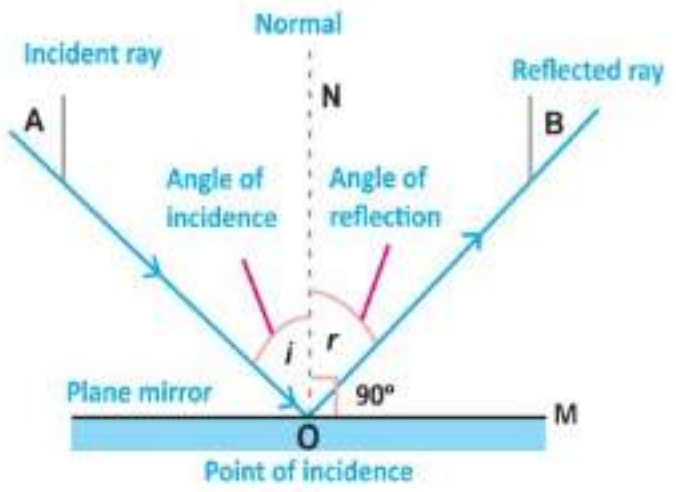


Fig. 14.1: Reflection of light

There are two types of reflection:

Regular/Specular Reflection : It takes place on smooth surfaces (like mirrors) where light reflects in one direction, forming a clear image.

Diffused/Irregular Reflection: It occurs on rough surfaces (like paper), where light scatters in different directions, so no clear image is seen.

Reflection is important for mirrors, periscopes, and optical devices, allowing us to see objects and form images.

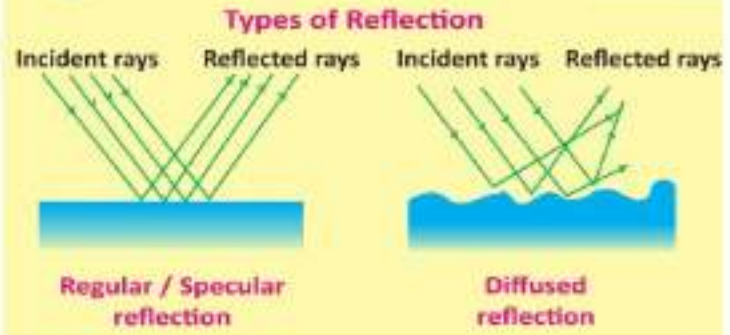
Laws of Reflection

The reflection of light follows two basic laws:

First Law: The incident ray, the reflected ray, and the normal (a line drawn perpendicular to the surface at the point of reflection) all lie in the same plane.

Second Law: The angle of incidence *(i)* is always equal to the angle of reflection *(r)*.

Do You Know?



$$\angle i = \angle r \quad \text{..... (14.1)}$$

These laws apply to all reflective surfaces, such as mirrors and water, and help us to understand how light bounces back to form images.

Activity 14.1: Finding the Image Position in a Plane Mirror

Objective: To observe and understand the position and characteristics of the image formed by a plane mirror.

Materials Needed: A plane mirror, an object, a measuring tape, a light source, and a white paper.

Procedure: Place the plane mirror in an upright (vertical) position. Position the object in front of the mirror. Ensure the object is not taller than the mirror. Shine light onto the object, so it is clearly visible (Fig. 14.2).

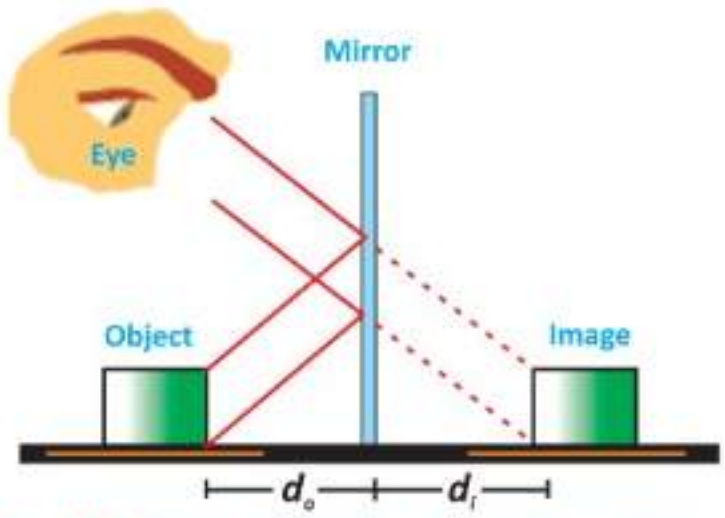


Fig. 14.2: Image formation by a plane mirror

Look at the mirror and observe the rays of light reflecting from the object. When two rays reflect off the mirror and reach the observer's eye, they appear to be coming from behind the mirror. By using a ruler and the law of reflection, we can draw the reflected rays on paper. Extend these reflected rays backward with dotted lines where they meet behind the mirror is the position of the image. This method shows the virtual image location.

There are four properties of an image formed by a plane mirror :

1. The image is erect – It appears upright, just like the object.
2. The image is of the same size – The size of the image is exactly equal to the size of the object. It can be written as: $d_i = d_o$
3. The image is laterally inverted – The left and right sides of the object appear reversed in the image as shown in Fig. 14.3.

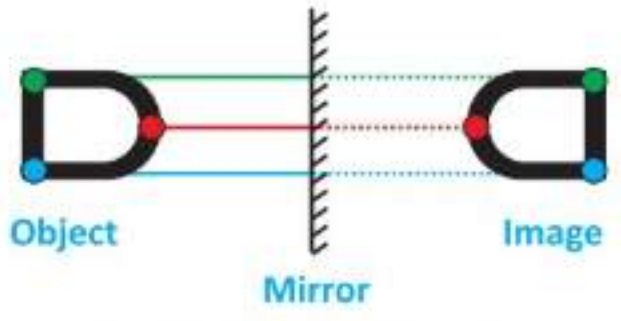


Fig. 14.3: Letter 'D' showing lateral inversion in a mirror

4. The image is virtual – It cannot be captured on a screen because it is formed behind the mirror where light rays do not actually meet.

14.2 Refraction of Light

Refraction of light occurs when light changes direction as it passes from one medium to another, such as from air to water or glass (Fig. 14.4). This happens because light travels at different speeds in different materials. When light moves from a rarer medium (air) to a denser medium (glass or water), it bends towards the normal. When it moves from a denser medium to a rarer medium, it bends away from the normal. The amount of bending depends on the refractive index of the medium. Refraction explains many everyday phenomena, such as a pencil appearing bent in water, the working of lenses in glasses and cameras, and the formation of rainbows.

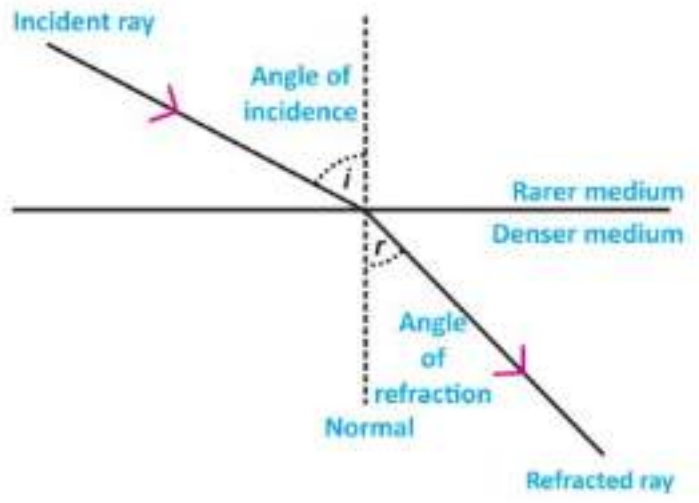


Fig. 14.4: Refraction of light

Laws of Refraction of Light

The bending of light during refraction follows two essential principles:

1. **First Law:** The incident ray, refracted ray, and the normal at the point where light enters a new medium all lie in the same plane.
2. **Second Law (Snell's Law):** The ratio of the sine of the angle of incidence i to the sine of the angle of refraction r remains constant for a specific pair of media.

$$\frac{\sin i}{\sin r} = n \quad \text{..... (14.2)}$$

Here, n is the refractive index of the second medium relative to the first. The refractive index indicates how much light bends when entering a different medium.

Speed of Light in a Medium

The speed of light varies depending on the medium through which it travels. In vacuum, light moves at its maximum speed of 3×10^8 m s^{-1}. However, when light passes through materials like air, water, or glass, it slows down due to interactions with medium particles. The denser the medium, the slower the speed of light. This change in speed is measured using the refractive index n, which is the ratio of the

speed of light in vacuum to its speed in a given medium. The variation in the speed of light, when it moves between different material, is what causes refraction, or the bending of light.

Refractive Index

The refractive index *n* of a medium is a measure of how much the speed of light changes when it enters that medium.

It is defined as the ratio of the speed of light in air or vacuum *c* to the speed of light in the given medium *v*:

$$\text{Refractive index} = \frac{\text{Speed of light in air}}{\text{Speed of light in a medium}}$$

$$\text{or} \quad n = \frac{c}{v} \quad \ldots\ldots\ldots (14.3)$$

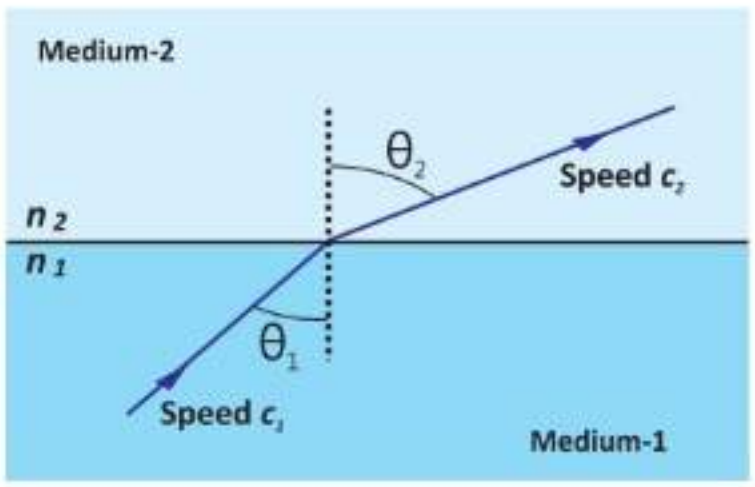


Fig. 14.5: Refraction of light at a boundary between two media

Figure 14.5 illustrates how a light ray changes direction when passing from medium-1 (with refractive index n_1 and speed c_1) to medium-2 (with refractive index n_2 and speed c_2). The angles θ_1 (angle of incidence) and θ_2 (angle of refraction) demonstrate how the light bends according to Snell's law due to the difference in refractive indices.

Example 14.1: A ray of light enters from air into water. The angle of incidence is 40° and the refractive index of water is 1.33. Find the angle of refraction.

Solution:

Given that; Angle of incidence $i = 40°$

Refractive index of water $n = 1.33$

To Find; Angle of refraction $r = ?$

Using Snell's law: $\frac{\sin i}{\sin r} = n$

Substituting the values: $1.33 \times \sin r = \sin 40°$

$\sin r = \sin 40° / 1.33$

$$\sin r = 0.483$$

$$r = \sin^{-1}(0.483)$$

$$\text{or} \quad r = 28.9°$$

Hence, the angle of refraction is 28.9°.

Example 14.2: The refractive index of water is 1.33. What is the speed of light in water?

Solution:

Given that;

Refractive index of water $n = 1.33$

Speed of light in vacuum $c = 3 \times 10^8$ m s^{-1}

To find; Speed of light in water $v = ?$

Using the formula: $n = c / v$

or $v = c / n$

Substituting the values

$$v = (3 \times 10^8 \text{ m s}^{-1}) / 1.33$$

$$v = 2.26 \times 10^8 \text{ m s}^{-1}$$

For your information

Convex Mirror	Concave Mirror
The Focus lies behind the mirror	The focus is in front of the mirror
The focus is virtual as the rays of light after reflection appear to come from the focus.	The focus is real as the rays of light after reflection converge at the focus.

Do You Know?

Some sign conventions for mirrors are:

Quantity	When Positive (+)	When Negative (–)
Object distance p	Real object	Virtual object
Image distance q	Real Image	Virtual image
Focal length f	Concave mirror	Convex mirror

Refraction Through Prism

A prism is a transparent optical object with at least two polished plane surfaces inclined towards each other. It is usually made of optical glass and is used to refract (bend) light. In the case of a triangular prism (Fig. 14.6), 60° angle each, the light passing through it does not emerge parallel to its original path but instead changes direction. When an incident ray (PE) strikes the prism at point E, it bends towards the normal N and travels inside the prism as refracted ray (EF). Inside the prism, the ray makes an angle of refraction *r* before reaching the second surface at point F. As it exits the prism, it bends again, forming an emergent ray (FS) at an angle e. The emergent ray (FS) is not parallel to the incident ray (PE) but is instead deviated by an angle D, known as the angle of deviation. This bending effect of light through a prism is widely used in optical instruments, spectrometry, and light dispersion experiments.

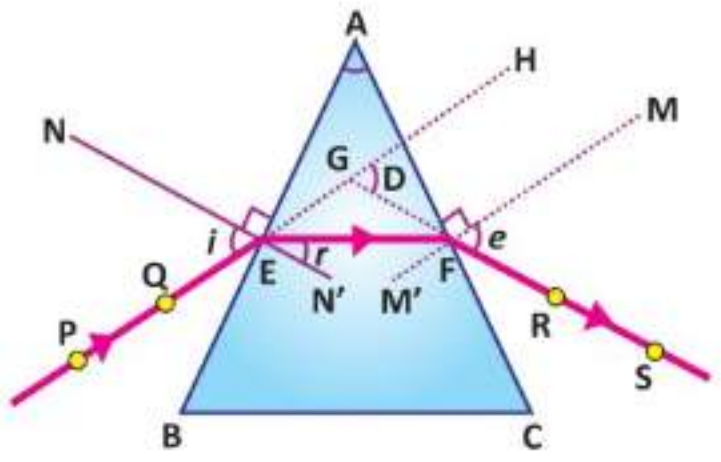


Fig. 14.6: Refraction through a triangular glass prism

Total Internal Reflection

When a light ray is incident at a boundary between two different media, it splits into two parts: one part reflects back into the original medium (reflected ray), and the other part passes into the second medium (transmitted or refracted ray), as shown in Fig. 14.7(a).

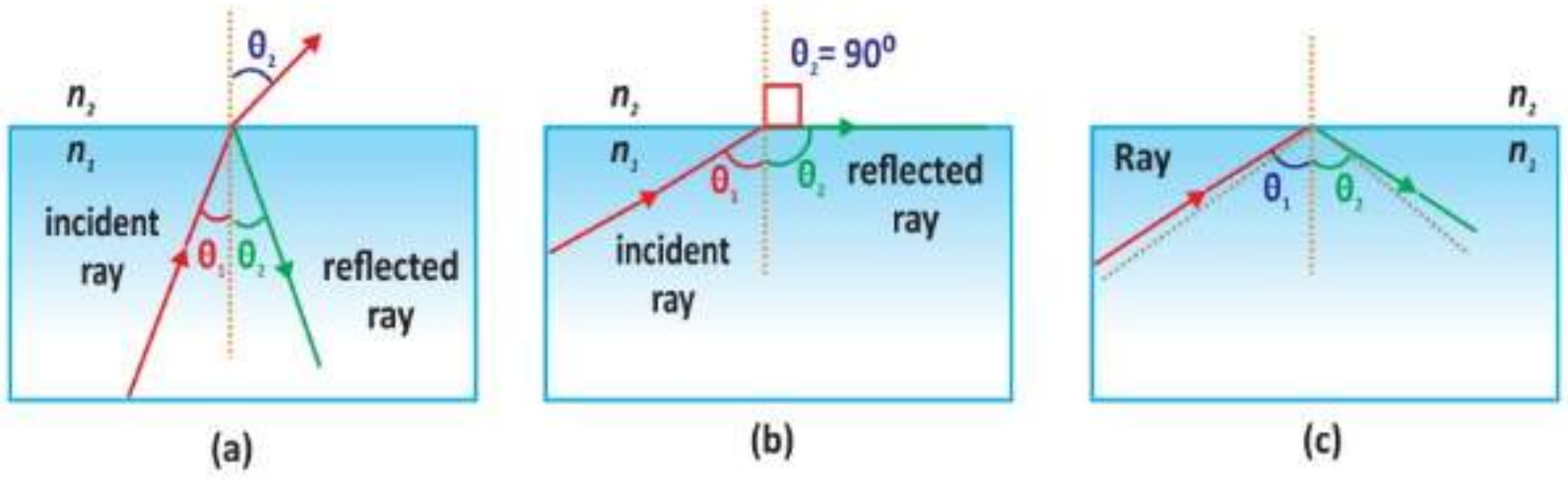


Fig. 14.7: Total internal reflection

If the angle of incidence increases then refraction angle also increases. The more the angle of incidence increases, the greater the angle of refraction becomes. At a particular angle, the refracted ray no longer enters the second medium but travels along the boundary. This angle is called the critical angle (Fig. 14.7-b), and is defined as:

The angle of incidence for which the angle of refraction is 90° is called the critical angle.

Now, if the angle of incidence is increased beyond the critical angle, the light ray does not refract at all. Instead, it reflects entirely back into the same medium. This phenomenon is called total internal reflection, as shown in Fig. 14.7(c).

Total internal reflection is the phenomenon of reflection of light ray back to the same medium when passing from denser medium to rarer medium in such a way that angle of incidence is greater than its critical angle.

The values of the refractive index, speed of light, and critical angle for different media are given in Table 14.1.

Table 14.1: Refractive index, speed of light, and critical angle for different media

Medium	Refractive Index	Speed of Light ($\times 10^8$ m s^{-1})	Critical Angle
Diamond	2.42	1.25	24.4°
Glass (flint)	1.66	1.81	37.0°
Glass (crown)	1.52	2.01	41.2°
Perspex	1.49	2.00	42.0°
Water	1.33	2.25	48.8°
Ice	1.31	2.30	49.8°
Air	1.00	2.99	88.6°
Vacuum	1.00	3.00	90.0°

Derivation of the formula for Total Internal Reflection

To derive a formula for total internal reflection, we start with Snell's law:

$$n_1 \sin i = n_2 \sin r \quad \ldots\ldots\ldots\ldots (14.4)$$

When total internal reflection occurs, the refracted angle becomes 90°. So, the equation becomes:

$$n_1 \sin i = n_2, \text{ because } \sin(90°) = 1$$

Now, if '*i*' is the critical angle *C*, the formula becomes:

$$\sin C = n_2 / n_1 \quad \text{..... (14.5)}$$

To find the critical angle C, we rearrange it as:

$$C = \sin^{-1}(n_2 / n_1) \text{ ..... (14.6)}$$

This only works when $n_1 > n_2$, meaning the light must travel from a denser medium to a rarer medium. If the second medium is air (where $n_2 = 1$), the equation becomes:

$$\sin C = 1 / n$$

From the above equation, the refractive index of the first material (denser medium) can be found as:

$$n = 1 / \sin C \quad \text{..... (14.7)}$$

This relation only holds true if the light is moving from a denser medium with refractive index *n* into air.

Experiment to Study Refraction

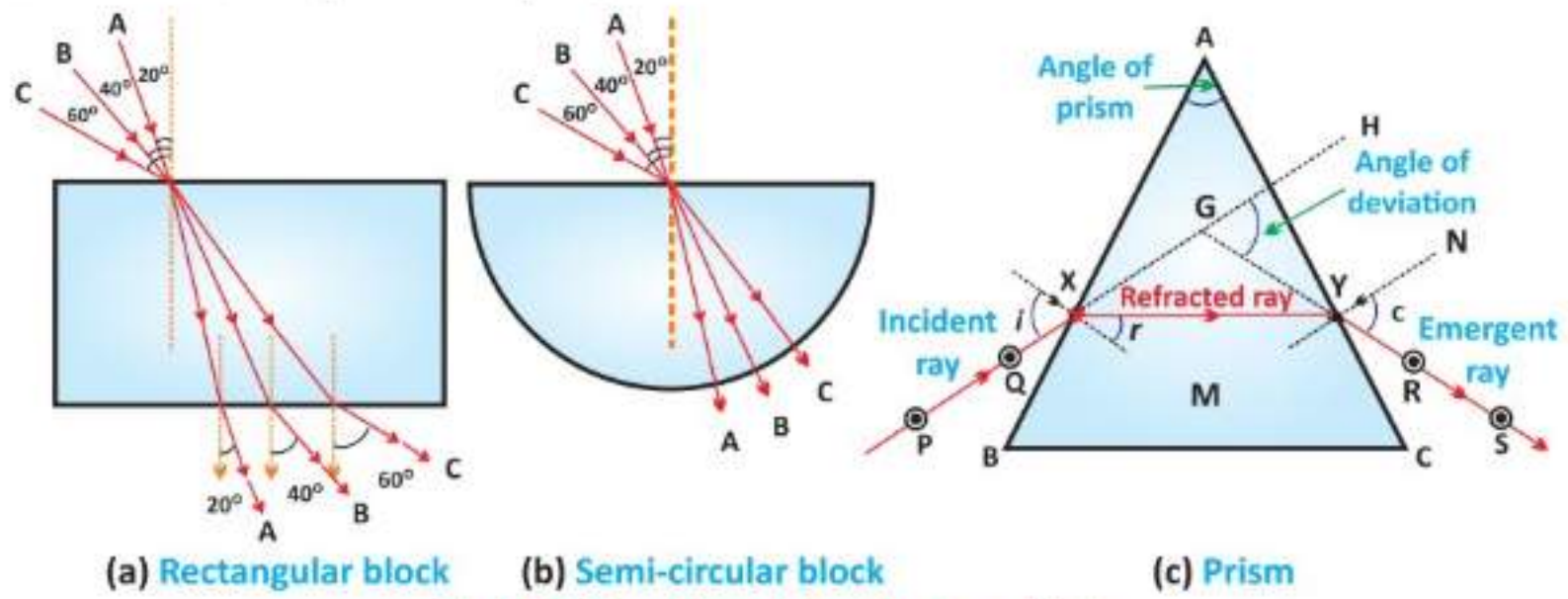
To understand how light bends (refracts) when it passes through different transparent materials, we can perform a simple experiment using blocks of different shapes right in our classroom or school laboratory (Fig. 14.8).

Aim of the Experiment

To observe how light refracts (bends) when it passes through a rectangular block, semi-circular block, and glass prism.

Materials Needed

Laser light, protractor, paper sheet, pencil, ruler, and Perspex blocks (rectangular, semi-circular, and prism-shaped).



(a) Rectangular block (b) Semi-circular block (c) Prism

Fig.14.8: Experiment for refraction of light

Method of Experiment

Place the rectangular glass block on a sheet of paper and observe its result.

- Draw a straight line at one edge where the light will enter.
- Draw a normal (a straight perpendicular line) at the point where light will hit the block.
- Shine the laser light at an angle on the block along the drawn line.

Tidbit

Diamonds sparkle because they have a very high refractive index, causing multiple total internal reflections inside.

Experiment to study Total Internal Reflection

Aim of the Experiment

To study how total internal reflection of light occurs using a semi-circular glass block (Fig. 14.9).

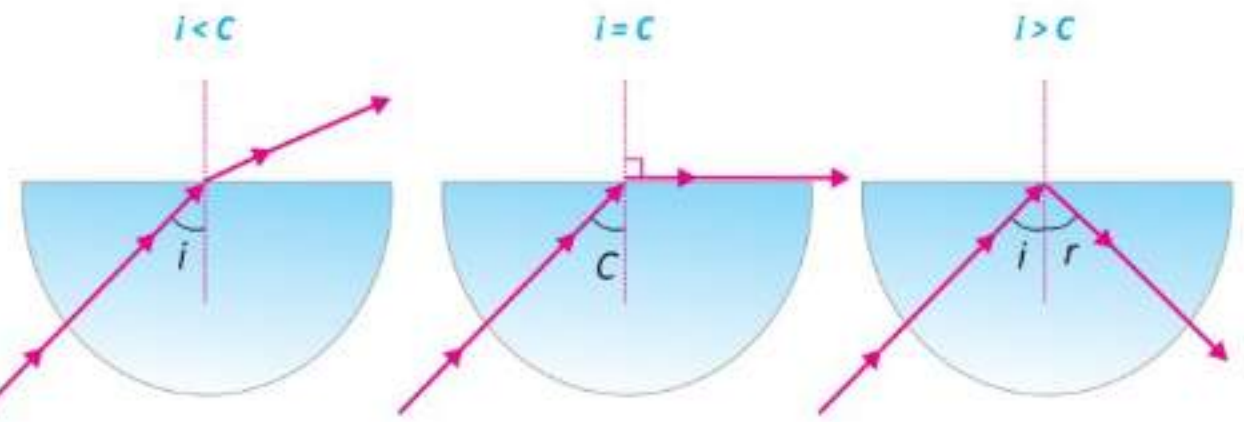
Materials Needed

Light ray, protractor, paper, pencil, ruler, and a semi-circular Perspex (glass) block.

Brain Teaser

Place a pencil in a glass of water, it appears bent. What does this tell about the speed of light in water compared to air?

Figure 14.9 (a) demonstrates the refraction, while Fig. 14.9 (b) and Fig. 14.9 (c) illustrate the critical angle and total internal reflection respectively.



(a) Refraction (b) The critical angle (c) Total internal reflection

Fig. 14.9: Experiment for total internal reflection

Example 14.3: Find the value of critical angle for water (refracted angle = 90°). The refractive index of water is 1.33 and that of air is 1.

Solution:

Using Snell's law:

$$n_1 \sin i = n_2 \sin r$$

For the critical angle, the refracted angle $r = 90°$ and $i = C$, so $\sin(90°) = 1$

$$n \sin C = 1$$

Rearranging for C:

$$C = \sin^{-1}(1 / n)$$

Substituting the values

$$C = \sin^{-1}(1 / 1.33)$$

$$C = \sin^{-1}(0.752)$$

$$C = 48.8°$$

The critical angle for water is 48.8°.

14.3 Optical Fibre

Optical fibres use the principle of Total Internal Reflection (TIR) to transmit light efficiently over long distances. These fibres are widely used in the telecommunication industry due to their high speed and reliability.

An optical fibre consists of thin, hair-like strands made of glass or plastic (Fig. 14.10). It has two main parts: the **core** and the **cladding**. The core is the inner part that carries the light and is made of a material with a higher refractive index. Surrounding the core is the cladding, which has a lower refractive index and helps in total internal reflection. When light enters one end of the core, it hits the core-cladding boundary at an angle greater than the critical angle, causing it to reflect back into the core (Fig. 14.11). This repeated reflection allows light to travel long distances with minimal energy loss.

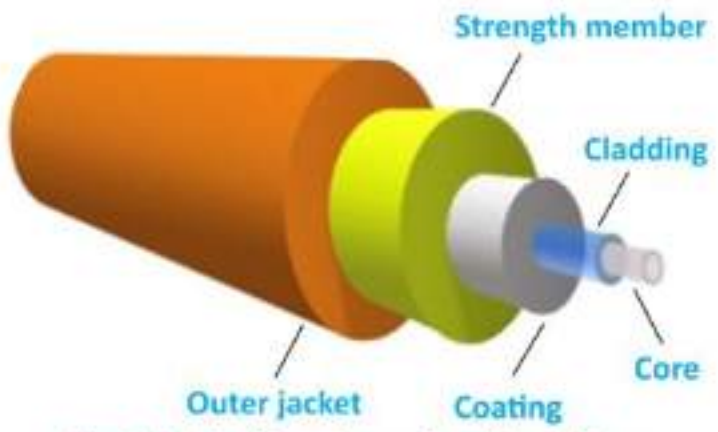


Fig. 14.10: Structure of optical fibre

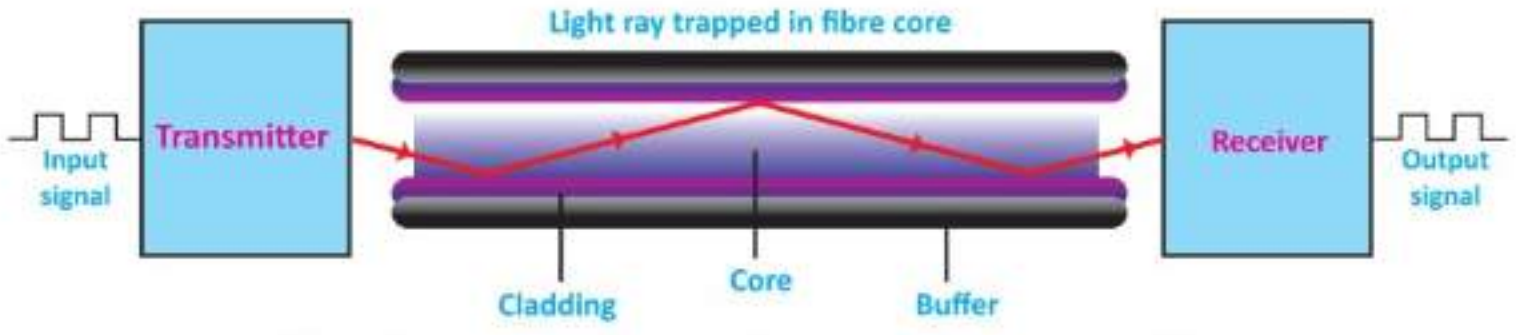


Fig. 14.11: Transmission of information through optical fibre

Advantages of Optical Fibres

Optical fibres are used in many areas of life, but their most common use is in modern telecommunications. Compared to traditional copper cables, optical fibres offer several key benefits:

High Bandwidth

Optical fibres can carry a much larger amount of data than copper wires. Bandwidth means how much data can be sent over a network per second. In today's world, where we need fast internet, optical fibres are the best choice because they support high-speed data transfer.

Low Power Consumption

They use less power than copper cables. Also, because they last longer and are more durable, they reduce the cost of repairs and maintenance.

Faster Speed

They send data using light pulses, which travel extremely fast almost at the speed of light. This allows data to move quickly from one place to another, faster than electrical signals in copper wires.

Long Distance Transmission

Optical fibres can carry data across very long distances without losing signal quality. This makes them ideal for use in undersea cables and connections between continents.

Resistance to Electrical Interference

Since optical fibres use light instead of electricity, they are not affected by electrical noise or interference. This is a big advantage over copper wires, which often face signal problems due to electrical disturbances.

Brain Teaser

Why can we use optical fibres to send data around bends and corners without much loss?

For Your Information

What is a Fibre Optic Cable?

Fibre optic cables are composed of very thin strand of extremely pure glass fibres.

- They transmit information using light from lasers of LEDs that is modulated with date or used in some cases as a light source.
- They have several thousand fibres that are insulated from one another by a protective jacket.
- Each fibre also has an internal cladding that bounces light inward to prevent signal loss.

14.4 Thin lenses

A lens is a transparent material with two surfaces, at least one of which is curved. It bends (refracts) light in a way that forms an image of an object. Lenses come in

different types and are widely used in optical devices such as cameras, eyeglasses, microscopes, telescopes, and projectors. They play an important role in correcting vision.

Types of Lenses

Lenses are classified based on how they bend light rays. A convex lens, also known as a converging lens, brings parallel light rays together at a point. It is thicker in the centre and thinner at the edges (Fig. 14.12). On the other hand, a concave lens, also called a diverging lens, causes parallel light rays to spread out. This lens is thinner in the centre and thicker at the edges (Fig. 14.13).

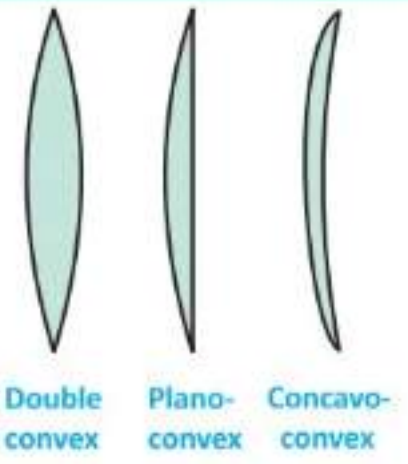


Fig. 14.12: Convex lenses

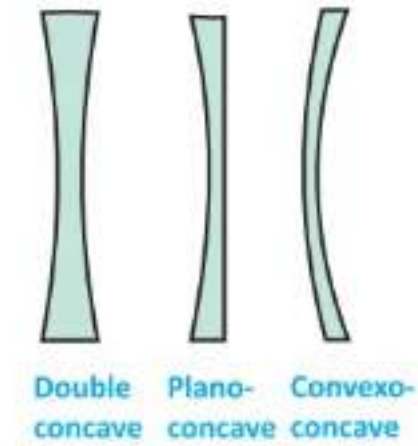


Fig. 14.13: Concave lenses

Important Terms Related to Lenses

To understand how lenses form images, it is important to learn some basic terms as illustrated in Fig. 14.14.

Focal Length

The focal length (*f*) is the distance from the lens (optical centre) to the principal focus, where light rays either meet (converge) or appear to spread out (diverge).

1. In converging lenses, focal length is positive and the rays meet at a point after passing through the lens.

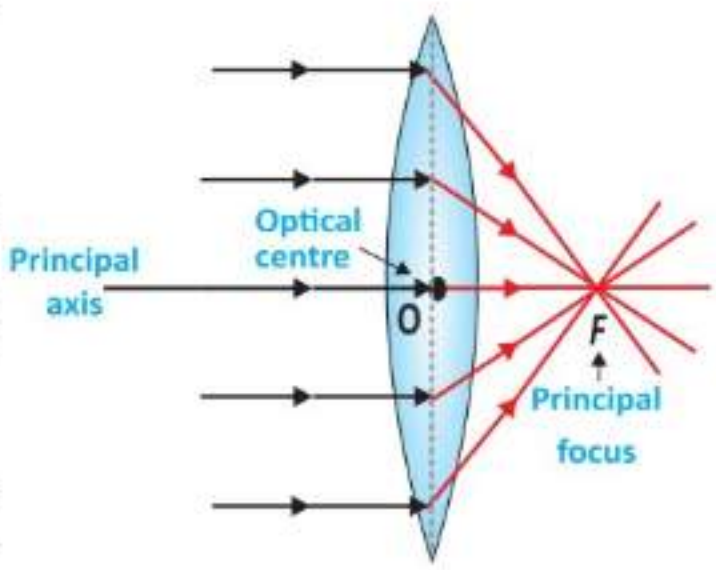


Fig. 14.14: Key terms of a lens

2. In diverging lenses, focal length is negative and rays seem to spread out from a virtual point on the same side of the lens as the light source.

Principal Axis

This is a straight, imaginary line that passes through the centre of the lens. Light rays that travel along the principal axis do not bend or change direction when passing through the lens.

Principal Focus (Focal Point)

The principal focus is the point on principal axis where light rays that are parallel to the principal axis come together (in converging lenses) or appear to come from (in diverging lenses).

1. For a converging lens, the focus is on the opposite side of the incoming rays.

2. For a diverging lens, the focus is on the same side as the incoming rays and appears to be behind the lens.

Optical Centre

The optical centre is the geometrical middle point of the lens through which the principal axis passes. Light passing through this point does not bend. It is usually marked as O.

Centre of Curvature

Lenses are made from parts of a sphere. The centre of this imaginary sphere is called the center of curvature. It is generally located at twice the focal length from the lens.

Lens and Mirror Formula

The relationship between the focal length f, object distance p, and image distance q for both lenses and mirrors is expressed by the lens/mirror formula as:

$$\frac{1}{f} = \frac{1}{p} + \frac{1}{q} \quad \text{..... (14.8)}$$

This fundamental equation helps determine the position and nature of the image formed by a given optical system.

Action of Lenses on Parallel Rays

When a set of parallel light rays pass through a lens, they refract and show specific patterns based on the lens type. Depending on how they interact with the rays, lenses are grouped into converging and diverging lenses.

Refraction and Convergence for Convex lens

As the rays enter the lens, they bend towards the principal axis due to refraction. This bending takes place because of the lens's curved surfaces and its refractive index. After passing through the lens, all the rays meet at a common point on the principal axis this is known as the focal point.

Formation of Image

The type of image formed depends on the object's distance from the lens. Generally, a converging lens forms a real and inverted image, but if the object is very close to the lens, the image can be virtual and upright.

The ray behaviour for a converging lens is shown in Fig. 14.15.

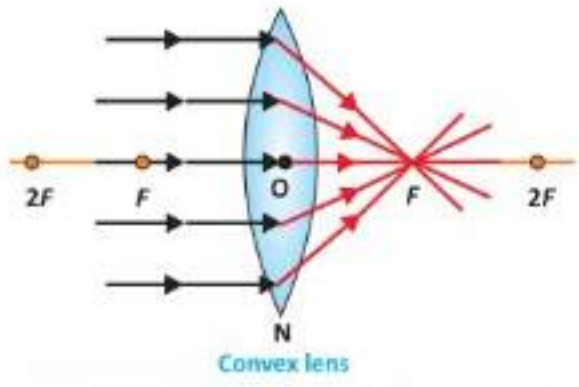


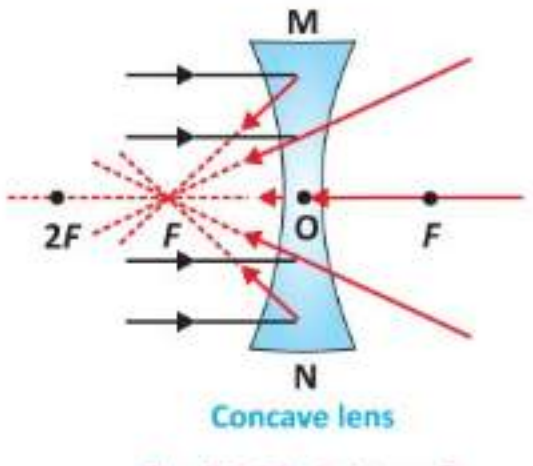
Fig. 14.15: Action of convex lens on parallel rays

Refraction and Divergence of Concave Lens

The rays are bent away from the principal axis. This bending gives the illusion that they originate from a point behind the lens, the virtual focus. This is a result of refraction through the curved surface of the lens.

Virtual Focal Point

In a diverging lens, the rays do not actually meet at a point. Instead, when extended backward, they appear to spread out from a common point on the same side of the lens. This is called a virtual focal point.



Concave lens

Fig. 14.16: Action of concave lens on parallel rays

Formation of Image

When an object is placed far from a diverging lens (at infinity), the image formed is virtual, upright, and smaller than the actual object.

This behaviour of diverging lenses is illustrated in Fig. 14.16.

Power of a Lens

The reciprocal of focal length (f) is called power of a lens.

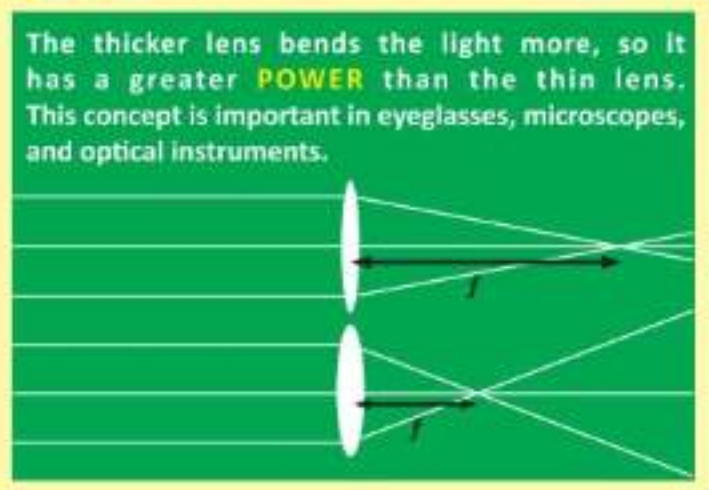
It is given by the formula:

$$P = 1 / f \quad \text{..... (14.9)}$$

The SI unit of power is diopter (D), where $1D = 1\ m^{-1}$. A convex lens has a positive focal length, so its power is positive.

A concave lens has a negative focal length, so its power is negative. Lenses with higher power bend light more strongly, and this concept is important in eyeglasses, microscopes, and optical instruments.

Do You Know?



Example 14.4: A concave lens has a focal length of -25 cm. Find its power.

Solution:

Given that;

$f = -25\ cm = -0.25\ m$

To find; $P = ?$

Using the formula:

$P = 1 / f$

$P = 1 / (-0.25\ m)$

$P = -4.0\ D$

Image Formation by Thin Lenses

Unlike mirrors, which form images through reflection, lenses create images through refraction. This process can be understood using ray diagrams.

Rules for Image Formation

For a convex lens, image formation follows three rules (Fig. 14.17).

1. A ray parallel to the principal axis passes through the focal point *F* after refraction from the lens (ray-1).

2. A ray passing through the optical centre of the lens continues straight without bending (ray -2).

3. A ray passing through the focal point after refraction from the lens, becomes parallel to the principal axis (ray-3).

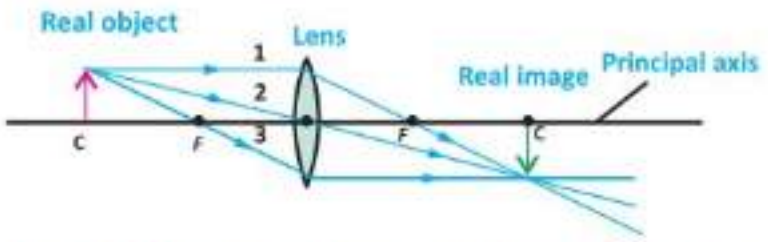


Fig. 14.17: Image formation by a convex lens

By tracing these rays, we can determine where and how an image is formed. The position, size, and nature of the image depend on where the object is placed in relation to the lens. These principles are important in devices like cameras, magnifying glasses, microscopes, and eyeglasses. The image formation by a convex lens for different positions is described in Table 14.2.

Tidbit

A convex lens can flip our image upside down, but when it is close to our eye (like in a magnifier), it stays upright and larger.

Table 14.2: Image formation by a convex lens

Position of the Object	Position of the Image	Size of the Image	Nature of the Image
At infinity	At ***F***	Highly diminished	Real and inverted
Behind **2*F***	Between ***F*** and **2*F***	diminished	Real and inverted
At **2*F***	At **2*F***	Same as that of the object	Real and inverted
Between ***F*** and **2*F***	Beyond **2*F***	Enlarged	Real and inverted
At ***F***	At infinity	Highly enlarged	Real and inverted
Between lens and ***F***	Same side as the object	Enlarged	Virtual and erect

Formation of Real Image by a Converging Lens

A convex lens produces a real image when the object is placed beyond *2F*. As illustrated in Fig. 14.18, the image appears on the opposite side of the lens from where the object is located.

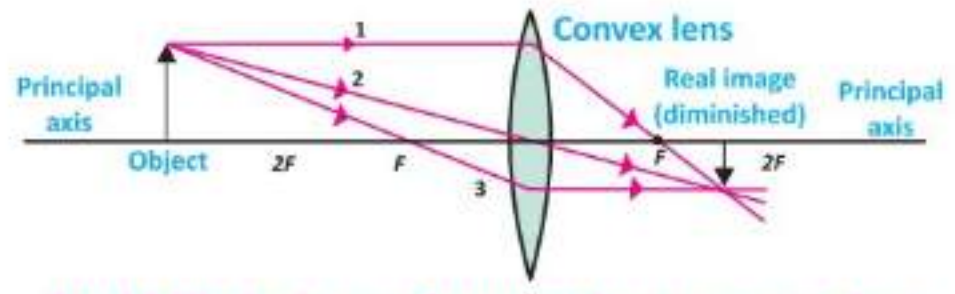


Fig. 14.18: Real image formation by a converging lens

Formation of a Virtual Image by a Converging Lens

For a convex lens to produce a magnified virtual image, the object should be placed within the focal length of the lens as illustrated in Fig. 14.19. In this arrangement, the image appears on the same side of the lens as the object. It is upright, larger in size, and cannot be projected onto a screen, as it is virtual. Such an image is visible only when viewed through the lens. This principle is used in magnifying glasses.

Brain Teaser

Why is the image in a plane mirror considered virtual, even though it looks real?

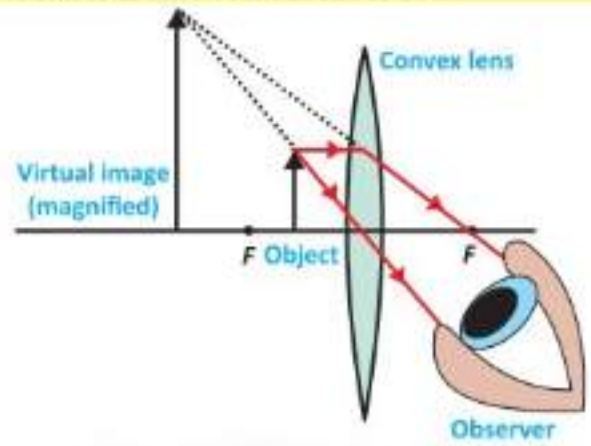


Fig. 14.19: Virtual image formation by a converging lens

Difference between real and virtual images

Real Image	Virtual Image
• Can be displayed or captured on a screen. • Always appears upside down (inverted). • Created when light rays actually meet after reflecting or refracting. • Result of actual light rays intersecting. • Can be displayed on a screen (like a wall or sensor).	• Cannot be projected or caught on a screen. • Always appears upright (erect). • Created when light rays only seem to meet, they do not actually converge. • Formed by the imaginary extension of diverging light rays.

Linear Magnification

Linear magnification is the ratio of the height (or length) of the image to the height (or length) of the object.

It indicates how much larger or smaller the image is compared to the object.

$$\text{Linear magnification} = \frac{\text{Image Height}}{\text{Object Height}}$$

or $$M = h_i / h_o \quad \ldots\ldots\ldots \quad (14.10)$$

Steps to Calculate Linear Magnification

1. Measure the height of the object h_o.
2. Measure the height of the image h_i.
3. Use the formula; $M = h_i / h_o$

Do You Know?

Facts About Magnifying Glass

Did you know that if your eyes can only focus to within about 15 cm in front of them? Anything closer will be blurry. If your eyes could focus you would not need magnifiers!

Example 14.5: An object 8 cm tall is placed in front of a concave mirror. The linear magnification is –2. Find the height of the image.

Solution:

Given that; $h_o = 8$ cm ; $M = -2$

To find; $h_i = ?$

Using the formula: $M = h_i / h_o$ or $h_i = M \times h_o$

$h_i = -2 \times 8 \text{ cm} = -16 \text{ cm}$

The negative sign shows that the image is inverted and twice the size of the object.

14.5 Optical devices

Now we discuss applications of lenses in some optical devices such as magnifying glass, camera, slide projector and photograph enlarger.

1. The Magnifying Glass

A magnifying glass is a convex (converging) lens used to make objects appear larger. When an object is placed closer to the lens than its focal length ($p < f$), the refracted light rays do not meet but appear to come from a point behind the lens. This creates a virtual, upright, and magnified image, which cannot be projected on a screen (Fig. 14.20). This simple use of a convex lens is also known as a simple microscope.

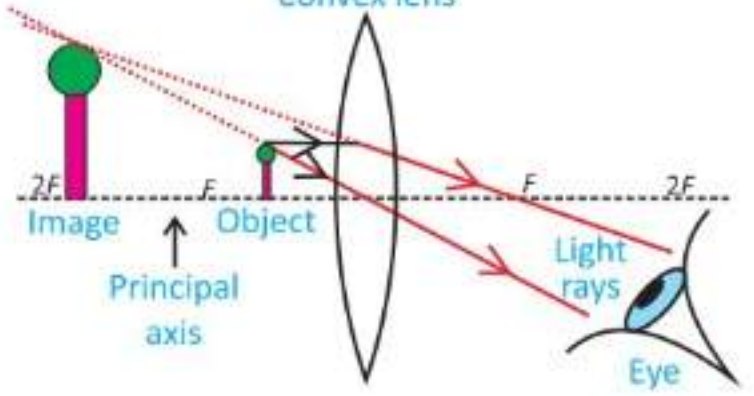


Fig. 14.20: Image formation by magnifying glass

2. Camera

A camera consists of a light-proof box with a convex lens at the front and a light-sensitive film or sensor at the back. The lens focuses light onto the film to capture an image. In a simple camera, the lens-film distance is fixed and equal to the focal length of the lens. The object is placed beyond $2F$, forming a real, inverted, and smaller (diminished) image on the film (Fig. 14.21).

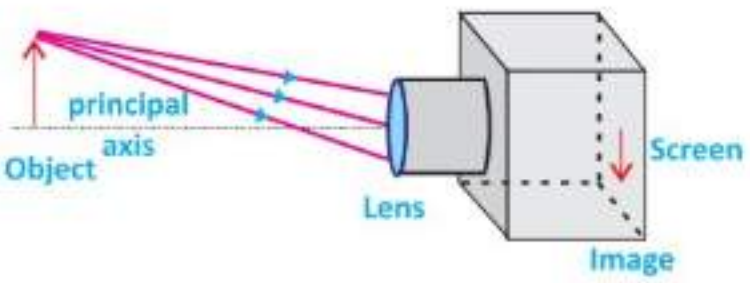


Fig. 14.21: Image formation by camera

3. Slide Projector

A slide projector works by projecting an enlarged image of a slide or film onto a screen (Fig. 14.22-a). It consists of: A light source at the centre of a concave mirror, which reflects light as parallel rays.

A condenser lens system (two plane convex lenses) that evenly distributes light across the slide. A projection lens (convex lens) that creates a real, large, and inverted image on the screen. To ensure the image appears correctly, the slide must be placed upside down because the projection lens inverts the image. The slide is positioned between *F* and *2F* to form a real, magnified, and inverted image on the screen (Fig.14.22-b).

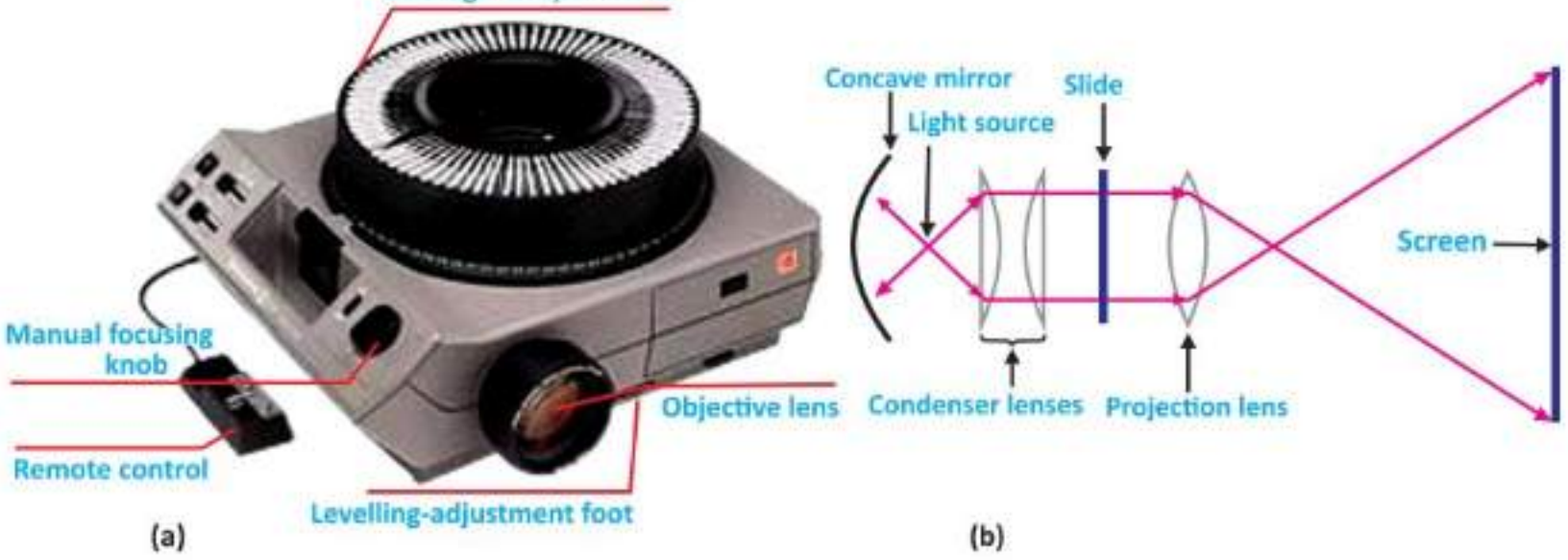


Fig. 14.22: (a) Slide projector (b) Ray diagram of slide projector

4. Photograph Enlarger

A photograph enlarger works similarly to a slide projector but is used to enlarge photographic negatives onto photographic paper (Fig. 14.23). The negative (object) is placed between *F* and *2F*, forming a real, inverted, and enlarged image on the paper. The convex lens ensures that the final image is magnified, allowing small negatives to be printed as large photographs. These optical devices use convex lenses to manipulate light, forming images that are magnified, reduced, or projected for various practical applications.

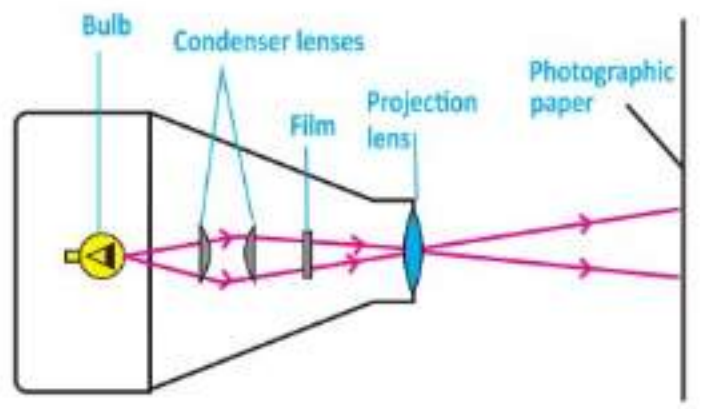


Fig. 14.23: Diagram of photograph enlarger

14.6 Image Formation in a Normal Eye

In a healthy eye, light rays from an object pass through the cornea and lens, and are focused directly onto the retina, forming a sharp and clear image. As shown in Fig. 14.24, rays from

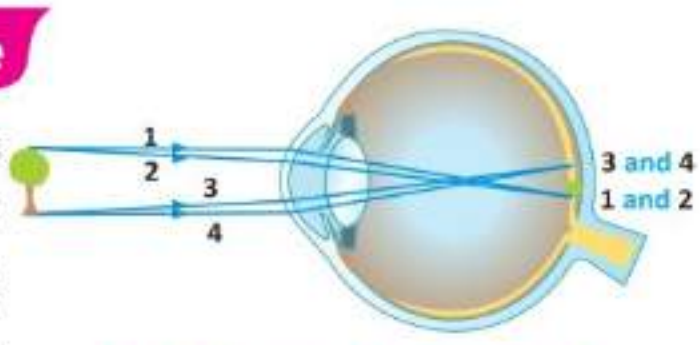


Fig. 14.24: Image formation by eye

the top and bottom of the object converge at specific points on the retina, allowing us to see a clear image. This process is similar to how a convex lens forms a real image.

Short-Sightedness (Myopia) and Its Correction

The closest distance from the eye where we can see things clearly is called near point. For a normal person, it is about 25 cm.

Short-sightedness is a condition where a person can clearly see nearby objects but struggles to see distant ones.

This occurs when the eye lens bends light rays too strongly, causing the image to form in front of the retina instead of on it (Fig. 14.25-a). As a result, distant objects look blurry. To correct this, concave lenses are used in glasses or contact lenses. A concave lens spreads out the light rays before they enter the eye, helping the eye's natural lens to focus them correctly on the retina (Fig. 14.25-b).

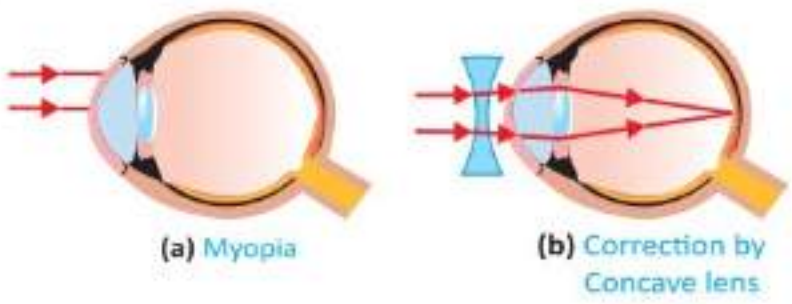


Fig. 14.25: Short-sightedness or myopia

Causes of Short-Sightedness (Myopia)

There are two main causes of short-sightedness:

1. Lens too strong: The eye lens becomes too curved, focusing light in front of the retina.

2. Eyeball too large: The distance between the cornea and retina increases, so the focused image falls short of the retina.

Long-Sightedness (Hypermetropia) and Its Correction

In a normal eye, light rays from nearby objects focus directly on the retina, creating a clear image (Fig. 14.26-a). However, in long-sightedness, a person can see distant objects clearly, but nearby objects appear blurry. This happens when the eye lens is too weak or the eyeball is too small, so the light rays from near objects are not bent enough. As a result, the rays focus behind the retina instead of on it (Fig. 14.26-b).

To correct this, convex lenses are used in glasses or contact lenses. A convex lens

bends the light rays more before they enter the eye, helping them focus directly on the retina (Fig. 14.26-c).

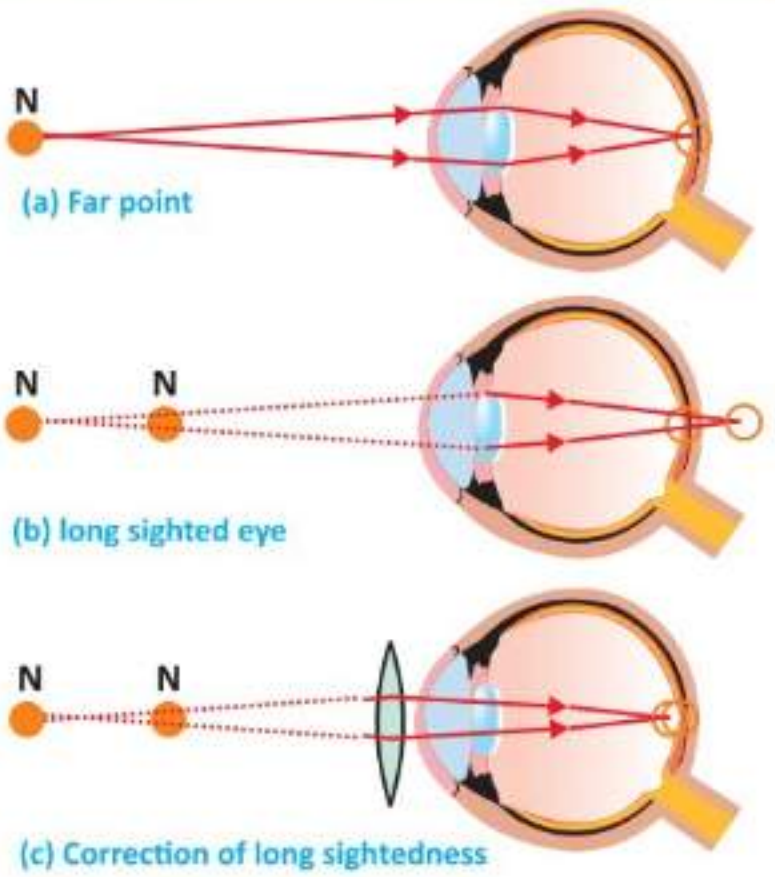


Fig. 14.26: Long-sightedness

Causes of Long-Sightedness

There are two main causes:

1. Lens too weak: The lens does not bend the light rays enough.

2. Eyeball too small: The retina is too close to the lens.

In both cases, the image is formed behind the retina, making close-up vision blurry.

14.7 Gravitational Lens and Acoustic Lens

Gravitational Lensing

Gravitational lensing occurs when the strong gravitational field of a massive object, like a black hole or galaxy, bends the path of light travelling near it. Just like an optical lens bends and focuses light, a massive celestial body acts as a "gravitational lens", altering the path of light from a distant object such as a star or galaxy. This effect can cause the distant object to appear magnified, distorted, or even duplicated, creating multiple images (Fig. 14.27). Gravitational lensing is a valuable tool in astronomy. It helps scientists study distant galaxies, dark matter, and the structure of the universe, providing insights into objects that are otherwise too far to observe directly.

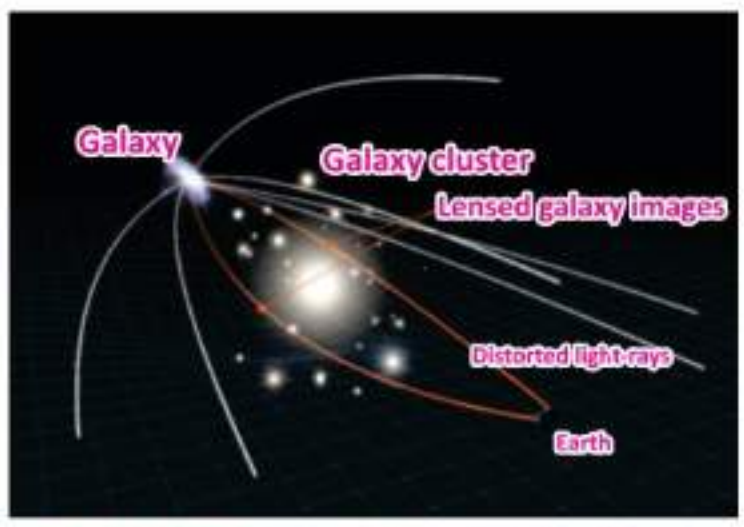


Fig.14.27: Diagram of gravitational lens

Acoustic Lenses

Acoustic lenses are special devices designed to focus or spread sound waves, similar to how optical lenses control light. These lenses are made from materials

with different acoustic properties and are shaped to redirect and focus sound waves. They can concentrate sound into a narrow beam or spread it over a wider area, improving sound clarity and control (Fig. 14.28). These lenses can focus sound to a specific point (like a microphone or sensor), or diverge sound to spread it over a wider area.

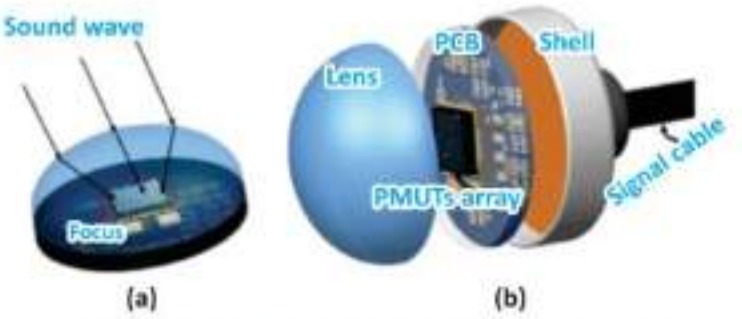


Fig. 14.28: Diagram of acoustic lens

Acoustic lenses are widely used in:

1. Medical imaging (e.g., ultrasound) to improve scanning accuracy.

2. SONAR systems to detect underwater objects.

3. Noise control to focus or reduce sound in specific areas.

Both gravitational and acoustic lenses demonstrate how the principles of wave manipulation apply to both light and sound, playing an important role in astronomy, medicine, and technology.

14.8 Dispersion of Light by Prism

A prism is an optical object typically made of glass with triangular and rectangular sides. It bends light passing through it due to refraction. Since visible light consists of a range of wavelengths, and refraction depends on wavelength, different wavelengths bend at different angles, causing dispersion.

The splitting of white light into its seven constituent colours when passing through a prism is called dispersion of light.

When white light enters a prism, it slows down and bends toward the normal. Each colour has a unique wavelength, and as light travels through the prism, each wavelength refracts at a different angle. Shorter wavelengths (violet, blue) bend more than longer wavelengths (red, orange). As a result, the light exiting the prism separates into seven distinct colours red, orange, yellow, green, blue, indigo, and violet forming the visible light spectrum (Fig. 14.29).

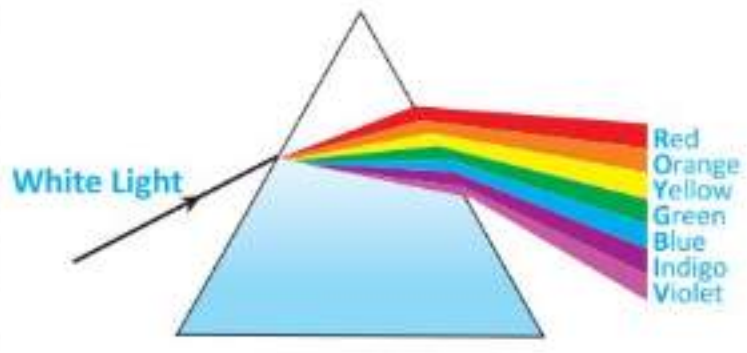


Fig. 14. 29: Dispersion of light by prism

Beyond the visible spectrum, prisms can also

disperse infrared (IR) and ultraviolet (UV) light, though these wavelengths are invisible to the human eye. Special detection methods, such as infrared thermometers with sensors, are used to measure these wavelengths.

Infrared Thermometers

These devices detect IR radiation emitted by objects, which correlates with their temperature. When dispersed light from a prism reaches an IR thermometer, it can measure both visible and infrared light. By analyzing the intensity of IR radiation, the thermometer determines the temperature of the emitting object. This technology allows for non-contact temperature measurement, such as checking human body temperature (Fig. 14.30).

Fig. 14. 30: Infrared thermometer

EXERCISE

A. Multiple Choice Questions

Tick (✓) the correct answer.

14.1 What type of image is always formed by a convex mirror?
(a) Real and inverted (b) Virtual and diminished
(c) Real and magnified (d) Virtual and magnified

14.2 The optical device which uses a convex lens to magnify an object by creating a virtual image:
(a) camera (b) microscope
(c) magnifying glass (d) slide projector

14.3 Which statement best describes the phenomenon of total internal reflection?
(a) Light bends when it enters a new medium
(b) Light is completely reflected at the boundary of two media
(c) Light slows down as it enters a denser medium
(d) Light passes through a medium without changing direction

14.4 A ray of light travelling from water to air bends:
(a) toward the normal
(b) away from the normal
(c) at 90° to the normal
(d) parallel to the normal

14.5 The optical device which works on the principle of inverting an image for projection is:
(a) magnifying glass (b) photograph Enlarger
(c) slide projector (d) plane mirror

14.6 What happens to light when it enters an optical fibre?
(a) It is absorbed by the fibre
(b) It undergoes total internal reflection
(c) It gets refracted at every point
(d) It travels in a straight line without deviation

14.7 Which of the following phenomenom explains why a pencil appears bent when partially immersed in water?
(a) Reflection (b) Diffraction (c) Refraction (d) Interference

B. Short Answer Questions

14.1 What happens when light passes from air to water?
14.2 Define refractive index. What is the refractive index of air and water?
14.3 What is the principle behind optical fibres?
14.4 Describe briefly how a convex lens forms a real or virtual image.
14.5 How does the power of a lens relate to its focal length?
14.6 Write Snell's law and define the terms used in the equation.

C. Constructed Response Questions

14.1 When a pencil is partially dipped in water, it appears bent or broken. What principle of light explains this phenomenon, and how does it relate to changes in speed?
14.2 Why can a prism separate white light into its component colours while a plane glass slab cannot, even though both cause refraction?
14.3 Why does light undergo total internal reflection when travelling from water to air at a certain angle but not the other way around?
14.4 Optical fibres use total internal reflection for signal transmission. What would happen if the cladding had a higher refractive index than the core, and why?
14.5 A person uses a magnifying glass to read small print. What must be the relationship between the object distance and the focal length of the lens for the image to be upright and magnified?

D. Comprehensive Questions

14.1 Explain the terms; normal, angle of incidence and angle of reflection in the context of light reflection. Provide a diagram to illustrate these terms.

14.2 Define the terms critical angle and total internal reflection. Explain the conditions required for total internal reflection to occur.

14.3 Derive the equation; ($n = 1 / \sin C$) for the refractive index in terms of the critical angle C. Include all steps and assumptions.

14.4 Describe the structure of an optical fibre. Write its any two advantages.

14.5 What is long-sightedness? Discuss its causes.

E. Numerical Problems

14.1 The speed of light in water is 2.25×10^8 m $s.^{-1}$ Calculate the refractive index of water. **[Ans: 1.33]**

14.2 A light ray in air (n_1=1.0) strikes a glass surface (n_2=1.5) at an angle of incidence 30°. Find the angle of refraction inside the glass. **[Ans: 19.5°]**

14.3 A beam of light in air hits a glass slab at an incidence angle of 40°.Find the angle of refraction inside the glass. **[Ans: 25°]**

14.4 A ray of light travels from air into an unknown liquid. The angle of incidence in air is 45°, and the angle of refraction in the liquid is 30°.Calculate the refractive index of the liquid. **[Ans: 1.41]**

14.5 A ray of light passes from air into a liquid. The angle of incidence in air is 50°, and the angle of refraction inside the liquid is 32°.The speed of sound in air is 340 m s^{-1} and in the same liquid is 1500 m s^{-1}.Calculate:(a) the refractive index of the liquid(b) the speed of light in the liquid.
[Ans: (a) 1.45,(b) 2.08×10^8 m s^{-1}]

14.6 Light travels inside a glass block of refractive index n = 1.6. It strikes the glass–air boundary. Calculate the critical angle for total internal reflection.
[Ans: 38.68°]

14.7 An object is placed 15.0 cm in front of a convex mirror, forming a virtual image 7.5 cm behind the mirror. What is the focal length of the mirror?
[Ans: -15 cm]

14.8 An object 30 cm tall is located 10.5 cm from a concave mirror with focal length 16 cm. (a) Where is the image located? (b) How high is it?
[Ans: (a) -30.6 cm (b) 87.3 cm]

14.9 An object is placed at 30 cm to the left of a concave lens with focal length -15 cm. Find the image distance and describe the image.
[Ans: -30 cm, image is virtual and upright formed on the same side of the object]

CHAPTER 15

ELECTROSTATICS

Student's learning outcomes (SLOs)

After studying this chapter, students will be able to:

- state that there are positive and negative charges [and charge is measured in coulombs].
- state that unlike charges attract and like charges repel.
- describe experiments to show electrostatic charging by friction.
- explain that charging of solids by friction involves only a transfer of negative charge (electrons).
- explain how a conductor can be charged by electrostatic induction and then "earthing."
- suggest how charging and discharging is used in the application of various devices (e.g., photocopier and electrostatic precipitator).
- describe an electric field as a region in which an electric charge experiences a force.
- state that the direction of an electric field line at a point is the direction of the force on a positive charge at that point.
- discuss and illustrate simple electric field patterns (including the direction of the field):
  - (a) around a point charge
  - (b) around a charged conducting sphere
  - (c) between two oppositely charged parallel conducting plates (end effects will not be examined).
- state examples of electrical conductors and insulators.
- describe an experiment to distinguish between electrical conductors and insulators.

- state and use a simple electron model to explain the difference between electrical conductors and insulators.
- explain how a lightning rod can protect humans.
- explain electrical breakdown (it occurs when a strong electric field passes through a gas and causes its atoms to ionize).
- state that corona discharge and Lichtenberg figures are visible examples of electrical breakdown.

Electrostatics is a branch of physics which deals with the study of charges at rest. It focuses on understanding the interaction between charges and electric field they create. Electrostatics plays an important role in everyday life. In this chapter, we will cover topics such as electric charge and its properties, electrostatic induction, applications of electrostatics, Coulomb's law and electric field. In addition to this, we will also learn about the practical applications and safety precautions related to the electrostatics.

15.1 Electric Charge

When a plastic comb (or rod) is rubbed through dry hair and is brought near small pieces of paper, it attracts them (Fig. 15.1). Similarly, amber rod when rubbed with silk attracts small pieces of paper. We often experience a shock when we touch a metal doorknob, after sliding across a car seat or walking on a synthetic carpet. In each of these cases, the electrostatic force, resulting from electric charges, is in action. This phenomenon of attraction or repulsion between objects is due to a property called electric charge. We have already learnt that an object's mass is an inherent property. Objects with smaller mass have less inertia than those with larger mass. Similarly, another intrinsic property of an object is its electrical charge. There are two types of electric charges, known as positive and negative, which can be

Fig. 15.1: Comb rubbed with dry hair attracts small pieces of paper

demonstrated through a simple experiment (Fig. 15.2). The SI unit of charge is the coulomb (C).

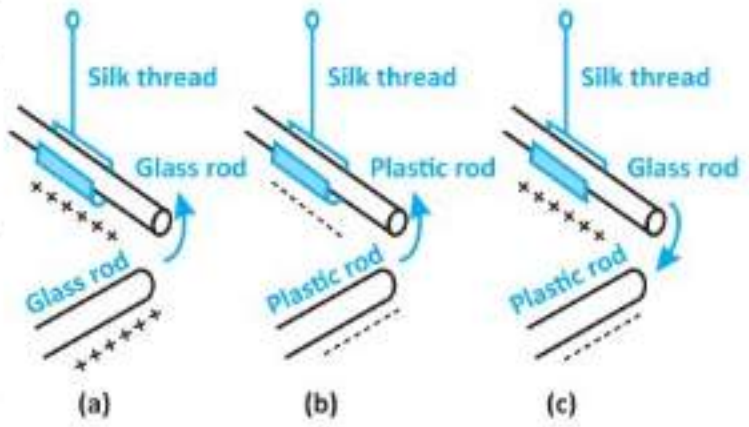


Fig. 15.2: Electrostatic interactions between glass rods and plastic rods after being charged by friction

Figure. 15.2 shows electrostatic interactions between glass and plastic rods after being charged by friction. In the first scenario (a), two glass rods that have been rubbed with silk cloth are brought close to each other. Since both rods acquire a positive charge, they repel each other due to the fundamental principle that like charges repel. In the second scenario (b), two plastic rods, likely rubbed with wool or fur, are placed near each other. Both rods gain a negative charge, leading to repulsion, as similar charges push away from each other. Lastly, in scenario (c), a positively charged glass rod (rubbed with silk) is brought near a negatively charged plastic rod (rubbed with fur or wool). Unlike the previous cases, attraction is observed because opposite charges attract. This set of experiments clearly demonstrates the basic electrostatic rule that like charges repel while opposite charges attract.

Properties of Charges

Matter is composed of atoms, which consist of subatomic particles. Among these, protons are positively charged particles located in the nucleus, while electrons are negatively charged particles that orbit around the nucleus (Fig.15.3). Since everything is composed of atoms, every material carries either a positive charge, a negative charge, or neutral. Charge is an essential property of materials that causes them to either attract or repel . Charge can be transferred between objects through various processes, including rubbing, direct contact, or induction. The total amount of charge in an isolated system remains constant.

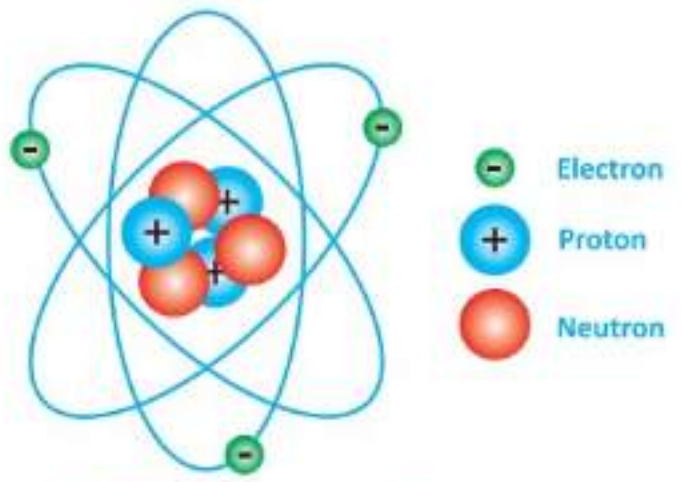


Fig. 15.3: Structure of an atom

15.2 Electrostatic induction

Activity 15.1: When a charged plastic rod is brought near a suspended neutral aluminium rod, both rods are drawn toward each other, as shown in Fig. 15.4. At first glance, this attraction suggests that the rods have opposite charges. However, this is not the case. The charged plastic rod causes a redistribution of positive and negative charges within the neutral aluminium rod, leading to the attraction. Despite this, the total charge on the aluminium rod remains zero. This indicates that attraction alone is not a reliable method to determine if an object is charged. The observed behaviour is an example of a phenomenon known as electrostatic induction.

Do You Know?

When a charged rod is brought near a conductor without touching it, the conductor still gets charged. That is the amazing effect of electrostatic induction.

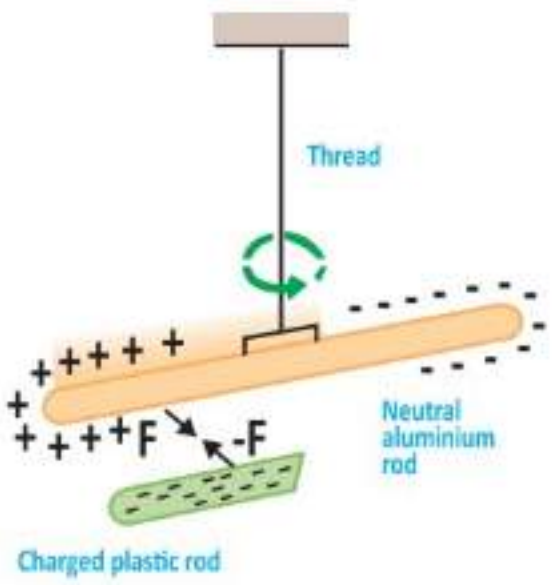


Fig. 15.4: Charged plastic rod attracts neutral aluminium rod

Activity 15.2: Take two metal spheres, A and B, and place them on insulated stands so that they are in contact with each other, as shown in Fig. 15.5(a). Now bring a positively charged rod close to sphere A, as shown in Fig. 15.5(b). The charged rod will attract the negative charges towards it and repel the positive charges away from it. This clearly shows that unlike charges attract each other, while like charges repel each other. As a result, negative charge accumulates on the left surface of sphere A, which is closer to the rod, while positive charge appears on the right surface of sphere B.

Now separate the spheres while keeping the charged rod near sphere A. Upon testing the two spheres, we will find that they are oppositely charged, as shown in Fig. 15.5(c). After removing the rod, the charges are evenly distributed across the surfaces of the spheres, as seen in Fig. 15.5(d). In this process, equal and opposite charges appear on each sphere. This phenomenon is known as charging by induction.

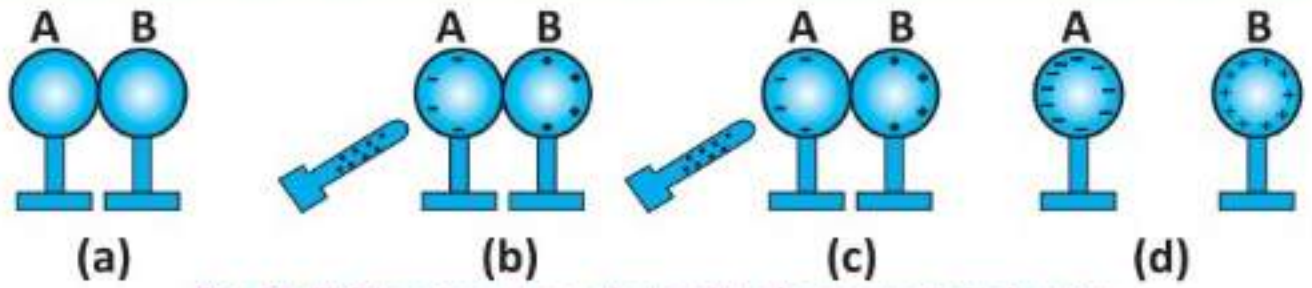


Fig. 15.5: Charging two spheres by electrostatic induction

In the presence of a charged object, an insulated conductor develops a positive charge at one end and a negative charge at the other end. This process is known as electrostatic induction.

Charging by Induction and Earthing

Charging by induction is a method of charging a conductor without directly touching it with a charged object. It involves the redistribution of electric charges within a conductor when exposed to a nearby electric field. Suppose we bring a negatively charged rod near a neutral metal sphere (conductor).The presence of the negatively charged rod causes free electrons in the conductor to move away due to repulsion, leaving the side near the rod positively charged and the far side negatively charged. This separation of charges is called electrostatic induction.

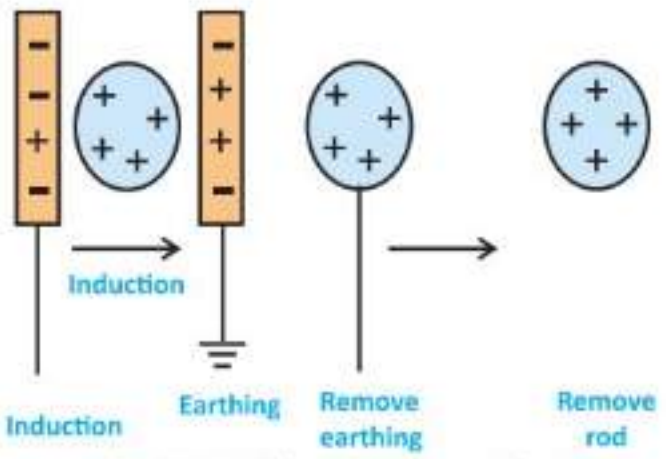


Fig. 15.6: Charging a conductor by induction and earthing

Earthing is the process of connecting a conductor to the Earth using a conducting wire. While the charged rod is still in place, the conductor is connected to the Earth using a wire (Fig. 15.6). Since the far side of the sphere is negatively charged, electrons flow from the sphere to the Earth, neutralizing the negative charge. After the unwanted charges have flowed away, the grounding connection is removed. The excess positive charge remains near the rod because the negative charges have left. Finally, the charged rod is taken away. The conductor now has a net positive charge, even though it was never touched by the rod.

Electroscope

The gold leaf electroscope is a sensitive device which is used to detect electric charges. It consists of a brass rod with a brass disk at the top and two thin gold leaves suspended at the bottom, as shown in Fig. 15.7. The rod passes through an insulating material, which holds it in place. Charges can move freely from the disk to the leaves via rod. Additionally, a thin aluminum foil is attached to the lower part of the inside of the jar. This aluminum foil is typically grounded by

connecting it to a copper wire, which helps in protecting the gold leaves from external electrical interference. To detect the presence of charge on an object, bring the object near the disk of an uncharged electroscope. If the object is neutral, there will be no deflection of the leaves, as shown in Fig. 15.8(a). However, if the object is charged either positively or negatively the leaves of the electroscope will diverge. For example, if the object is negatively charged, electrostatic induction will cause a positive charge to appear on the disk and a negative charge to accumulate on the leaves, as shown in Fig. 15.8(b). Since both leaves carry the same charge, they will repel each other and move apart. The extent of the divergence depends on the amount of charge present on the object. An electroscope can also serve to distinguish between conductors and insulators. To perform this test, bring a charged object near the disk of the electroscope without allowing contact. If the leaves collapse from their previously diverged position, it indicates that the material is a good conductor, as charge can flow.

Brain Teaser

Rub a balloon on your dry hair and then hold it close to a wall. The balloon sticks to the wall. But why does this happen when the wall is not charged?

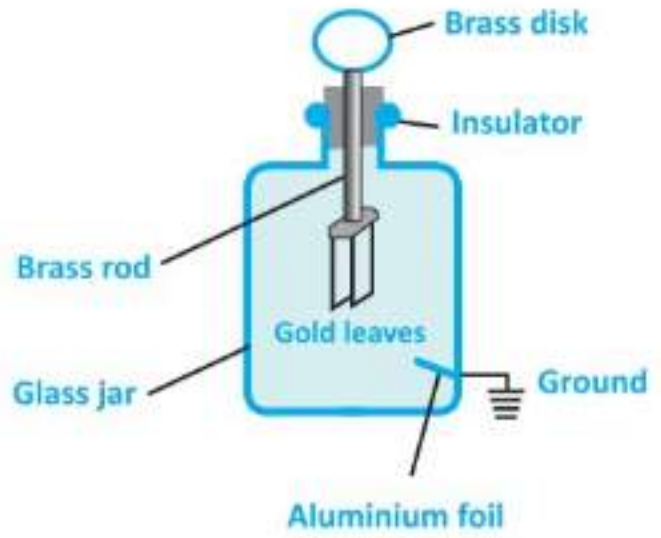


Fig. 15.7: Uncharged electroscope

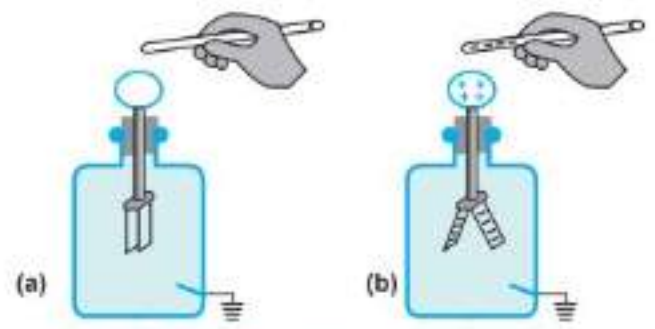


Fig. 15.8: Detecting charge using a gold leaf electroscope

Brain Teaser

Why do the leaves of an electroscope diverge when a charged object is brought near, even if the object does not touch the electroscope?

15.3 Applications of Electrostatics

There are many application of electrostatics with conductors, as shown in Fig 15.9. Charging and discharging are fundamental processes in the operation of various devices, such as photocopiers and electrostatic precipitators, which rely on electrostatic principles.

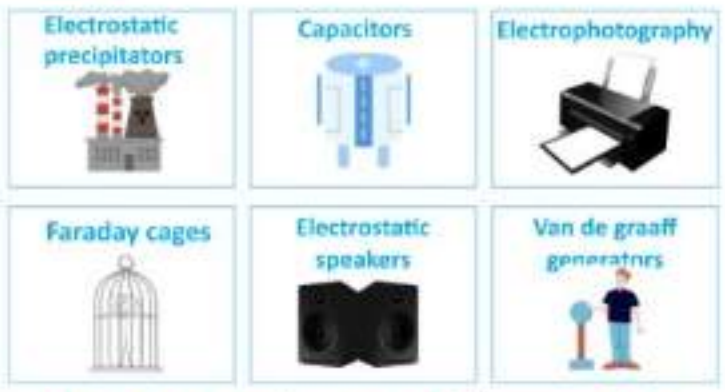


Fig. 15.9: Applications of electrostatics

Photocopier

A photocopier is an electronic machine used to make copies of documents and images. It works on a process called xerography. The xerography is derived from the Greek words "xeros" (dry) and "graphos" (writing), meaning "dry writing."

The central part of the photocopier machine contains a rotating drum which is composed of aluminium and coated with a layer of selenium. Aluminium is a good conductor of electricity, while selenium is a photoconductor, it behaves like an insulator in the dark but conducts electricity when exposed to light.

The process of photocopier begins by applying a positive charge to the drum. In the dark, this charge stays on the surface of the drum because selenium does not allow current to pass. When light falls on the drum, electrons from the aluminium move through the selenium and remove the positive charge from those areas. When the image of the document is projected on the drum, the bright (light) areas lose their charge, and the dark areas remain positively charged. This creates an invisible electrostatic image on the drum. A fine, dry black powder called toner is given a negative charge and spread over the drum. It sticks only to the positively charged image areas. A neutral sheet of paper passes under the drum with a slightly positive roller behind it, which pulls the toner onto the paper. Finally, the paper goes through heated rollers that melt and press the toner into the paper, making the image permanent.

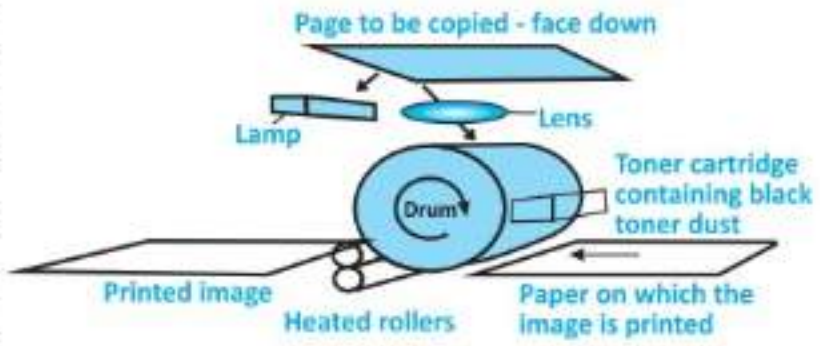


Fig. 15.10: Labelled diagram of a multifunction photocopier machine

Electrostatic Precipitator

An electrostatic precipitator (ESP) is a device used to remove particulate matter from industrial exhaust gases. Charging and discharging are critical to its operation. Corona discharge is an electrical phenomenon where a high-voltage ionizes the air around a conductor (e.g., a thin wire), creating a plasma region that releases electrons. These electrons attach to nearby gas molecules, forming negative ions. The device charges the particles in the gas stream by passing them through a corona discharge, which imparts a negative charge to the particles. These charged particles are then attracted to positively charged collection

plates, where they adhere and are removed from the gas stream. Periodically, the collection plates are discharged to remove the accumulated particles, which fall into a hopper for disposal. This process ensures efficient removal of pollutants from the air, making electrostatic precipitators essential in reducing industrial emissions. Both applications demonstrate how controlled charging and discharging can be harnessed for practical and environmentally beneficial purposes. The diagram of an electrostatic precipitator is shown in Fig. 15.11.

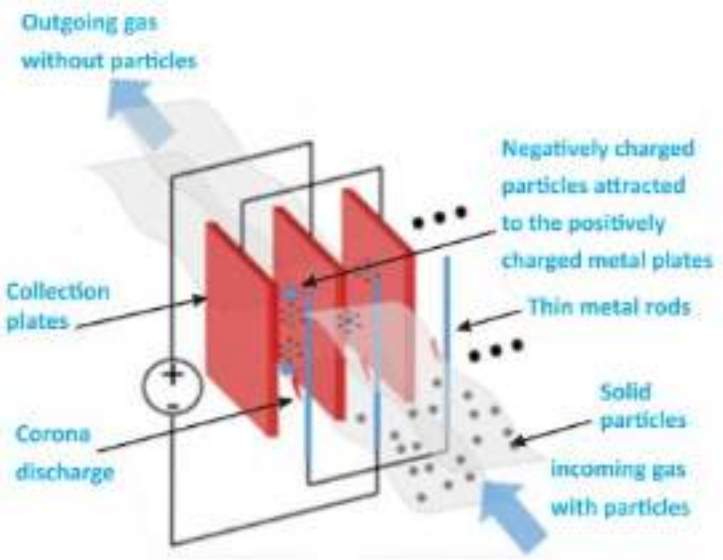


Fig. 15.11: Electrostatic precipitator

15.4 Coulomb's Law

Charges can repel and attract each other with a force called electrostatic force. Charles Coulomb in 1785, provided an experimental law to explain the nature and magnitude of electrostatic force between the charges. Coulomb's law states that;

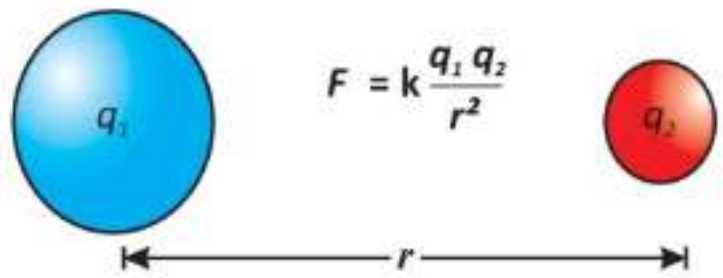


Fig. 15.12: Coulomb's law

The magnitude of the electrostatic force between two point charges is directly proportional to the product of magnitude of these charges and inversely proportional to the square of the distance between them.

Consider two charges q_1 and q_2, seperated by distance r (Fig.15.12).

Mathematically;

$$F \propto q_1 q_2 \quad \ldots\ldots\ldots\ldots \quad (15.1)$$

and $$F \propto \frac{1}{r^2} \quad \ldots\ldots\ldots\ldots \quad (15.2)$$

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

or $$F = k\frac{q_1 q_2}{r^2} \quad \ldots\ldots\ldots\ldots \quad (15.3)$$

where k is a constant of proportionality which quantifies the strength of the electrostatic force between two point charges. The value of k is determined by the medium between the charges. In vacuum or air, k is approximately 9×10^9 N m^2 C^{-2}. Coulomb's law is applicable primarily to point charges whose sizes are negligible compared to the distance separating them.

15.5 Electric Field

One charge exerts a force on another charge. This force is present everywhere around the charge, theoretically extending to infinity. However, the strength of the force decreases with distance.

An electric field is the region around a charge where it exerts a force on other charges.

The electric field strength decreases with distance from the charge, following an inverse square law for point charges.

Mathematically;

$$E = k\frac{q}{r^2} \quad \ldots\ldots\ldots\ldots \quad (15.4)$$

Consider a test charge q_o is brought into the electric field of a source charge Q as shown in Fig. 15.13. The source charge will exert an electrostatic force **F** on the test charge.

The electrostatic force per test charge (unit positive charge) when it is brought to the electric field of a source charge is called electric field intensity.

Do You Know?

Newton Vs. Coulomb

- Similar formulae inverse square laws
- Gravitational forces are only attractive
- Are important when dealing with large masses and distances
- Electrical forces are attractive and repulsive
- Are important when dealing with small masses and distances

Tidbit

If the charges are opposite in sign (one positive and one negative), they will attract each other. If the signs are reversed, making both charges positive or both negative, they will repel each other. The magnitude of the force will remain the same, but the direction of the force will change. This is an example of how Coulomb's law works with both attraction and repulsion.

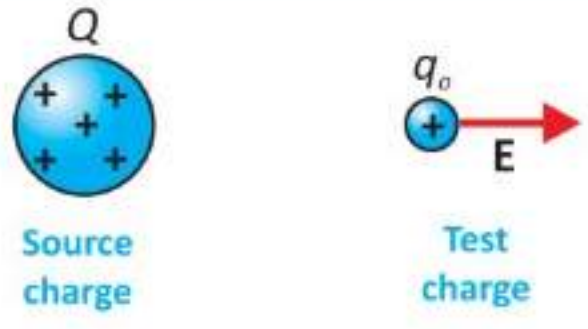


Fig. 15.13: Electric field intensity

Mathematically;

$$\mathbf{E} = \mathbf{F}/\, q_{\circ} \quad \text{.....(15.5)}$$

The SI unit of electric field intensity is newton per coulomb ($N\,C^{-1}$).

Electric field intensity (electric field strength) is a vector quantity having both magnitude and direction. The direction of electric field intensity at a point will be the direction of force on a positive test charge at that point is same as that of electric force.

Do You Know?

Electric Fields

- Electric fields are represented by electric field lines. (Imaginary) and show the direction of the force at that point.
- Electric field direction is from a positive charge to a negative charge.
- Electric field lines (also known as electric flux) do not cross each other.
- Electric field lines represent the path that a small positive test charge would follow in an electric field.

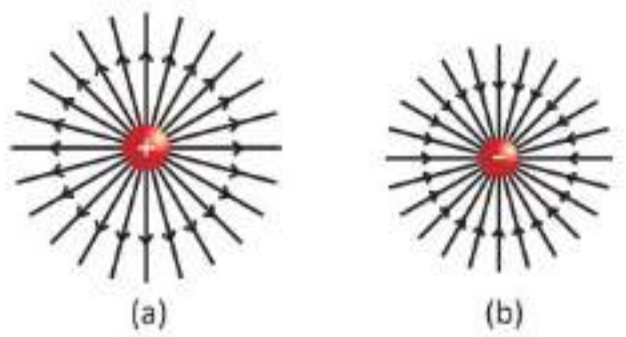
The electric field for an isolated positive charge | The electric field for an isolated nagative charge

Electric Field Lines

The concept of an electric field demonstrates how a charged object affects other nearby charged objects. The electric field is a vector field, which means it has both magnitude and direction. The direction of the electric field at any point is the direction in which a positive test charge would move if placed at that location. Here, we will explain and show the electric field patterns for three common situations:

(a) Around a Point Charge

Around a point charge, the electric field is radial, extending outward in all directions. For a positive point charge (Fig. 15.14-a), the electric field lines radiate outward, indicating that a positive test charge placed nearby would be repelled. In contrast, for a negative point charge (Fig. 15.14-b), the electric field lines point inward, showing that a positive test charge would be attracted towards it. This reflects the repulsive force around positive charges and the attractive force around negative charges.



(a) (b)

Fig. 15.14: Electric field lines for isolated positive and negative point charges

(b) Around a Charged Conducting Sphere

A charged conducting sphere distributes its charge evenly on its surface, and the electric field around it behaves similar to that of a point charge, but only outside the sphere. Outside, the electric field lines are radial,

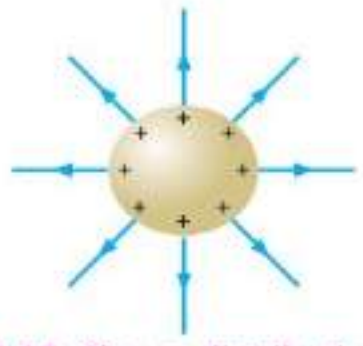


Fig. 15.15: Charge distribution on a positively charged sphere

radiating outward for a positively charged sphere and inward for a negatively charged one (Fig. 15.15). Inside the sphere, the electric field is zero because the charges on the surface rearrange to cancel any internal electric field.

(c) Between Two Oppositely Charged Parallel Conducting Plates

When two large parallel conducting plates are given equal and opposite charges, a uniform electric field is created between them, commonly used in capacitors (Fig. 15.16). The electric field lines point from the positively charged plate to the negatively charged plate, and they are parallel and equally spaced, showing a uniform electric field. This uniformity means the electric field has the same magnitude and direction at all points between the plates, which is due to the plates being large and close together, minimizing edge effects.

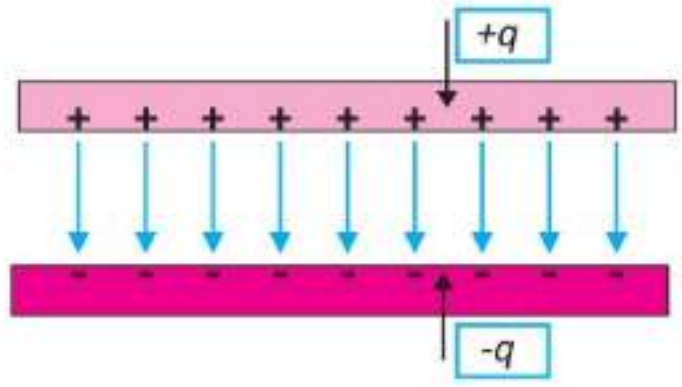


Fig. 15.16: Electric field between two oppositely charged parallel plates

Example: A point charge $q = 10\ \mu C$ is placed in air. Calculate the electric field at a distance of 0.5 m from the charge.

Solution:

Given that;

$$k = 9.0 \times 10^9\ N\,m^2\,C^{-2}$$

$$q = 10 \times 10^{-6}\ C$$

and $r = 0.5\ m$

To find; $E = ?$

Using the formula:

$$E = kq / r^2$$

Substituting the values

$$E = (9.0 \times 10^9 \times 10 \times 10^{-6}) / (0.5)^2$$

$$E = 3.6 \times 10^5\ N\,C^{-1}$$

Do You Know?

The electric field inside a charged conducting sphere is always zero, that is why people inside metal cars or airplanes are safe during lightning strikes.

15.6 Conduction of Electric Charges

Electrical Conductors

Electrical conductors are materials that allow electric charge to flow freely through them. They have loosely bound electrons in their atomic structure, which can flow easily when a voltage is applied, creating an electric current.

Examples of electrical conductors include metals, such as copper, aluminum, and silver, as well as materials like graphite and electrolytes .

Electrical Insulators

Electrical insulators are materials that resist or prevent the flow of electric charge. In insulators, electrons are tightly bound to their atoms and cannot move freely. As a result, they do not allow electric current to pass through them. Examples of electrical insulators include rubber, plastic, glass, wood, and ceramics . These materials are used to block the flow of electricity and provide safety in electrical systems.

Experiment: To explore this concept, we can conduct a simple experiment: Build a circuit with a battery, a bulb, and a gap to test materials. Insert objects like a metal key, a plastic spoon, or a wooden stick into the gap. If the bulb lights up, the material is a conductor; if it stays OFF, it is an insulator. This hands-on activity turns us into an electricity detective, revealing the hidden properties of everyday items.

Free Electron Model

Electrical conductors and insulators can be explained using a simple electron model. In conductors, such as metals, the outermost electrons of atoms are loosely bound and can move freely throughout the material. These "free electrons" act like a sea of mobile charges, allowing electric current to flow easily when a voltage is applied. In contrast, insulators, like rubber or plastic, have electrons that are tightly bound to their atoms and cannot move freely. When a voltage is applied to an insulator, the electrons remain fixed, preventing the flow of electric current. This difference in electron behaviour explains why conductors allow electricity to flow while insulators block it.

15.7 Accumulation of Charges

The accumulation of charges, often referred to as static electricity, occurs when electrons are transferred from one object to another, leading to an imbalance of positive and negative charges. This buildup can have several consequences. In everyday life, it can cause minor shocks when touching metal objects or make clothes cling together. In industrial settings, accumulated charges can be more serious, potentially damaging electronic components, igniting flammable substances, or disrupting manufacturing processes. Proper grounding, anti-

static measures, and humidity control are often employed to mitigate these risks and prevent the harmful effects of charge accumulation.

Electrical breakdown

Electrical breakdown occurs when a strong electric field passes through a gas (or insulating material), causing its atoms to ionize. This ionization creates free electrons and ions, which can conduct electricity. When the electric field is strong enough, it can lead to a sudden, dramatic increase in conductivity, often resulting in a spark or arc. This phenomenon is responsible for natural events like lightning, where the electric field in the atmosphere ionizes air, creating a conductive path for the discharge.

Corona discharge

Corona discharge is a visible form of electrical breakdown that occurs when a high-voltage electric field ionizes the air around a conductor, typically near sharp points or edges where the electric field is the strongest (Fig . 15.17). This ionization produces a faint glow or "corona" and is often seen around high-voltage power lines or antennas, while less intense than a full spark.

Tidbit

When the electric field around a high-voltage power line becomes intense, it can ionize nearby air molecules. This causes a phenomenon known as **corona discharge,** where the air gives off a faint blue or violet glow. This is why we may see a bluish light near sharp edges of electrical equipment in the dark.

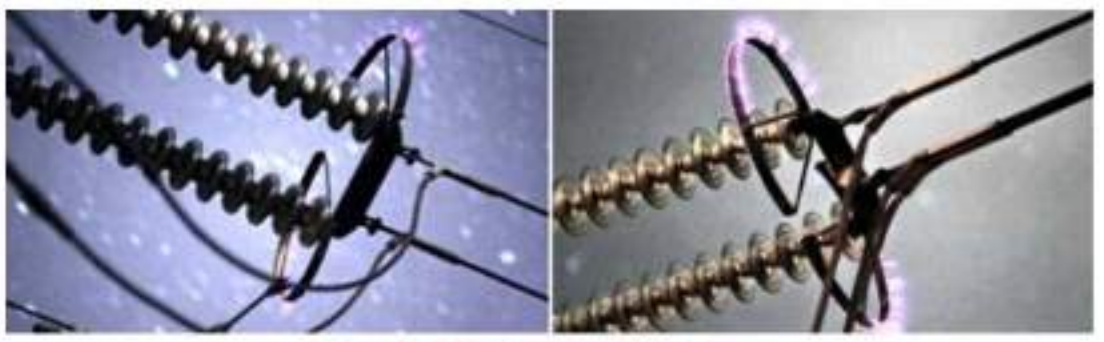


Fig. 15.17: Corona discharge

Lichtenberg Figures

These are branching, tree-like patterns that form on insulating materials (like wood or acrylic), when a high-voltage electrical discharge passes through them as shown in Fig 15.18. The patterns result from the electrical breakdown of the material, leaving behind visible traces of the discharge path. They are named after the German physicist Georg Christoph Lichtenberg, who first documented them. Both corona discharge and Lichtenberg figures are visible examples of electrical breakdown, demonstrating how strong electric fields can ionize materials and create conductive paths.

A sequence of zooms showing the "self-similar" property of lichtenberg figures

Fig. 15.18: Self-Similarity in lichtenberg figures

Lightning conductors

Lightning conductors, or lightning rods, are protective devices installed on tall structures to safeguard them from lightning strikes. A lightning rod provides a low-resistance path for the electrical discharge to follow, directing the massive current safely into the ground. This prevents the lightning from passing through the building, which could cause fires, structural damage, or harm to humans. By channeling the lightning's energy safely away, the rod protects both the structure and its occupant (Fig. 15.19).

Lightning is generated through a complex process involving charge separation, electric field buildup, and discharge. It begins with friction between water molecules suspended in clouds during thunderstorms or between smoke particles in volcanic plumes, leading to the accumulation of electric charge. As these charges separate within the cloud, an intense electric field develops. When this field reaches a critical level, the surrounding air undergoes electrical breakdown, forming lightning streamers ionized channels that create a conductive path for current flow. In the case of cloud-to-ground lightning, the strong electric field from the charged clouds induces an opposite charge on the Earth's surface, particularly in conductive materials. When the electric potential difference becomes large enough, it overcomes air resistance, allowing a rapid discharge of electricity between the cloud and the ground. This discharge results in the brilliant flash and thunder that characterize lightning, with some strikes occurring from cloud to cloud or even from the ground to the cloud in response to charge redistribution.

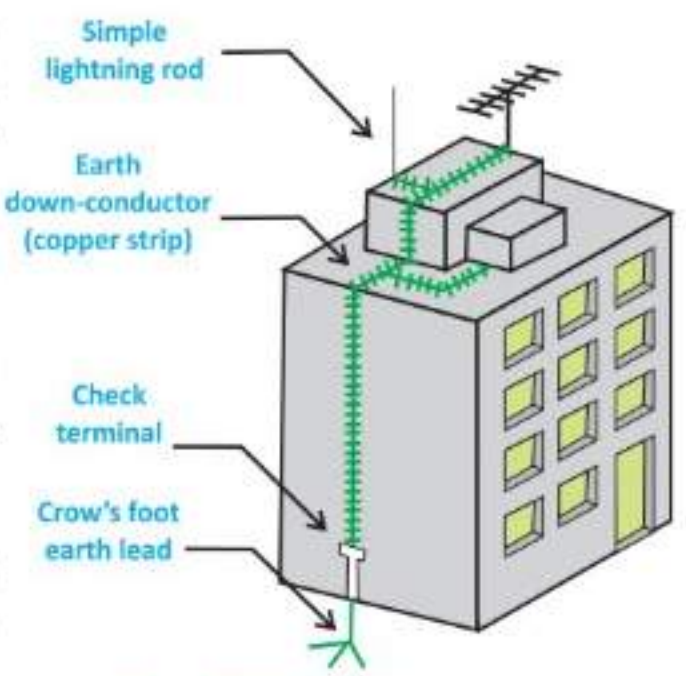


Fig. 15.19: Lighting conductors installed in building

Do You Know?

Lichtenberg figures are fern-like patterns that may appear on the skin of lightning strike victims that disappear in 24 hours.

EXCERISE

A. Multiple Choice Questions

Tick (✓) the correct answer.

15.1 Electrical breakdown is:
(a) the process of ionizing a gas due to a strong electric field
(b) the process of neutralizing a charged object
(c) the process of charging an insulator
(d) the process of discharging a conductor

15.2 Which of the following is a visible example of electrical breakdown?
(a) Corona discharge (b) Electric current
(c) Magnetic field (d) Electric potential

15.3 What happens when two unlike charges are brought close to each other?
(a) They attract (b) They repel
(c) They neutralize each other (d) Nothing happens

15.4 According to Coulomb's law, what happens to the attraction of two oppositely charged objects as their distance of separation increases?
(a) Decreases (b) Increases
(c) Remains unchanged (d) Cannot be determined

15.5 The device which works on the principle of electrostatics:
(a) electric bell (b) photocopier (c) electric heater (d) transformer

B. Short Answer Questions

15.1 State Coulomb's law of electrostatics and write its mathematical form.

15.2 What is an electric field?

15.3 Give two examples each of electrical conductors and electrical insulators.

15.4 List some applications of electrostatics in daily life.

15.5 What happens when like charges and unlike charges are brought close to each other?

15.6 What is meant by electrical breakdown, and when does it occur?

15.7 What are the dangers of static electricity?

C. Constructed Response Questions

15.1 Why do some materials gain electrons while others lose electrons when rubbed together? What property of the materials determines this behaviour?

15.2 A charged comb attracts small pieces of paper, but after some time, the paper pieces fall off. Why does this happen?

15.3 Why do dust particles often get attracted to television screens or computer monitors after they are turned ON?
the water bends toward the balloon. What does this tell us about the nature of water molecules?

15.4 If we rub a balloon on our dry hair and place it near a thin stream of water, the water bends toward the balloon. What does this tell us about the Nature of water molecules?

15.5 A conductor and an insulator are both placed in an electric field. How will their behaviour differ, and why?

D. Comprehensive Questions

15.1 Discuss the working of a gold leaf electroscope. How can it be used to determine the nature and magnitude of charge on a body?

15.2 How does Coulomb's law help in understanding the interaction between charged particles? What factors affect the force between them?

15.3 Explain the concept of electric field intensity. How can the electric field of a point charge and a parallel plate capacitor be represented using field lines?

15.4 Explain how and why electrical conductors and insulators behave differently in terms of charge transfer and movement of electrons.

15.5 Discuss how electrostatics plays a role in real-life hazards, such as dust explosions in factories and static shocks from synthetic clothing. How can these hazards be minimized?

E. Numerical Problems

15.1 A positive test charge of 25 μC is placed in an electric field. The force on it is 0.500 N. What is the magnitude of the electric field at the location of the test charge? **[Ans: 2.0×10^4 N C^{-1}]**

15.2 Two point charges, q_1 = 8 μC and q_2 = 4 μC, are placed at a distance of 120 cm. What will be the Coulomb's force between them? Also, find the nature of the force. **[Ans: 0.2 N, the direction of repulsion]**

15.3 Two identical charges repel each other with a force of 0.2 N when they are 9 cm apart. Find the force between them when they are 3 cm apart.

[Ans: 1.8 N]

15.4 A point charge q=10 μC is placed in air. Calculate the electric field strength at a distance of 0.5 metres from the charge. **[Ans: 3.6×10^5 N C^{-1}]**

15.5 Two small equally charged metal spheres having charge 3 μC are brought close together such that the distance between them is 2.0 cm. Calculate the magnitude of repulsive force that each sphere exerts on the other.

[Ans: 202.5 N]

15.6 Two small equally charged metal spheres repel each other with a force of 0.5 N when placed 3 cm apart in the air. Calculate the charge on each sphere. **[Ans: 224 μC]**

15.7 A force of 85 N acts between two charges placed 3.2 cm apart. If one charge is 25 μC, determine the other charge. **[Ans: 3.87 μC]**

CHAPTER 16

ELECTRICITY

Student's learning outcomes (SLOs)

After studying this chapter, students will be able to:

- define and calculate electric current, using the equation; $I = Q/t$.
- explain electrical conduction in metals in terms of the movement of free electrons.
- state that current is measured in amperes and that one ampere is equal to one coulomb per second ($C\ s^{-1}$).
- differentiate between direct current D.C and alternating current A.C.
- differentiate between conventional and electronic current.
- justify and illustrate the use of ammeters (analog and digital) with different ranges.
- define e.m.f. as the electrical work done by a source in moving a unit charge around a complete circuit, using the equation; $E = W/Q$.
- define potential difference (p.d.) as the work done by a unit charge passing through a component, using the equation; $V = W/Q$.
- state that e.m.f. and p.d. are measured in volts and that one volt is equal to one joule per coulomb ($J\ C^{-1}$).
- illustrate the use of voltmeters (analog and digital) with different ranges.
- calculate the total e.m.f when multiple sources are arranged in series.
- state that the e.m.f of identical sources connected in parallel is equal to the e.m.f. of one of the sources.
- define and calculate resistivity, explaining its direct proportionality to resistance and length, and inverse proportionality to cross-sectional area.

- define and apply Ohm's law using the equation; $R = V/I$.
- describe the effect of temperature increase on the resistance of a resistor, such as in a filament lamp.
- draw circuit diagrams using components such as cells, batteries, power supplies, generators, switches, resistors, thermistors (NTC), light-dependent resistors (LDRs), lamps, motors, ammeters, voltmeters, transformers, fuses, relays, diodes, and LEDs.
- calculate the combined resistance of resistors in series.
- calculate the combined resistance of resistors in parallel.
- calculate current, voltage, and resistance in parts of a circuit or the whole circuit.
- describe the action of negative temperature coefficient (NTC) thermistors and light-dependent resistors (LDRs) and their use as input sensors.
- analyze the function of variable potential dividers in circuits, using the equation; $R_1/R_2 = V_1/V_2$.
- justify and illustrate the use of colour codes for resistors.
- use the equation; power = current × voltage $(P = IV)$ to solve simple problems.
- use the equation energy = current × voltage × time $(E = IVt)$ to solve simple problems.
- define the kilowatt-hour (kWh).
- explain the need to choose components with suitable power ratings.
- calculate the cost of using electrical appliances where the energy unit is the kWh.
- explain the use and operation of trip switches and fuses and choose appropriate fuse ratings and trip switch settings.
- explain what happens when a live wire touches a metal case that is earthed.
- explain why the outer casing of an electrical appliance must be either non-conducting (double-insulated) or earthed.
- state that a mains circuit consists of a live wire (line wire), a neutral wire, and an earth wire.
- explain why fuses and circuit breakers are connected into the live wire for the circuit to be switched OFF safely.
- explain why domestic supplies are connected in parallel.

Electricity is a branch of physics which deals with the flow of charges. The movement of charges results in the flow of electric current which plays an important role in our daily lives. The electricity illuminates our homes, fuels our industries, and connects us across vast distances. In this chapter, we will learn the basic concepts of electricity, including electric current, potential difference, Ohm's law, electrical resistivity, and common uses of electricity, benefits and its hazards. These contents will help in building up basic knowledge about electricity.

16.1 Electric Current

In an atom, the electrons and positively charged nucleus are held together by strong force. However, in metals some electrons can move freely as these are not tightly bonded with the nucleus. These electrons move randomly within a metallic conductor. However, when an external electric field is applied, these electrons move in a specific direction (Fig. 16.1). This flow of charges is called an electric current. The electric current can be caused due to movement of both positive and negative charges.

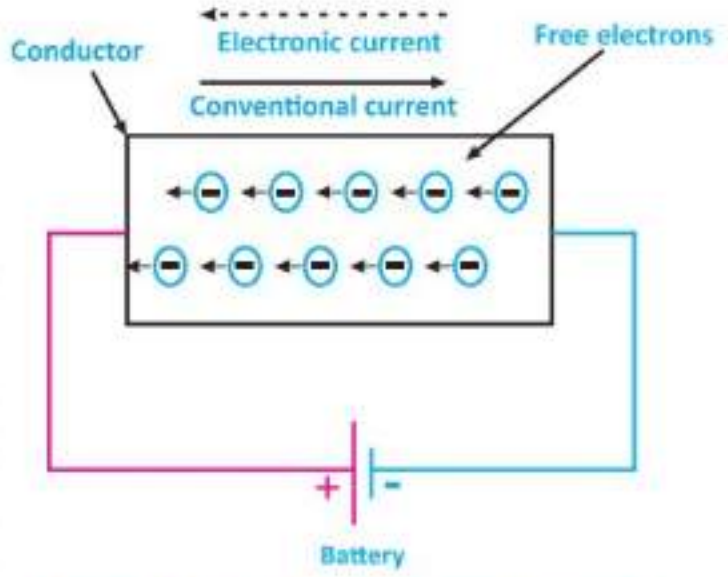


Fig. 16.1: Flow of electrons in a circuit

Amount of charge passing through any cross section of a conductor per unit time is called electric current.

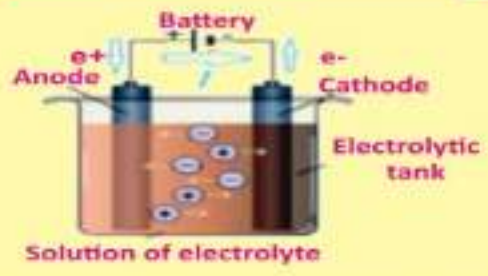
If Q charge flows in time t, then current I can be expressed as:

$$I = \frac{Q}{t} \quad \text{..... (16.1)}$$

The SI unit of electric current is ampere (A). One ampere is defined as the flow of one coulomb of electric charge per second, which can be written as; $1\ A = 1\ C\ s^{-1}$.

Before the discovery of electrons, the electric current was considered to be due to flow of positive charges, named as Conventional Current. These charges move from positive terminal to the negative terminal of the power source. Later, after the discovery of electrons, the electric current was described due to the movement of electrons which was named

Do You Know?



In electrolysis, current is produced due to flow of both positive and negative ions. In the electrolyte, negative ions are attracted to the anode. This movement of ions within the electrolyte constitutes an electric current within the internal circuit.

as electronic current. The movement of electrons in one direction corresponds to the movement of positive charges in opposite direction. Despite this difference, both concepts are used in practice, with conventional current being the standard in circuit analysis.

Types of Electric Current

1. Direct Current (DC)
2. Alternating Current (AC)

Direct Current (D.C) is an electrical current where the electric charge flows in one direction only (Fig.16.2-a). In a D.C circuit, the voltage remains constant over time, and the strength of the current does not change. The current provided by a battery is an example of direct current.

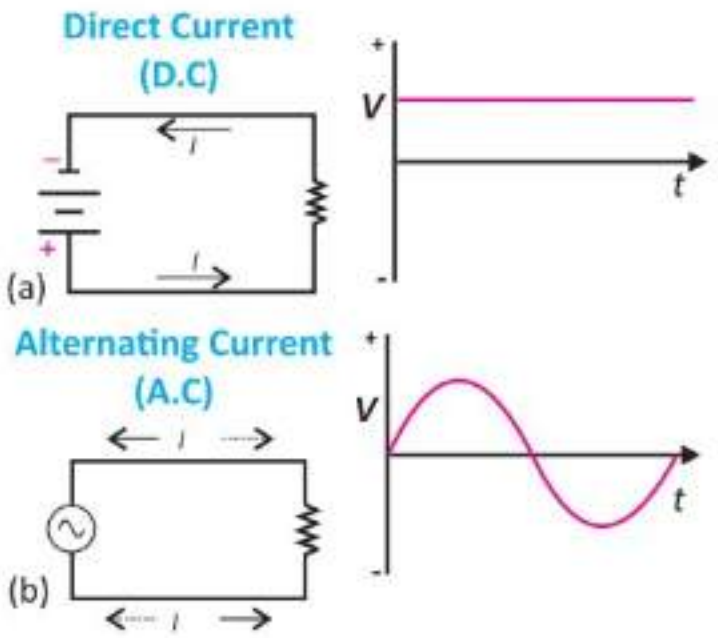


Fig. 16.2: Types of current (a) D.C (b) A.C

Alternating Current (A.C) is a type of current that periodically reverses its direction (Fig. 16.2-b). Most power stations in our country produce alternating current. A.C changes direction every 1/50 second, and its frequency is 50 hertz (Hz). One advantage of A.C over D.C is that it can be transmitted over long distances with low power loss.

Tidbit

In any circuit, electric current prefers the path of least resistance, just like water flowing downhill.

Ammeter

An ammeter is a device used to measure the current flowing through a circuit. It must be connected in series with the component whose current is to be measured. There are two main types of ammeters: analog ammeters and digital ammeters. Both types are available in different current ranges to measure both small and large currents. In Fig. 16.3, we can see the digital ammeter (left) and analog ammeter (right) side by side, illustrating the difference in display type and range options. Both types are connected in series with the load to measure current, but the display method and

Fig. 16.3: Comparison of digital and analog ammeters

ease of reading differ significantly.

Types of Ammeters

Analog Ammeter: An analog ammeter uses a needle and scale to indicate the current. The current flowing through the circuit generates a magnetic field that moves the needle on the scale. The scale usually has multiple ranges, and the correct range must be selected depending on the expected current. Analog ammeters typically have multiple selectable ranges, such as 0–10 mA, 0–100 mA, etc. The correct range must be selected to avoid damage to the device and to ensure accurate readings.

Use: Ideal for visual indication of current flow in basic experiments, and often used in educational settings due to its simplicity.

Digital Ammeter: A digital ammeter provides a numerical reading of the current on a digital display. It offers more precision compared to an analog ammeter. Digital ammeters also come with various ranges, and some automatically adjust the range depending on the detected current. They are typically more accurate and easier to read than analog meters. Digital ammeters are widely used in scientific, industrial, and electrical applications where precise measurements are critical.

Do You Know?

A.C is More Dangerous than D.C

Direct Current (D.C) is a current that travels from negative to the positive terminal. It does not change its direction. It is the current, we can get from a battery. It can cause burning if the positive and negative wires can come into contact.

Range Selection

Ammeters are equipped with multiple ranges to accommodate different magnitudes of current. Selecting the correct range is important to ensure that ammeter is not damaged and to provide an accurate measurement. Low-range ammeters (e.g. 0–1 A) are used to measure small currents, typically in laboratory experiments.

High-range ammeters (e.g. 0–10 A) are used to measure larger currents, such as those in power systems or industrial circuits.

16.2 Electromotive Force and Potential Difference

Electromotive force (e.m.f.) and potential difference (p.d.) are two important concepts, both measured in volts (V). One volt is defined as one joule of energy per coulomb of charge (1 V = 1 J C^{-1}). This means that if 1 joule of energy is used to

move 1 coulomb of charge, the voltage is 1 volt.

Electromotive Force (e.m.f.)

A source of electromotive force (e.m.f.) converts non-electrical energy, like chemical, thermal, or mechanical energy, into electrical energy. Examples of such sources include batteries (which convert chemical energy), thermocouples (which convert thermal energy), and generators (which convert mechanical energy). When a conductor is connected to a battery, current flows due to the potential difference between the battery's terminals. The battery provides energy to move positive charges from the positive terminal through the conductor to the negative terminal (Fig. 16.4). Once the charge reaches the negative terminal (lower potential), the battery does work to push it back to the positive terminal (higher potential). This cycle keeps the current flowing continuously. In short, the e.m.f. supplies the energy needed to keep the charges in motion.

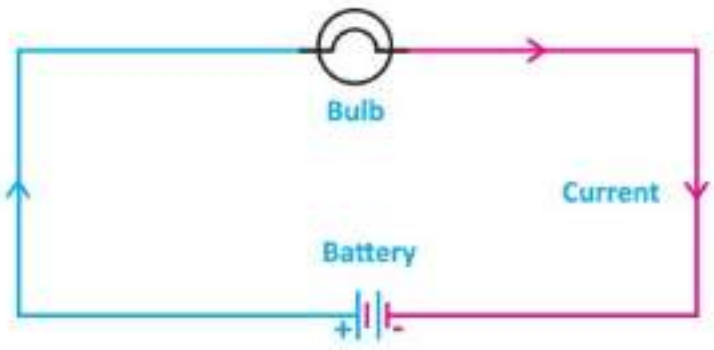


Fig. 16.4: Electromotive force

Electromotive force is the electric potential energy supplied by a battery to a unit positive charge when it flows through the closed circuit.

Mathematically;

$$\text{e.m.f} = \frac{\text{Energy}}{\text{Charge}} \quad \ldots\ldots\ldots\ldots \quad (16.2)$$

$$\text{or} \qquad E = \frac{W}{Q} \quad \ldots\ldots\ldots\ldots \quad (16.3)$$

E is the e.m.f., W is energy converted from non-electrical forms to electrical form and Q is the charge. Emf of a battery can be measured directly by connecting its terminal to a voltmeter as shown in Fig. 16.5.

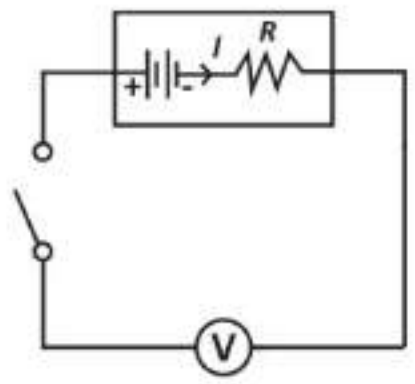


Fig. 16.5: Schematic diagram for measuring e.m.f. of the battery

Potential Difference

A battery converts chemical energy into electrical energy. Inside the battery, a chemical reaction causes a buildup of electrons at the negative terminal and a shortage of electrons at the positive terminal. This imbalance creates a potential difference between the terminals, which allows electrons to flow through a connected circuit, generating an electric current. The battery continues to drive this

flow as long as the chemical reaction is active, providing a steady supply of energy. In short, the chemical action inside the battery creates a potential difference that allows the current in the circuit.

Electric potential (*V*) is the amount of electric potential energy (*W*) per unit charge (*Q*) at a specific point in an electric field.

$$\text{i.e;} \qquad V = \frac{W}{Q} \qquad \ldots\ldots\ldots\ldots \quad (16.4)$$

The potential difference is the difference in the values of electric potential between two points in the electric field (Fig. 16.6). The unit of electric potential is volt (V). One volt is equals to one joule per coulomb ($V=J\ C^{-1}$). Potential difference is also called voltage which is the energy used by a component in the circuit. Voltage can also be referred to e.m.f. which is the energy supplied by a source like a battery. Both potential difference and e.m.f. are measured in volts.

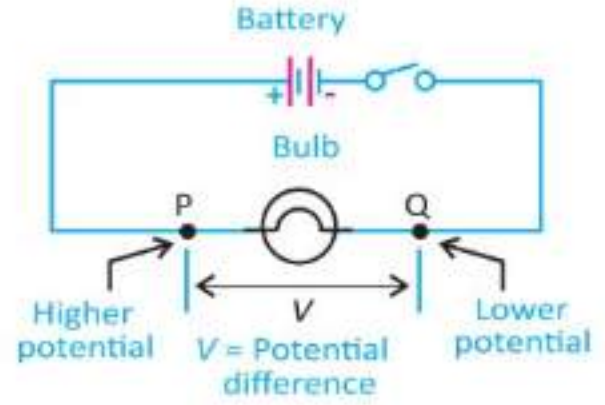
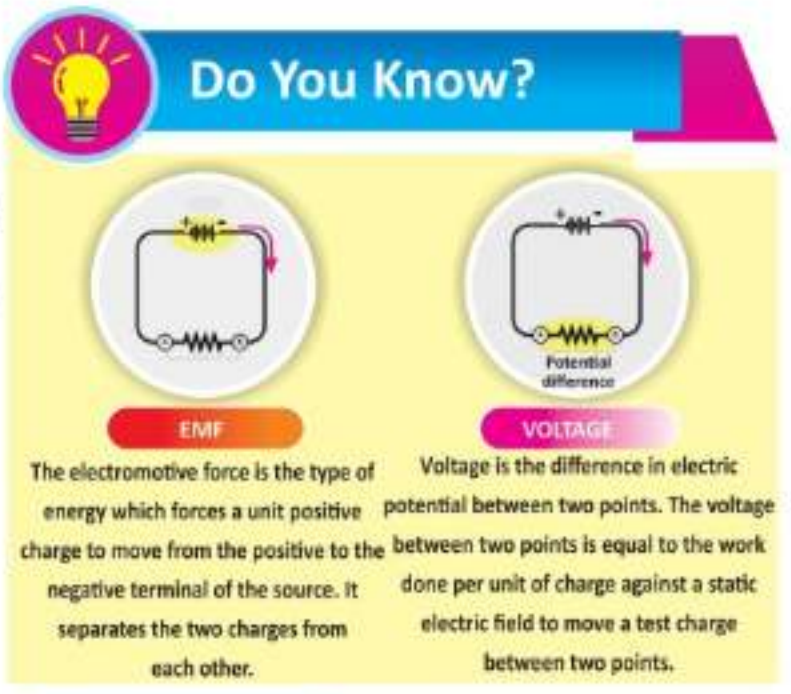


Fig. 16.6: Potential difference across two points in a circuit

Voltmeter

Voltage can be measured using a device called voltmeter. Voltmeter can also be of analog and digital types. Both types are available with different ranges, allowing them to measure voltages of varying magnitudes. Analog voltmeters use a needle and a scale to display the voltage, making them useful for observing changes or trends over time. Digital voltmeters, on the other hand, show the voltage as a numerical value on a screen, offering greater precision and ease of reading. For example, a low-range voltmeter might measure millivolts (mV),



Analog voltmeter

Digital voltmeter

Fig. 16.7: Types of voltmeters

while a high-range voltmeter could measure hundreds or even thousands of volts. Choosing the right range is important, using a low-range voltmeter for a high voltage could damage the device, while using a high-range voltmeter for a small voltage, might not provide accurate readings. Analog and digital voltmeters are shown in Fig. 16.7.

Example 16.1: A battery does 120 J of work to move a charge of 20 C through a circuit. What is the potential difference across the circuit?

Solution:

Given that; $W = 120\ J,\ Q = 20\ C$

To find; $V = ?$

Using the formula; $V = W / Q$

Substituting the values; $V = 120\ J / 20\ C = 6\ V$

Total E.M.F. of Series Connected Sources

When multiple voltage sources (e.g., batteries) are connected in series (Fig. 16.8), their total electromotive force (e.m.f.) is simply the sum of their individual e.m.f. This is because the voltage sources add energy to the charges one after the other.

Formula: $E_{total} = E_1 + E_2 + \ldots + E_n$

where

E_{total} = total e.m.f.

$E_1, E_2, \ldots, E_n$ = e.m.f. of the individual sources

Example: If four batteries, each with an e.m.f. of 1.5 V (Fig. 16.8), are connected in series, the total e.m.f. would be 6 V.

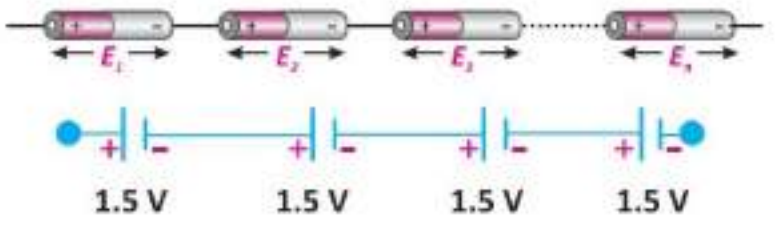


Fig. 16.8: Series combination of batteries

E.M.F. of Identical Sources Connected In Parallel

When multiple identical sources (such as batteries with the same voltage) are connected in parallel (Fig. 16.9), the total e.m.f. across all of them remains equal to the e.m.f. of a single source. This is because, in parallel connections, each

battery is connected directly across the same two points, meaning the voltage (e.m.f.) does not change. However, the total current supplied by the sources will increase due to the additional paths available for current to flow.

For Your Information

In a series combination, the total e.m.f. increases, making it easier to push electric charges through the circuit. However, the total current depends on the overall resistance in the circuit.

Explanation: In a parallel connection, each source contributes current independently while maintaining the same voltage across each of them. This results in the total e.m.f. remaining equal to the e.m.f. of one of the individual sources, but the total current becomes the sum of the individual currents provided by each source.

Fig. 16.9: Four 1.5 V batteries connected in parallel

Brain Teaser

Three identical 5 V cells are connected in parallel. What is the total e.m.f. of the combination?

Formula: For identical sources in parallel:

$$E_{total} = E_1 = E_2 = \ldots = E_n$$

where

E_{total} is the total e.m.f. across the parallel sources.

E_1, E_2, ..., E_n are the e.m.f's of the individual sources (which are identical for each source in the parallel connection).

Example: In Fig. 16.9, four 1.5 V batteries are connected in parallel. The total e.m.f. across the combination will still be 1.5 V, just as it is for a single battery.

16.3 Ohm's Law

In 1826, George Simon Ohm made an investigation of the relationship between electric potential difference across a conductor and the current flowing through it. The current in a conductor was increased by increasing the potential difference across its ends. According to Ohm's law;

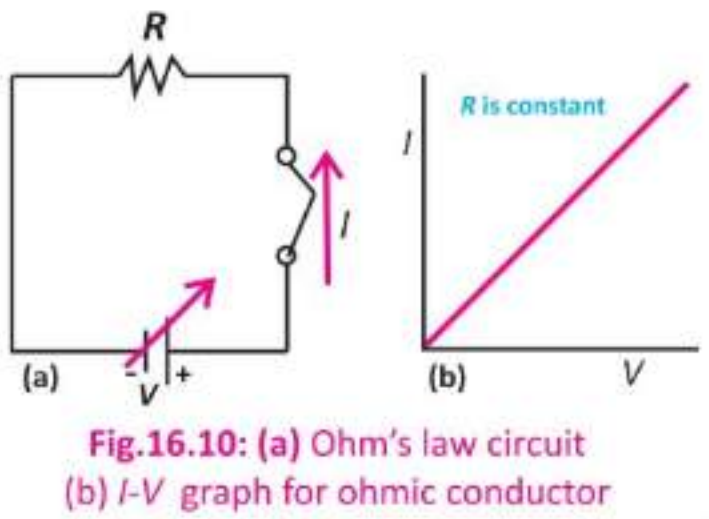


Fig.16.10: (a) Ohm's law circuit
(b) *I-V* graph for ohmic conductor

The current flowing through a conductor is directly proportional to the potential difference *V* across its two ends of a conductor, provided the physical state (dimension, temperature, etc.) of the conductor remains same .

Mathematically;

$$I \propto V$$

$$I = \frac{1}{R}V$$

$$V = IR \quad \text{..... (16.5)}$$

where R is constant of proportionality called resistance of a conductor. The SI unit of resistance is ohm (Ω) and $1\ \Omega = V\ A^{-1}$.

16.4 Combination of Resistances

A number of resistors can be connected in a circuit to increase or decrease the net resistance of the circuit. The resistors are connected either in series or in parallel and the equivalent resistance of the circuit depends upon the type of combination.

Series Combination of Resistors

When resistors are connected in such a way that there is only one path for the current to flow, then it is called series combination of resistors. For example, consider three resistors R_1, R_2 *and* R_3 connected in series as shown in Fig. 16.11. When this combination is connected to a battery of V volts, it draws current I from the battery. Let R_e be a single resistor representing the total resistance of the circuit, also called equivalent resistance.

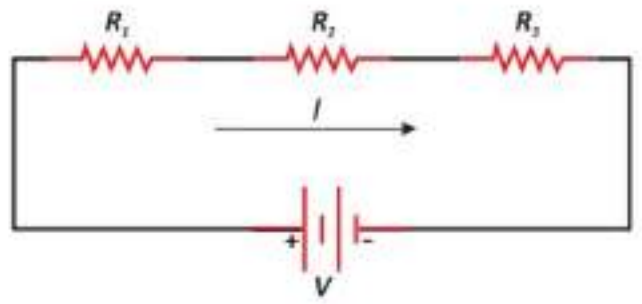


Fig.16.11: Resistors in series

The total voltage in the circuit will be the sum of voltage across the three resistors.

i.e; $V = V_1 + V_2 + V_3$

Applying Ohm's law:

$$V_1 = IR_1,\ V_2 = IR_2 \text{ and } V_3 = IR_3$$

or $IR_e = IR_1 + IR_2 + IR_3$

$$IR_e = I(R_1 + R_2 + R_3)$$

$$R_e = R_1 + R_2 + R_3 \quad \text{..... (16.6)}$$

Thus, equivalent resistance is equal to the sum of individual resistances.

Parallel Combination of Resistors

When there are multiple paths for current flow in a circuit (as indicated in the diagram), the combination of resistances is referred to as parallel combination. The electric potential across each resistance is the same and equal to the applied potential. Each resistor has a steady current flowing through it. Consider three resistors R_1, R_2 and R_3 connected in parallel (Fig. 16.12). When these are connected to a battery of V volts, it draws a current I from the battery. R_e is a single resistor. This resistor is such that when it is connected to the same battery of V volts, it also draws current I from the battery. This resistor is therefore called equivalent resistor and its resistance is called equivalent resistance. The total current in the circuit will be the sum of currents flowing through the resistors;

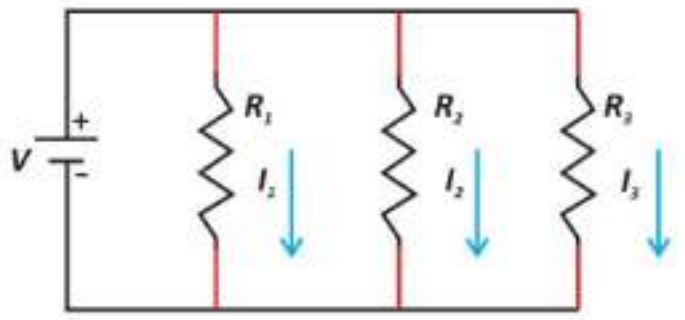


Fig.16.12: Resistors in parallel

$$I = I_1 + I_2 + I_3$$

Applying Ohm's law:

$$V = I_1 R_1,\ V = I_2 R_2,\ V = I_3 R_3$$

or $$I_1 = \frac{V}{R_1}, I_2 = \frac{V}{R_2}, I_3 = \frac{V}{R_3}$$

or $$\frac{V}{R_e} = \frac{V}{R_1} + \frac{V}{R_2} + \frac{V}{R_3}$$

or $$\frac{V}{R_e} = V\left[\frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3}\right]$$

$$\frac{1}{R_e} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} \quad \ldots\ldots\ldots\ldots \quad (16.7)$$

Tidbit

Birds are safe because both their feet touch the same potential wire. There is no voltage difference, so no current flows through their bodies.

Thus, the reciprocal of equivalent resistance is equal to the sum of reciprocals of individual resistances.

Example 16.2: Two resistors of 8 Ω and 24 Ω are connected in parallel across a 30 V power supply. Calculate the total resistance and the current drawn from the power supply.

Solution:

Given that; $R_1 = 8\ \Omega$, $R_2 = 24\ \Omega$ and $V = 30$ V

To find; $R_e = ?$ and $I = ?$

Using the formula for parallel resistance: $1/R_e = 1/R_1 + 1/R_2$

Substituting the values; $1/R_e = (1/8) + (1/24)$

$1/R_e = (3/24) + (1/24)$

$1/R_e = 4/24$ or $R_e = 24/4 = 6\ \Omega$

Now, we calculate total current by using Ohm's Law:

$I = V / R_e = 30\ V / 6\ \Omega = 5\ A$

16.5 Electrical Resistivity

The opposition to the flow of electric current is called resistance.

This resistance is directly proportional to the length of the conductor and inversely proportional to its area. If A is the area and R is the resistance of a conductor (Fig. 16.13), then mathematically we can write it as:

$$R \propto L \text{ or } R \propto \frac{1}{A}$$

$$R = \rho \frac{L}{A}$$

$$R = \rho \frac{L}{A} \quad \ldots\ldots (16.8)$$

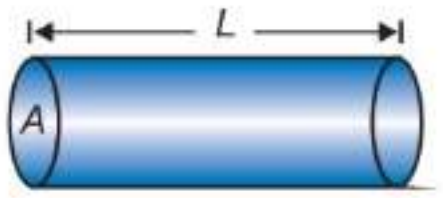


Fig.16.13: Resistivity of a material

Table 16.1: Electrical resistivity of different materials

Material	Electrical resistivity ($10^{-8}\ \Omega$ m)
Silver	1.7
Copper	1.69
Aluminium	2.75
Tungsten	5.25
Platinum	10.6
Iron	9.8
Nuchrome	100
Graphite	3500

Here, ρ is a constant called electrical resistivity of a material which quantifies how strongly a material resists to electric current. Materials with high resistivity are poor conductors of electricity, while those with low resistivity are good conductors. The SI unit of resistivity is the ohm-metre (Ω m).

Resistance of a cubic metre of a material is called resistivity.

Effect of Temperature on Resistance of a Conductor

The resistance and the resistivity of a conductor can change with temperature. In most conductors such as metals, the electrical resistance increases with temperature because atomic vibrations resist electron flow.

For example, in a filament lamp, when the

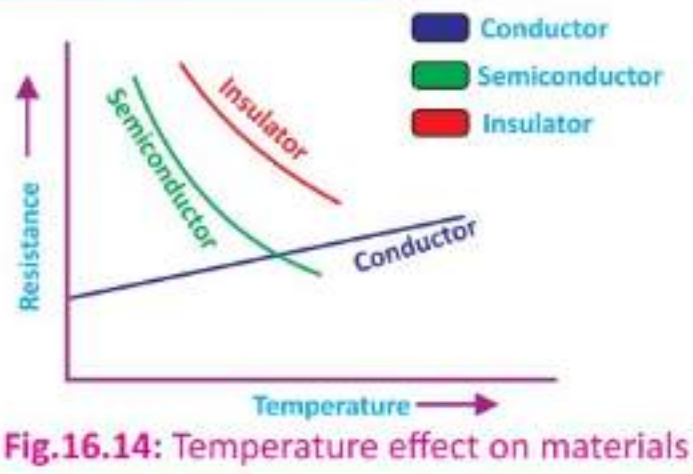


Fig.16.14: Temperature effect on materials

temperature of the filament (resistor) increases, its resistance also increases. This occurs because the filament is made of metal, and metals have free electrons that causes the flow of electric current. The increase in the temperature of a resistor increases the vibration of its atoms. These vibrations make it harder for the electrons to move. As a result, the flow of current becomes more difficult, and the resistance goes up. So, a hot filament has more resistance than a cold one.

In the case of semiconductors and insulators, resistance may decrease with temperature due to increase in the mobility of free charge carriers. For example, thermistor, which is made up of a semiconductor material, is a type of resistor whose resistance decreases as its temperature increases. At low temperatures, the semiconductor material has fewer free charge carriers (electrons or holes), resulting in high resistance. As the temperature rises, more charge carriers are released, increasing conductivity and reducing resistance. Due to change in resistance, the resistivity also changes accordingly. The effect of temperature on resistance of different materials is graphically shown in Fig. 16.14.

Example 16.3: An aluminium wire has a length of 15 m, a cross-sectional area of 3×10^{-6} m^2, and a resistivity of 2.82×10^{-8} Ω m. Calculate its resistance.

Solution:

Given that; Resistivity $\rho = 2.82 \times 10^{-8}$ Ω m

Length $L = 15$ m, $A = 3 \times 10^{-6}$ m^2

To find; Resistance $R = ?$

Using the formula: $R = \rho\ (L / A)$

Substituting the values

$R = (2.82 \times 10^{-8}\ \Omega\ m) \times (15\ m / 3 \times 10^{-6}\ m^2)$

$R = (2.82 \times 10^{-8}) \times (5 \times 10^{6})$

$R = 0.141\ \Omega$

The resistance of the wire is 0.141 Ω.

16.6 Potential Divider Circuit

A potential or voltage divider is a circuit that divides a voltage into smaller parts using resistors. It consists of two or more resistors connected in series across a voltage source (Fig. 16.15). The voltage across each resistor is proportional to its resistance relative to the total resistance of the circuit.

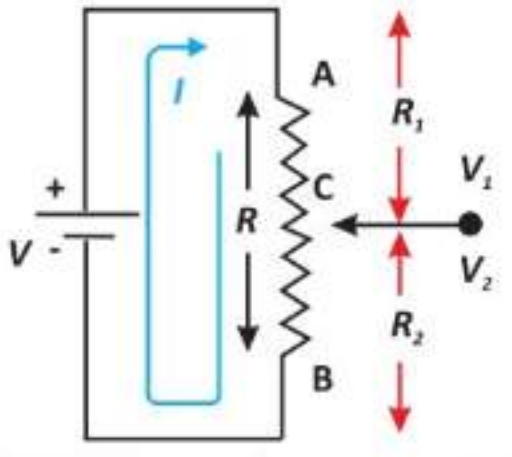


Fig.16.15: Potential divider circuit

Consider two resistors R_1 and R_2 connected in series. The voltage across each resistor is given by

$$\frac{R_1}{R_2} = \frac{V_1}{V_2} \quad \text{..... (16.9)}$$

where V_1 = voltage across R_1

and V_2 = voltage across R_2

The total voltage (V_{total}) is the sum of V_1 and V_2:

$$V_{total} = V_1 + V_2 \quad \text{..... (16.10)}$$

The voltage across each resistor can also be calculated using the formulae:

$$V_1 = IR_1 = \frac{V_{total}}{R_e} x\ R_1$$

$$V_1 = V_{total}\ x\ \frac{R_1}{R_1 + R_2} \quad \text{..... (16.11)}$$

Similarly

$$V_2 = V_{total}\ x\ \frac{R_2}{R_1 + R_2} \quad \text{..... (16.12)}$$

16.7 Resistor Colour Codes

The resistor colour codes is a system of coloured bands printed on resistors to indicate their resistance value and tolerance (Fig.16.16). Tolerance means how much a resistor's real value can be different from the value written on it. In this way, resistor's values can be identified without using multimeter. Each colour represents a specific digit and multiplier. In a four band resistor, the first and second bands indicate 1st and 2nd digit, the 3rd and 4th bands show multiplier and tolerance. For example, a resistor has four bands Red, Violet, Yellow and Gold. First two digits show 27, Yellow band is a multiplier (10^4), gold shows tolerance (±5 %). The final value of resistance is 270,000 Ω or 270 kΩ. The standard resistor colour codes are given in Table 16.2.

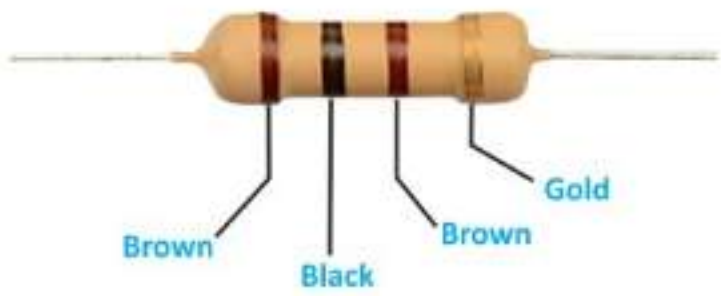


Fig.16.16: 100-ohm resistor colour codes

Table 16.2: Standard resistor colour codes

Colour	Number	Multiplier	Tolerance
Black	0	10^0	-
Brown	1	10^1	-
Red	2	10^2	-
Orange	3	10^3	-
Yellow	4	10^4	-
Green	5	10^5	-
Blue	6	10^6	-
Violet	7	10^7	-
Grey	8	10^8	-
White	9	10^9	-
Gold	-	10^{-2}	± 05 %
Sliver	-	10^{-1}	± 10 %
Colourless	-	-	± 20 %

Negative TemperatureCoefficient (NTC) Thermistors

A Negative Temperature Coefficient thermistor (NTC) and its circuit diagram is shown in Fig. 16.17. It is a type of resistor whose resistance decreases as the temperature increases. This behaviour is due to the negative temperature coefficient, meaning that the material used in the thermistor conducts electricity better as the temperature rises. The increase in temperature gives more energy to the charge carriers (electrons), allowing them to move more freely through the material, which reduces the resistance.

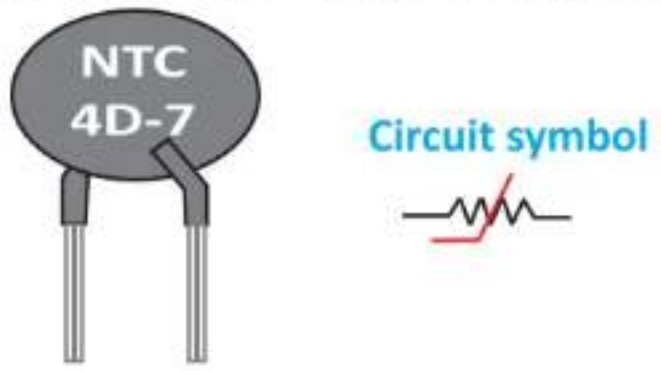


Fig. 16.17: NTC thermistor

Action and Use

As the temperature increases, the resistance of the NTC thermistor decreases. This makes it useful for applications where changes in temperature need to be detected. NTC thermistors are commonly used in temperature-sensing circuits, such as those found in electronic devices (e.g., thermometers, temperature monitoring circuits, and temperature compensation in circuits).

Applications

1. Temperature sensors in electronic devices.

2. Over current protection in power supplies, where the thermistor can limit current based on temperature changes.

Light-Dependent Resistors (LDRs)

A circuit diagram of a light dependent resistor (LDR) is shown in Fig. 16.18. It is a type of resistor whose resistance decreases as the intensity of light increases. The more light that falls on the LDR, the more current flows through it, as its resistance decreases. This occurs because the photoconductive material inside the LDR absorbs light energy, which excites electrons, allowing them to move more freely and thus reduces the resistance.

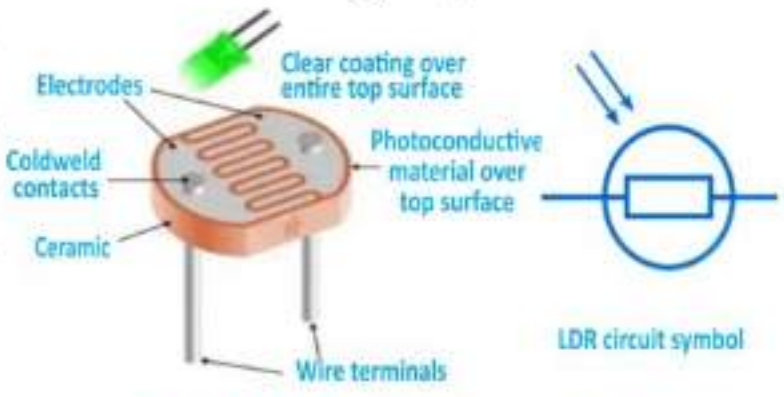


Fig. 16.18: Light dependent resistor

Action and Use

As light intensity increases, the resistance of the LDR decreases, allowing more

current to pass through. LDRs are widely used in light-sensing circuits, where changes in light intensity are monitored. They are commonly used in automatic lighting systems, brightness sensors in cameras, and other applications where light level detection is needed.

Applications

1. Street lighting that automatically turns ON when it gets dark.

2. Brightness sensors in cameras that adjust exposure based on ambient light levels.

16.8 Common Use of Electricity

Electricity is one of the most versatile forms of energy that is used in our daily lives. One of its most common uses is heating, where it powers devices like electric heaters, stoves, and water heaters to keep us warm and cook our food. It also plays a key role in lighting, from the bulbs in our homes to streetlights and flashlights, making it possible to see and work even after dark. Another important use is battery charging, as electricity powers the chargers for our phones, laptops, electric vehicles, and other portable devices. Additionally, electricity is essential for powering motors, which are found in appliances like washing machines, refrigerators, and industrial machinery, as well as in electric cars and trains. Electricity is the backbone of electronic systems, running computers, televisions, smartphones, and other gadgets that keep us connected and entertained. In short, electricity is everywhere, making our lives easier, safer, and more efficient.

16.9 Electric Power

Electric power is the rate at which electrical energy is transferred or consumed in a circuit.

It measures how quickly work is done or energy is used. The SI unit of power is watt (W).

$$P = W/t$$

$$1\ W = J\ s^{-1}$$

Electric power P is commonly written as product of current I and voltage V.

$$P = IV \quad \ldots\ldots\ldots\ldots \quad (16.13)$$

As $V = IR$

So $P = I^2R$

or $P = V^2/R \quad \ldots\ldots\ldots\ldots \quad (16.14)$

Joule's Law

Heat produced by an electric current and the resistance of the conductor can be described by Joule's law. According to this law:

The heat energy produced in a resistance is equal to the product of square of the current, resistance and time.

Mathematically; $H = I^2Rt$

or $H = P \times t$ ..... (16.15)

This is the relationship between electric power P and total heat energy which shows that the total heat energy H is the product of power and time. The power of a resistor determines how quickly heat is produced. For example, a 100 W electric bulb produces heat at a rate of 100 joules per second. The total heat energy depends on how long the electric bulb operates.

Tidbit

Power bills measure energy, not electricity. Our electricity bills show kilowatt-hours (kWh), a measure of energy used, not electricity consumed.

For instance, if the 100 W electric bulb runs for 10 seconds, the total heat energy produced is:

$$H = P \times t = 100 \text{ W} \times 10 \text{ s} = 1{,}000 \text{ J}$$

Kilowatt-hour

Electrical energy is commonly consumed in very large quantity. The unit which is used to measure large amount of electrical energy is called kilowatt-hour. It is defined as:

The amount of energy delivered by a power of one kilowatt in one hour is called kilowatt-hour.

One kilowatt-hour (1 kWh)= 1,000 W ×1 hour ..... (16.16)

$$= 1{,}000 \text{ W} \times (3600 \text{ s})$$

$$= 3.6 \times 10^6 \text{ J} = 3.6 \text{ MJ}$$

The energy in kilowatt-hour can be obtained by the formula:

$$\text{The amount of electrical energy in kilowatt-hour} = \frac{\text{Power in watts x time of use in hours}}{1{,}000}$$

The electric meter installed in our houses measures the consumption of electrical energy in the units of kilowatt-hour according to which we pay our

electricity bills. If the cost of one kilowatt-hour i.e., one unit is known, we can calculate the amount of electricity bill by the formula:

Cost of electricity = Number of units consumed × Cost of one unit

$$= \frac{\text{Power in watts x time of use in hours}}{1{,}000} \times \text{Cost of one unit}$$

When designing circuits, it is important to choose components with suitable power ratings. Selecting components with the right power ratings ensures safety, reliability, and efficiency.

Brain Teaser

If two appliances are rated 100 W and 1,000 W, both used for 1 hour. Do they consume equal energy or different? Why?

Example 16.4: Calculate the one-month cost of using a 100 W ceiling fan for 10 hours daily in your room. Assume that the price of one unit is Rs.25.

Solution:

Given that; Power $P = 100\ W = 0.1\ kW$

Time $t = 10$ hour per day

Number of days $= 30$

To find; One month cost of electricity = ?

Number of units consumed = Power × Time × Days

$= 0.1 \times 10 \times 30 = 30$ units

Total cost = Units consumed × Price per unit

16.10 Household Circuits and Safety Measures

Household circuits safely distribute electricity through different pathways in a home. Safety measures protect against electrical hazards.

Household Circuits

In a parallel circuit, every appliance like our refrigerator, bulbs, or TV gets its own direct connection to the power supply. In the parallel circuits, each appliance works independently. We can turn OFF the lights in the kitchen without shutting down the

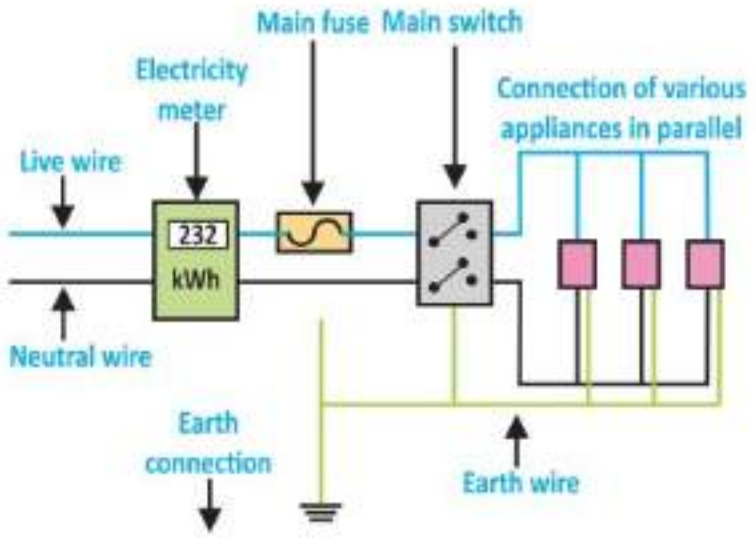


Fig. 16.19: Household circuit

TV in the living room. The parallel circuits are safer and more reliable. If one appliance breaks or a fuse blows, the rest of our home's power stays ON. In short, connecting our home's electrical system in parallel is like giving every appliance its own superpower consistent voltage, independent operation, and reliable performance. It is the smartest way to keep our home running smoothly and efficiently. Figure. 16.19 demonstrates a household circuit.

Hazards of Electricity and Safety Measures

Common electric hazards occur due to:

1. Malpractice (incorrect use) or lack of maintenance, and they can lead to serious accidents like shocks, fires, or even fatalities.

2. One major hazard is damaged insulation, where the protective covering on wires wears out or gets cut, and exposing live wires. This can cause electric shocks or short circuits.

3. Another danger is overheating cables, which happens when wires carry more current than they are designed for, causing them to heat up and potentially start a fire.

4. Overloading is a common issue plugging too many devices into a single socket, extension lead, or power strip can draw excess current, overheating the circuit and causing fires.

Fuses and trip switches (circuit breakers) are essential safety devices to avoid these hazards. Fuses contain a thin wire that melts due to flow of high current. As a result, breaking of the circuit stops the flow of electricity. Different types of fuses are shown in Fig. 16.20. Trip switches, on the other hand, automatically cut OFF power when they detect a fault, like an overload or short circuit (Fig. 16.21). Both devices are connected to the live wire of the circuit, ensuring that the entire circuit is switched OFF safely in case of a problem. One of the most critical safety features in a circuit is the earth wire. If a fault occurs such as a live wire

Fig. 16.20: Different types of fuses

Fig. 16.21: A trip switch

touching a metal casing, the earth wire provides a low-resistance path for the current to flow safely into the ground. This prevents the casing from becoming live and triggers the fuse or trip switch to cut OFF the power. This is why the outer casing of an electrical appliance must be either non-conducting (double-insulated) or earthed. Double-insulated appliances, like many power tools, have casings made of plastic, which cannot conduct electricity. Appliances with metal casings, like washing machines, are connected to the earth wire for safety.

Brain Teaser

Why can a tiny device like a smartphone charger trip the main switch if something goes wrong?

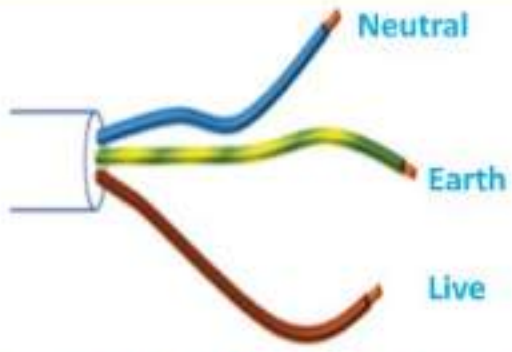


Fig. 16.22: Main circuit wires

Brain Teaser

Imagine your home has no Earth wire. What could happen if the live wire touches the metal body of an appliance?

A typical main circuit consists of three wires:

The live wire (line wire), which carries the current from the power supply; the neutral wire, which completes the circuit; and the earth wire, which provides a safety path for fault currents (Fig. 16.22). Despite these safety measures, electric shocks can still occur, and they can be extremely dangerous. When electricity passes through the human body, it can cause burns at the entry and exit points. More seriously, it can disrupt the body's electrical signals, leading to cardiorespiratory failure (where the heart and lungs stop working) or seizures. This is why proper safety mechanisms like fuses, circuit breakers, and earthing are so important which help to prevent accidents and protect lives. The symbols of various electrical components are shown in Fig. 16.23.

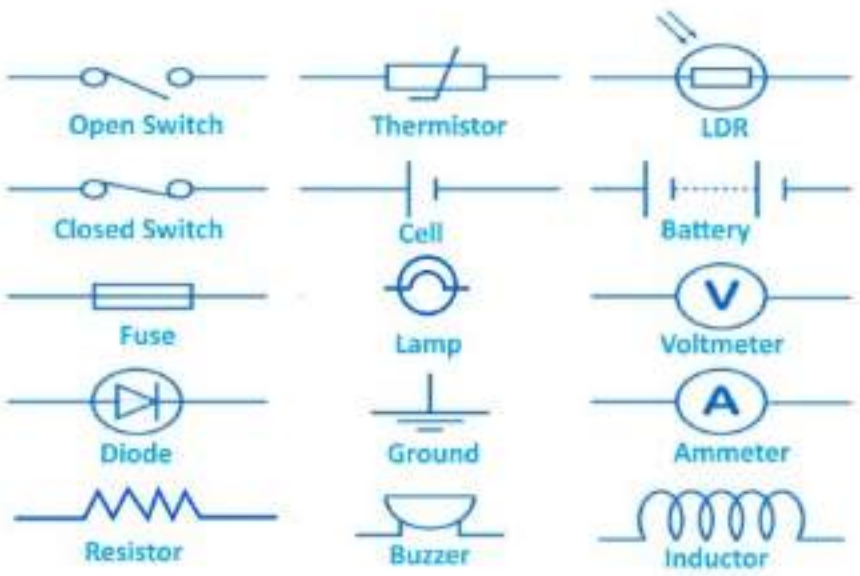


Fig. 16.23: Symbols of various electrical components

EXERSICE

A. Multiple Choice Questions

Tick (✓) the correct answer

16.1 The direction of conventional current is:
(a) from negative to positive terminal
(b) from positive to negative terminal
(c) in both directions at the same time
(d) it does not have a fixed direction

16.2 What type of electric current flows in one direction only?
(a) Alternating current (b) Direct current
(c) Induced current (d) None of these

16.3 The device used to measure electric current:
(a) voltmeter (b) ammeter (c) ohmmeter (d) wattmeter

16.4 What is the function of an electromotive force (e.m.f.) source in a circuit?
(a) To reduce resistance in the circuit
(b) To provide energy to drive charges through the circuit
(c) To store electrical energy for later use
(d) To convert electrical energy into mechanical energy

16.5 The relationship between voltage, current, and resistance is:
(a) $V = IR$ (b) $V = I/R$ (c) $V = I^2R$ (d) $V = R/I$

16.6 What happens to the resistance of a metal conductor when its temperature increases?
(a) It decreases (b) It remains constant
(c) It increases (d) It becomes zero

B. Short Answer Questions

16.1 How does an ammeter measure electric current?

16.2 What is the main difference between direct current and alternating current ?

16.3 Define electromotive force (e.m.f.).

16.4 State Ohm's law and define resistivity.

16.5 What is the formula for calculating the equivalent resistance of resistors connected in series ?

16.6 How does temperature affect the resistance of a conductor?

C. Constructed Response Questions

16.1 Why is it important that an ammeter has very low resistance and is connected in series, while a voltmeter has very high resistance and is connected in parallel? What would happen if they were connected incorrectly?

16.2 If a copper wire is replaced with an aluminum wire of the same dimensions, how would the current and power consumption change in the same circuit? Explain using the concept of resistivity.

16.3 In a household lighting circuit, what practical problems might arise if the bulbs were connected in series instead of parallel?

16.4 You are tasked with designing a fuse for a device that operates at 230 V and 5 A. What rating would you choose for the fuse and why? What could go wrong if the rating is too low or too high?

16.5 Explain why A.C is more suitable for power transmission across cities, even though D.C is used in batteries and portable electronic devices.

D. Comprehensive Questions

16.1 Explain the concept of electric current. How is it related to the movement of charges, and how is it measured in a circuit?

16.2 Define electromotive force (e.m.f.) and potential difference. How does a battery create a potential difference, and what is the role of e.m.f. in maintaining the flow of current?

16.3 State and explain Ohm's law. How does the resistance of a conductor affect the flow of current, and how can Ohm's law be applied in practical electrical circuits?

16.4 Differentiate between series and parallel combinations of resistors. Provide mathematical expressions for calculating the total resistance in both types of circuits.

16.5 What is meant by resistivity of a material? How does it depend on the material, and what role does temperature play in changing the resistivity of conductors and semiconductors?

E. Numerical Problems

16.1 A charge of 25 coulombs passes through a circuit in 10 seconds. Calculate the current flowing through the circuit. **[Ans: 2.5 A]**

16.2 Three resistors of 4 Ω, 6 Ω, and 8 Ω are connected in series to a 24 V battery. Find the total resistance and the current flowing through the circuit. **[Ans: 18 Ω, 1.33 A]**

16.3 Two resistors of 10 Ω and 30 Ω are connected in parallel across a 20 V power supply. Calculate the total resistance and the current drawn from the power supply. **[Ans: 7.5 Ω, 2.67 A]**

16.4 Four 1.5 V batteries are connected in series in a flashlight. Determine the total electromotive force (e.m.f.) supplied to the circuit. **[Ans: 6 V]**

16.5 A circuit has a 5 A current passing through a 7 Ω resistor. Calculate the power dissipated in the resistor and the energy consumed in 10 minutes. **[Ans: 175 W, 105 kJ]**

CHAPTER 17

ELECTROMAGNETISM

Student's learning outcomes (SLOs)

After studying this chapter, students will be able to:

- describe the pattern and direction of the magnetic field due to currents in straight wires and in solenoids.
- state the effect on the magnetic field of changing the magnitude and direction of the current.
- describe how the magnetic effect of a current is used in relays and loudspeakers (including giving examples of their application).
- describe an experiment to show that a force acts on a current-carrying conductor in a magnetic field (including the effect of reversing:
  (a) the current
  (b) the direction of the field
- state and use the relative directions of force, magnetic field, and current.
- describe the magnetic field patterns between currents in parallel conductors and relate these to the forces on the conductors (excluding the Earth's field).
- state that a current-carrying coil in a magnetic field may experience a turning effect and that the turning effect is increased by increasing:
  (a) the number of turns on the coil
  (b) the current
  (c) the strength of the magnetic field
- describe the operation of an electric motor, including the action of a split-ring commutator and brushes.
- describe and explain the action of relays in switching circuits.
- state that it is theorized that the Earth's magnetic field is generated by the rotation of the Earth and its molten iron core that contains charged particles in motion.

Electromagnetism is the branch of physics that deals with the interactions between electric and magnetic fields. It explains how electric charges produce electric fields, and how moving charges, like an electric current, create magnetic fields. This connection helps us to understand how modern devices work. Electromagnetism is an essential part of everyday life, powering electric circuits, communication systems and generators. Even light is an electromagnetic wave, showing how important this force is in science and technology. Learning about electromagnetism gives us the knowledge to build useful machines and to understand the science behind today's technology.

17.1 Magnetic Effects of Steady Current

The magnetic effects of a steady current can be demonstrated through experiments involving a current-carrying conductor.

Magnetic Field B Due to Current in a Straight Wire

Hans Christian Orsted stated that, a steady electric current in a conductor generates a magnetic field **B** around it. This can be demonstrated by passing a current-carrying wire through a vertical cardboard sheet and connecting it to a battery. When current flows, magnetic field is produced around it whose direction can be determined using right hand grip rule. Concentric circles are formed by the magnetic field around the conductor. This can be observed by placing small compasses or sprinkling iron filings on the cardboard. The compass needles align themselves along the direction of the magnetic field, pointing tangentially to the circular lines of force (Fig. 17.1-a). If the direction of the current is reversed by switching the battery terminals, the compass needles and iron filings also reverse their alignment, indicating that the magnetic field direction depends on the current flow (Fig. 17.1-b). In the dot and cross convention, a dot (.) represents current flowing out of the paper, while a cross (×) indicates into the paper. The magnetic field is strongest near the conductor and weakens with distance. This concept is essential in electrical engineering, particularly with alternating currents.

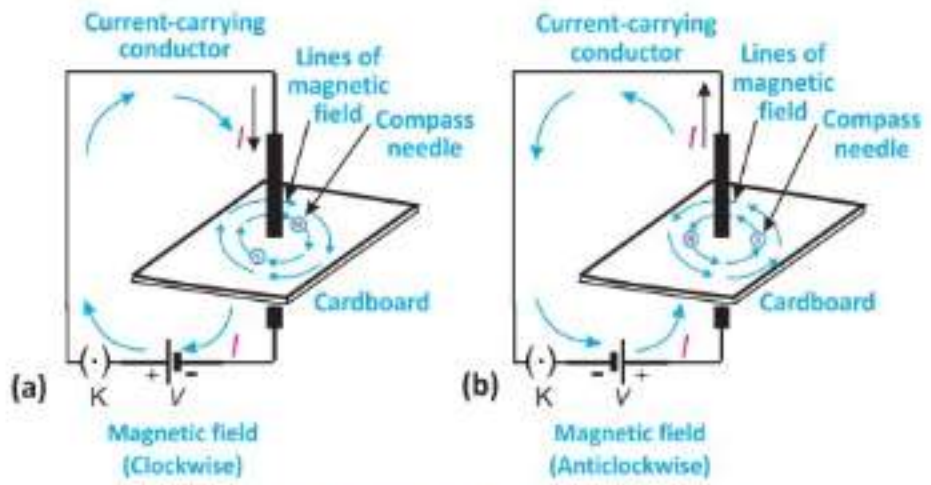


Fig. 17.1: Magnetic effects of a current

Direction of the Magnetic Field of a Current-Carrying Wire

The direction of the magnetic field **B** around a current-carrying straight wire can be found using the right-hand grip rule, as shown in Fig. 17.2 .

According to the right-hand grip rule:

If you hold the wire in your right hand with your thumb pointing in the direction of the current, then your fingers curl around the wire in the direction of the magnetic field.

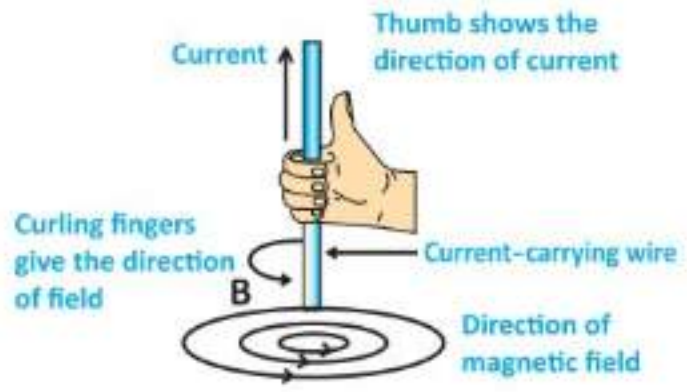


Fig. 17.2: Current-carrying conductor

This simple method helps us to quickly find the magnetic field direction around any straight current-carrying wire. The magnetic field forms circular loops around the wire, and its direction depends on the direction of the current. If the current changes direction, the direction of magnetic field also changes.

Magnetic Field Due to Current in a Solenoid

A solenoid is a coil of wire wounded in the shape of a cylinder that generates a magnetic field when current flows through it. The combined effect of all loops of the wire of solenoid makes the field strong and uniform, like a bar magnet with north and south poles. A solenoid acts as a magnet and can attract or repel a bar magnet. This temporary magnet, powered by electricity, is called an electromagnet (Fig. 17.3). The right-hand rule helps to find out the direction of the magnetic field produced by the solenoid (Fig. 17.4). According to this rule:

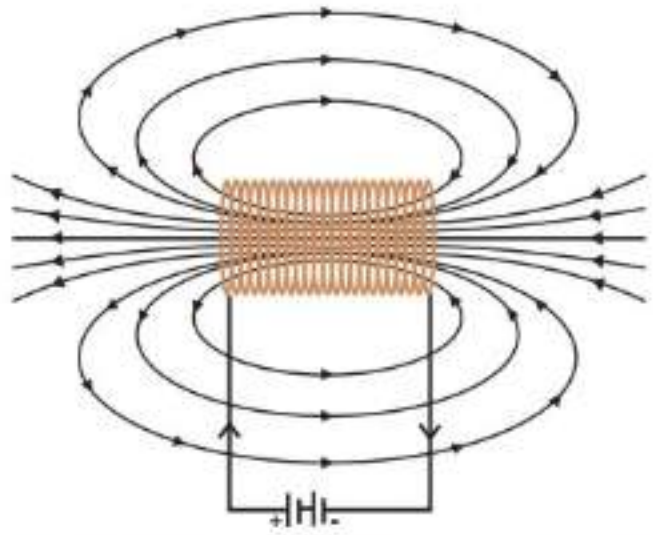


Fig. 17.3: Magnetic field due to solenoid

If you grip the solenoid with your right hand such that the curled fingers point in the direction of the conventional current, then the thumb will point towards the north pole of the solenoid.

Electromagnets are useful in motors, relays, and magnetic locks because their magnetic strength can be controlled by adjusting the current.

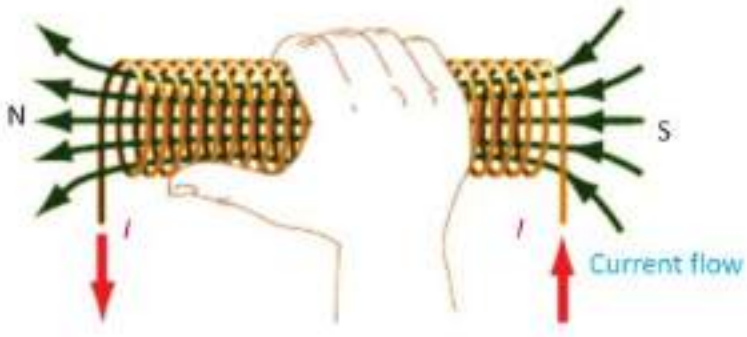


Fig. 17.4: Right hand rule for a solenoid

Properties of Magnetic Field Lines

Magnetic field lines, just like electric field lines, are imaginary. They do not physically exist but are a way to visualize the magnetic field. These lines have important properties:

1. Magnetic field lines always start from the north pole and end at the south pole.
2. Magnetic field lines always form closed loops.
3. At any point, the tangent to a magnetic field line shows the direction of the magnetic field.
4. Magnetic field lines never cross (intersect) each other.
5. Where magnetic field lines are closer together, the magnetic field is stronger; where they are spread apart, the magnetic field is weaker.

Understanding these properties helps us to visualize how magnetic fields behave around magnets, current-carrying wires, and in devices like motors and generators. These ideas are very important in real-world technologies.

Forces on Parallel Current-Carrying Conductors

When two wires carry electric current in the same direction, they create magnetic fields around themselves. As shown in Fig. 17.5(a), the magnetic fields between the two wires interact in such a way that the opposite poles are near each other, and the two wires attract each other. This happens because the magnetic fields support each other between the wires and pull them together.

However, if the current in the two wires flows in opposite directions, their magnetic fields

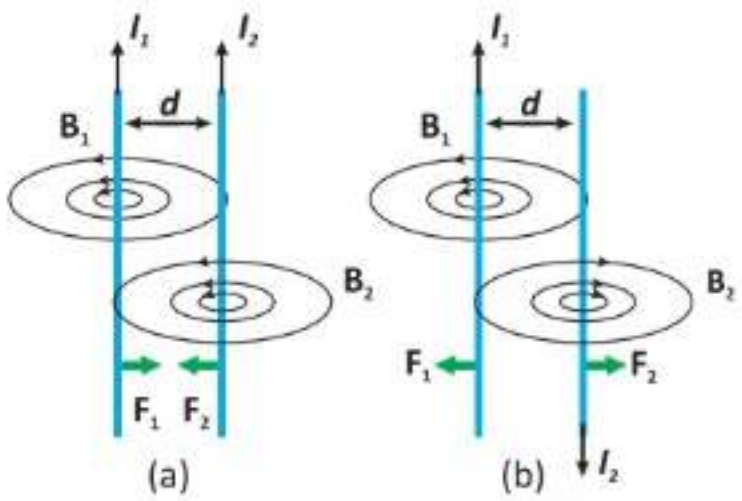


Fig. 17.5: Forces between parallel wires

oppose each other, and the wires will repel each other (Fig.17.5-b). This important behaviour is the basic idea behind electromagnetic devices and technologies like electric motors and electromagnets.

17.2 Force on a Current-Carrying Conductor in a Magnetic Field

It is known that an electric current generates a magnetic field, much like a permanent magnet does. Since a magnetic field exertes a force on a permanent magnet, it follows that a current-carrying conductor should also experience a force when placed in a magnetic field.

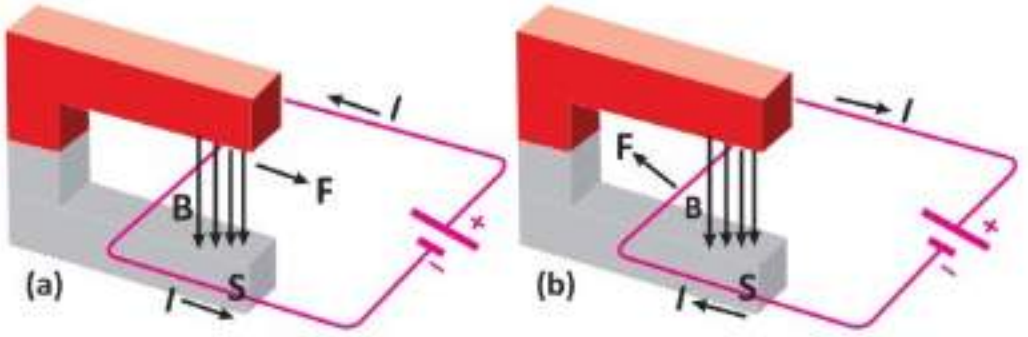


Fig. 17.6: Force on a current-carrying wire in magnetic field

The effect of a magnetic field on a wire carrying current can be illustrated using the setup in Fig. 17.6. A battery creates an electric current in the wire positioned inside the magnetic field of a permanent magnet. This wire then generates its own magnetic field, which interacts with the magnetic field of the magnet. As a result, a force acts on the wire. Based on the direction of the current, the wire is either pushed tot he right (Fig.17.6-a) or pulled to the left (Fig. 17.6-b).

Michael Faraday found that this force is always at right angles to both the direction of the magnetic field and the direction of the current. The force becomes stronger if:

1. The electric current (*I*) in the wire increases

2. The magnetic field (*B*) becomes stronger

3. Length (*L*) of the wire inside the magnetic field

The magnitude of this force is given as:

$$F = ILB\sin\theta$$

The direction of this force can be determined using **Fleming's left-hand rule**, which states:

Extend the thumb, forefinger, and middle finger of the left hand so that they are at right angles to one another. If the forefinger represents the magnetic field direction and the middle finger shows the current direction, then the thumb will point in the direction of the force acting on the conductor.

As illustrated in Fig. 17.7, the force on the conductor is perpendicular to both the current and the magnetic field, in accordance with Fleming's left-hand rule.

Fig 17.7: Direction of force on a current-carrying conductor placed in a magnetic field

The SI unit of magnetic field (also called magnetic flux density) is the tesla (T).

1 tesla (T) is defined as:

The magnetic field strength one tesla which causes a force of 1 N on a 1 metre length of wire carrying a current of 1 A perpendicular to the magnetic field.

i.e; $1T = 1\ N\ A^{-1}\ m^{-1}$

17.3 Turning Effect on a Current-Carrying Coil in Magnetic Field

Let us imagine a rectangular coil PQRS that is carrying a current and is placed in a magnetic field, as shown in Fig. 17.8. The coil is positioned in such a way that it is perpendicular to the magnetic field of a permanent magnet. Now, if we connect the ends of the coil to a battery, electric current starts flowing through the coil. When this happens, we can apply Fleming's Left Hand Rule to understand what force acts on the different parts of the coil. According to the rule:

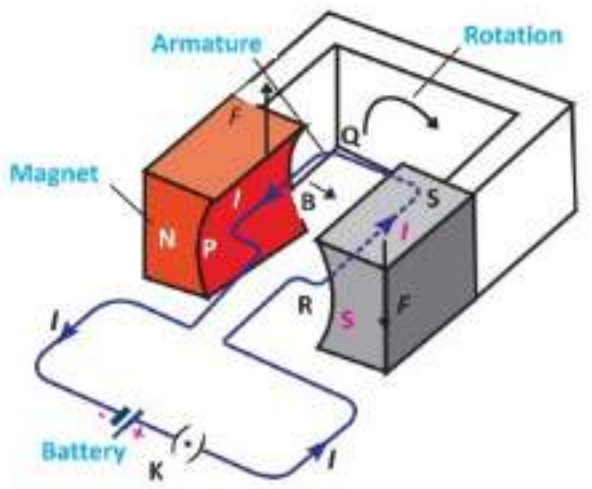


Fig. 17.8: A current-carrying coil in a magnetic field

On the side PQ of the coil, the force acts outward. On the side RS, the force acts inward. This happens because the current flows in opposite directions on the two sides of the coil. As a result, two forces are produced that are equal in magnitude but opposite in direction. These opposite forces form a couple. A couple produces a rotational effect or torque, which causes the coil to start rotating.

Thus, we can say that:

When a current-carrying coil is placed in a magnetic field, it experiences a couple of forces that makes the coil rotate, as shown in Fig.17.8. This is the working principle

of electric motors, which are used everywhere around us from fans to cars.

The turning effect on the coil can be made stronger by

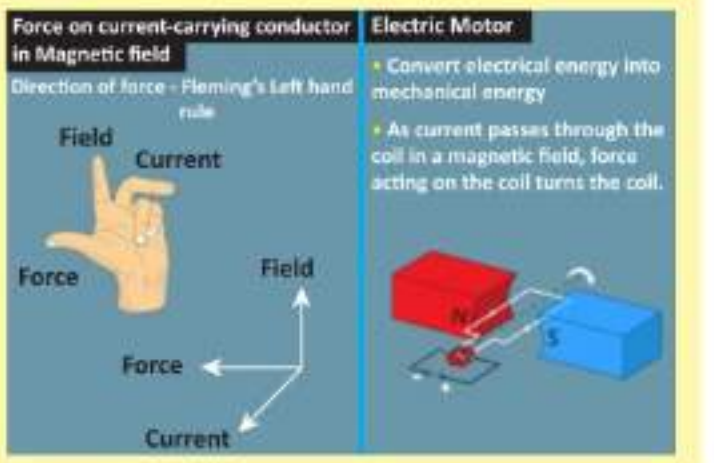
1. increasing the number of turns of the coil. More loops mean a stronger turning effect of force.

2. increasing the current flowing through the coil. More current creates a stronger torque.

3. increasing the strength of the magnetic field. A stronger magnet makes the coil to rotate with more torque.

These factors help to make electric motors more powerful and efficient.

Do You Know?



17.4 Electric Motor

An electric motor is a device that converts electrical energy into mechanical energy. There are two types of electric motors, one is Alternating Current (A.C) motor and the other is Direct Current (D.C) motor. A D.C motor operates using the interaction between a current-carrying coil (armature) and a magnetic field. When a coil is placed in a magnetic field, it experiences forces that cause it to rotate (Fig. 17.9).

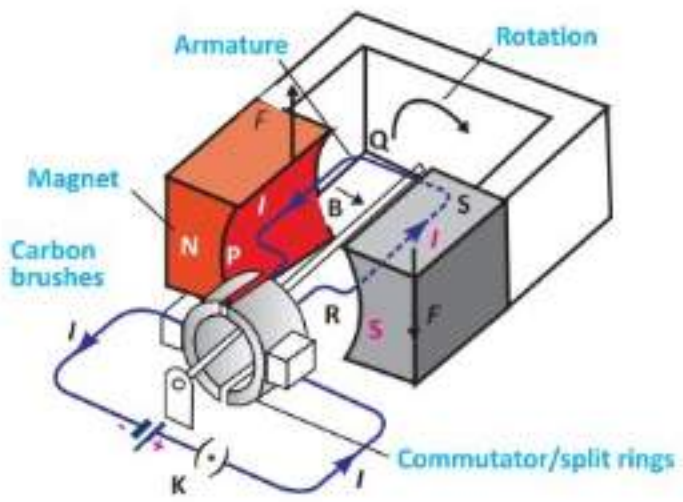


Fig. 17.9: Working principle of D.C motor

However, without any external help, the coil would stop rotating after 90°, as the forces acting on its sides (such as PQ and RS) push it into a vertical position, making the coil perpendicular to the magnetic field. At this point, the net force becomes zero, preventing further rotation. To keep the coil rotating, the current direction must be reversed just as the coil reaches the vertical position. This is achieved using a split ring commutator, which is a metal ring divided into two halves, each connected to one end of the coil. Carbon brushes maintain contact with the commutator, allowing current to flow. As the coil rotates, the commutator also rotates, and when the coil reaches the vertical position, each half of the commutator

switches brushes, reversing the current direction. As a result, direction of the current changes the direction of the forces which allows continuous rotation of the coil. The speed of the motor can be adjusted by controlling the current flowing through it.

Tidbit

What is the special role of a split ring commutator in D.C motor?

17.5 Use of Magnetic Effects of Current

The magnetic effects of electric current are used in modern technology. The principle of creation of magnetic field due to current flow in a wire is utilized in relays and loudspeakers which rely on the interaction between electric currents and magnetic fields to perform their functions. These applications demonstrate how the magnetic effects of current enable the conversion of electrical energy into mechanical energy or sound, making them essential in electrical and electronic systems.

Relay

A relay is an electrical device that uses magnetism to control another circuit. It acts like a bridge between the input and output circuits, allowing a small current to provide a larger current. As shown in figure 17.10 (a), a relay uses the magnetic effect of a current to switch an output circuit ON or OFF. A mechanical relay consists of several important parts:

(a) Coil and Core

The relay has a coil made of wire wound around a magnetic core. When an electrical current passes through the coil, it creates a magnetic field. This magnetic field is the key that makes the relay work.

(b) Armature

The armature is a small movable piece inside the relay. When the coil becomes magnetised and demagnetised, it pulls the armature towards itself. This movement helps to open or close the switch connected to the relay.

(c) Return Spring

The return spring is connected to the armature. It brings the armature back to its original position when the current stops. In simple words, it acts like a reset button that resets the relay when electricity is cut off.

(d) Moving Contact

The moving contact is attached to the armature. When the armature moves due to magnetism, the moving contact also moves. This contact either joins or breaks the circuit, allowing or stopping the flow of current to the device (like a lamp). Similarly, it helps to open door lock, starting of motor car and heavy machines.

How a Relay Works?

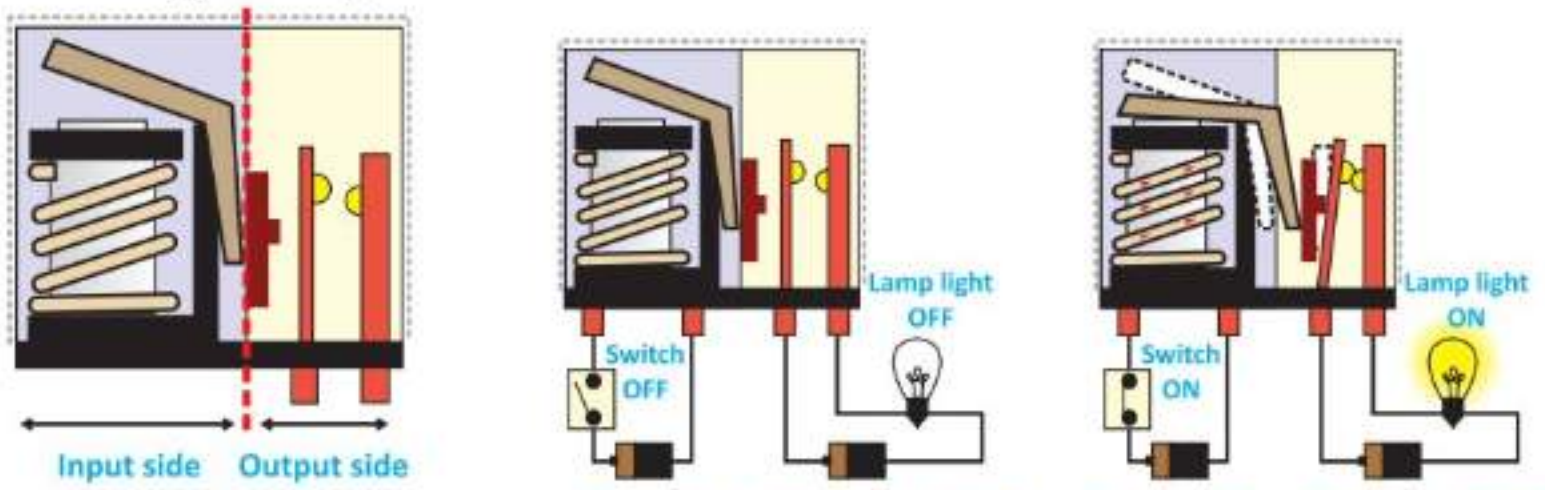
A relay helps to turn ON and OFF a lamp easily:

When the switch is OFF

No current flows through the coil. The armature stays in its normal position. As a result, the lamp's circuit remains open, and the lamp does not glow, as shown in Fig. 17.10 (b).

When the switch is ON

Current starts flowing through the coil. The coil becomes magnetised and pulls the armature towards it. This action closes the lamp's circuit and the lamp glows, as shown in Fig. 17.10 (c).

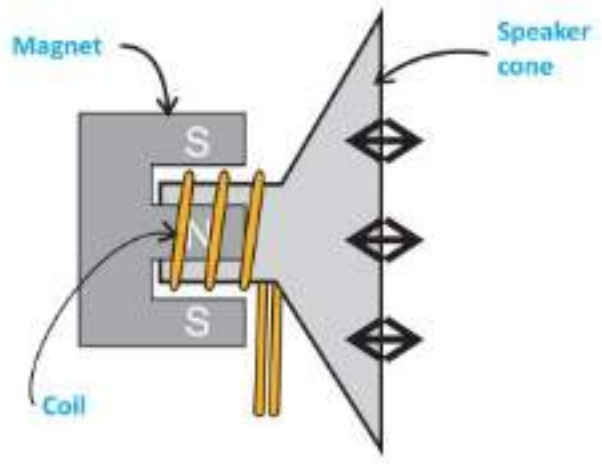


(a) A mechanical relay (b) The switch of the relay is OFF (c) The switch of the relay is ON

Fig. 17.10: Relay

Loudspeaker

A loudspeaker also uses the magnetic effects of current to convert an electrical signals into sound. It consists of a coil (attached to a diaphragm) which is placed in a permanent magnetic field as shown in Fig. 17.11. When an alternating current (audio signal) flows through the coil, it generates a varying magnetic field that interacts with the permanent magnetic field. This interaction generates a force on the coil, causing it to move back and forth. The movement of the coil vibrates the diaphragm, producing sound waves that correspond to the



Fig, 17.11: Magnetic effects in loudspeakers

electrical signal. Loudspeakers are used in audio systems, public address systems, and televisions etc.

17.6 Earth's Magnetic Field

Earth's magnetic field acts like an invisible shield that surrounds the planet and stretches into space (Fig. 17.12). It is similar to the field of a bar magnet, with a north and south pole, but unlike a regular magnet, it constantly shifts and can even flip over time. This magnetic field is essential because it protects the Earth from dangerous solar winds and cosmic radiations by pushing away harmful charged particles and radiations. It also helps with navigation, guiding both humans and animals like migratory birds and sea turtles by allowing them to sense Earth's magnetic direction.

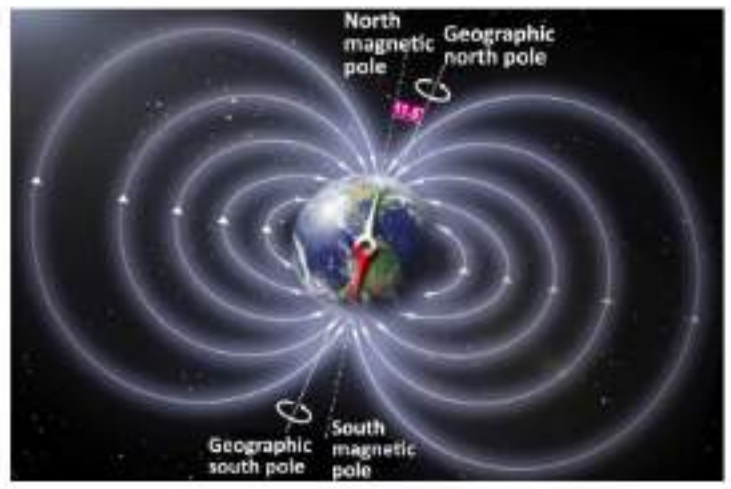
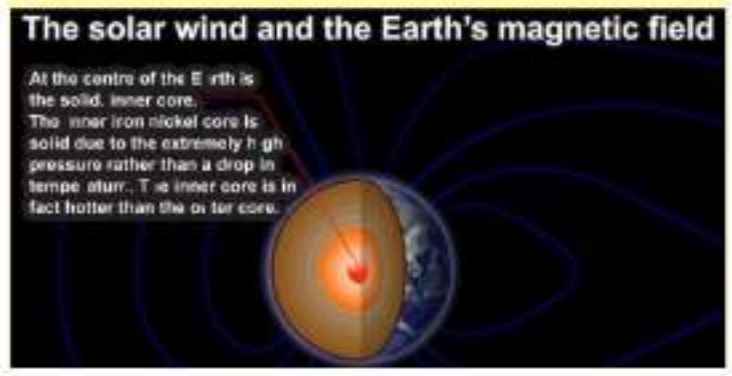


Fig. 17.12: Earth's magnetic field

Origin of Earth's Magnetic Field

The Earth acts like a giant magnet. Scientists believe this is because its molten iron core is constantly spinning and the movement of these charged particles creates a huge magnetic field. Earth's magnetic field is thought to be generated by the movement of liquid metal in its core, a process known as the dynamo effect (Fig. 17.13). The core has two parts: a solid inner core and a liquid outer core made of molten iron and nickel. As the Earth spins, heat from the inner core causes the liquid metal to flow, creating electric currents. These currents produce magnetic fields, which combine and grow stronger due to the Earth's rotation. This process, called magneto-hydrodynamics, keeps the magnetic field active and forms the magnetosphere, a protective barrier that shields Earth from harmful solar wind and space radiation.

Do You Know?



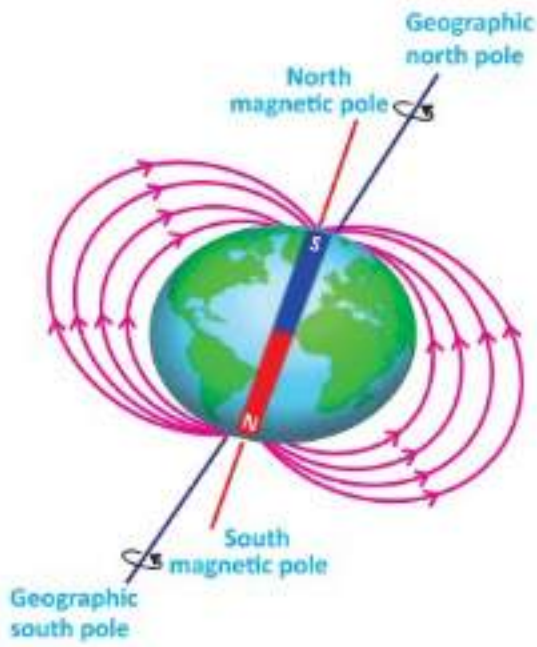


Fig. 17.13: Origin of Earth's magnetic field

EXERCISE

A. Multiple Choice Questions

Tick (✓) the correct answer.

17.1 Which statement is true about the magnetic poles?
(a) Unlike poles repel
(b) Like poles attract
(c) Magnetic poles do not affect each other
(d) A single magnetic pole does not exist

17.2 A D.C motor converts:
(a) mechanical energy into electrical energy
(b) mechanical energy into chemical energy
(c) electrical energy into mechanical energy
(d) electrical energy into chemical energy

17.3 The part of a D.C motor that reverses the direction of current through the coil every half-cycle:
(a) the armature
(b) the commutator
(c) the brushes
(d) the split rings

17.4 The two main layers of the Earth's core that contribute to the generation of the magnetic field are:
(a) crust and mantle
(b) inner core and outer core
(c) lithosphere and asthenosphere
(d) troposphere and stratosphere

17.5 What does a steady electric current in a conductor generate around it?
(a) Electric field
(b) Light
(c) Magnetic field
(d) Sound waves

17.6 What happens to the magnetic field direction when the direction of the current is reversed?
(a) The magnetic field remains unchanged
(b) The magnetic field also reverses direction
(c) The magnetic field becomes stronger
(d) The magnetic field disappears

B. Short Answer Questions

17.1 What is the direction of the magnetic field around a straight current carrying wire?

17.2 What happens to the magnetic field if the magnitude of the current in a wire is increased?

17.3 How can you identify the north and south poles of an unmarked magnetized steel bar?

17.4 What rule determines the direction of force on a current-carrying conductor placed in a magnetic field? Explain briefly.

17.5 What role does the commutator play in a D.C motor?

17.6 What is the source of the Earth's magnetic field according to the theory?

C. Constructed Response Questions

17.1 Why does a magnetic field form around a conductor when current flows through it, but not when the current is OFF? What does this reveal about the nature of electricity and magnetism?

17.2 In a D.C motor, why does the coil stop turning after 90° if the direction of the current is not reversed? What mechanical feature solves this issue?

17.3 How does placing a wire at different angles to a magnetic field affect the magnetic force it experiences, and why is this important in designing motors?

D. Comprehensive Questions

17.1 How is a magnetic field created around a current-carrying wire, and what factors affect its strength?

17.2 Explain the concept of the right-hand grip rule and how it helps determine the direction of the magnetic field around a current-carrying conductor.

17.3 Describe an experiment that demonstrates the magnetic field produced by a current-carrying conductor using a compass or iron filings.

17.4 Discuss the theory behind the Earth's magnetic field and the role of the Earth's molten core in generating it.

CHAPTER 18

ELECTROMAGNETIC INDUCTION AND ELECTROMAGNETIC (E.M.) WAVES

Student's learning outcomes (SLOs)

After studying this chapter, student will be able to:

- describe an experiment to demonstrate electromagnetic induction.
- use the fact that the magnitude of an induced e.m.f. is affected by the rate of change of the magnetic field or the rate of cutting of magnetic field lines, and the number of turns in a coil, to solve simple electromagnetic problems.
- use the fact that the effect of the current produced by an induced e.m.f. is to oppose the change producing it (Lenz's law).
- describe how a.c. generators work (rotating coil or rotating magnet setup) and the use of slip rings and brushes where needed.
- sketch and interpret graphs of e.m.f. against time for simple A.C. generators (including relating the position of the generator coil to the peaks, troughs and zeros of the e.m.f.).
- explain the principle of operation of a simple iron-cored transformer.
- use the terms primary, secondary coils and step-up and step-down transformer.
- use the equation $V_P / V_S = N_P / N_S$ (where P and S refer to primary and secondary) to solve problems.
- describe the deflection of an electron beam by electric fields and magnetic fields.
- interpret wave forms on oscilloscopes.
- state that the speed of all electromagnetic waves in: vacuum is 3.0×10^8 m s^{-1}, air is approximately the same as in a vacuum.
- explain qualitatively, how scattering of light by molecules in the air give the sky its blue colour during the day and its shades of red during sunset
  (use of the terms Rayleigh and Mei scattering are not required).

- state that theoretically light can also be considered to be made of massless particles that carry energy and momentum called 'photons'.
  (Students should know as an example of this particle nature, light exerts pressure on objects (very slight) and this has been used by satellites that have 'solar sails' that accelerate with the help of force from light rays.)

Have you ever wondered how electricity can be created without a battery? When a magnet moves near a wire, it produces electricity, a fascinating process called electromagnetic induction. This simple idea powers huge machines like generators and even charges our phone wirelessly. But the story does not end there. These changing electric and magnetic fields can travel through space as electromagnetic (E.M) waves bringing us light, radio signals, Wi-Fi, and even microwaves that heat our food. From lighting up cities to connecting people across the world, electromagnetic induction and E.M waves are the hidden forces shaping our everyday lives. Let us dive into the science behind these amazing wonders.

18.1 Electromagnetic Induction

Electromagnetic induction is the process by which a changing magnetic field produces an electric current in a conductor.

This principle, first discovered by Michael Faraday and at the same time Joseph Henry in 1831, is fundamental to the operation of many devices such as generators, transformers, and inductors. To understand the phenomena of electromagnetic induction let us perform experiments.

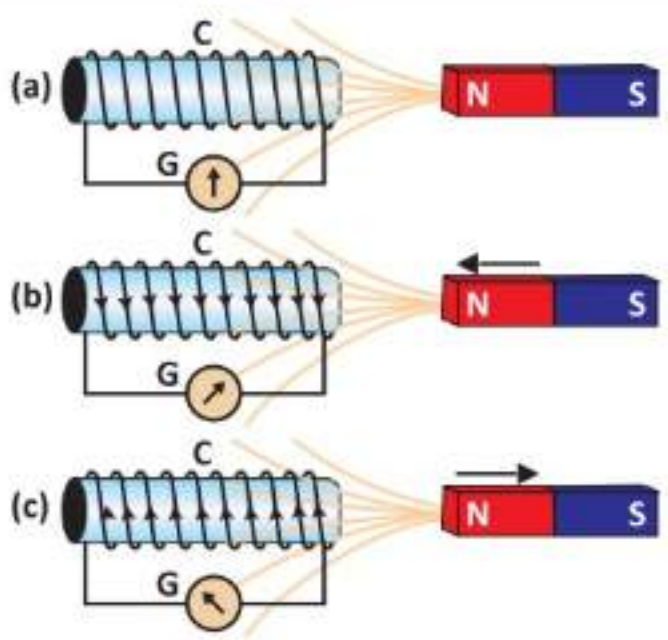


Fig. 18.1: Induced current in a coil by moving a magnet

Take a coil of conducting wire, labelled C, and connect it to a galvanometer G, as shown in Fig. 18.1. First, keep the magnet still near the coil. We will notice that the galvanometer needle does not move, no electricity is produced because there is no change happening in the magnetic field (Fig 18.1-a)

Now, move the magnet towards the coil. The galvanometer needle deflects in one

direction, meaning that current is being produced (Fig. 18.1-b).

Move the magnet away from the coil. This time, the galvanometer needle deflects in the opposite direction, showing the current has reversed (Fig.18.1-c).

There are different ways to produce induced e.m.f. Imagine a straight wire of length (ℓ) placed in the magnetic field of a permanent magnet as shown in Fig. 18.2. This wire is connected to a sensitive galvanometer, forming a closed circuit or loop without using any battery. When the loop is still in the magnetic field, no current flows, and the galvanometer shows no deflection. But when the loop is moved from left to right, the wire cuts through the magnetic field lines, and current starts to flow through the loop. The galvanometer shows this current. When the motion stops, the current also stops. If the loop is moved in the opposite direction, the current also changes direction, which is shown by the galvanometer deflecting in the opposite direction. The amount of the induced current depends on how fast the wire is moved and the resistance in the loop. If we change the resistance of the loop by connecting different resistors and move the loop at the same speed each time, we notice that the product of the current *I* and resistance *R* always remains constant.

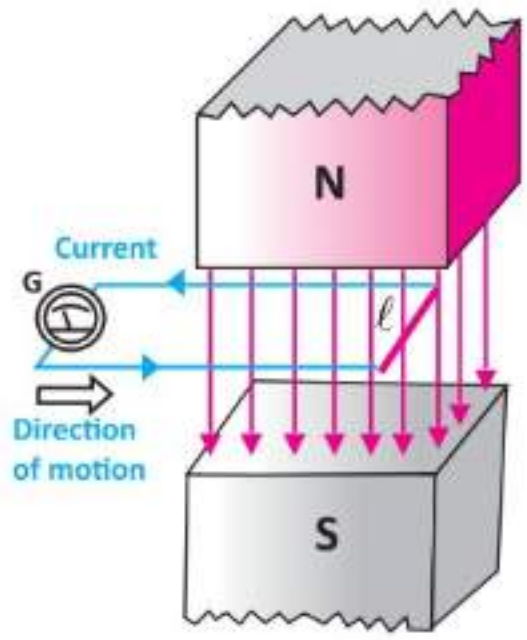


Fig. 18.2: Induction of current by moving a wire through a magnetic field

i.e; $I \times R$ = constant

This constant value is the induced e.m.f. When the circuit is complete, this induced e.m.f. causes a current to flow. The induced current can be increased in the following ways:

(i) using a stronger magnetic field

(ii) moving the loop more quickly

(iii) using a coil with many turns instead of a single loop

We can also do the experiment in another way: instead of moving the loop through the magnetic field, we can keep the loop still and move the magnet. The result is the same in both cases. This shows that it is the relative motion between the loop and the magnet that creates the induced e.m.f. In simple terms, this movement changes the magnetic flux through the loop.

Magnetic flux is the number of magnetic field lines passing through a certain area.

The magnetic flux (ϕ) is given by

$$\phi = B A \cos\theta \quad \ldots\ldots\ldots \quad (18.1)$$

B = Magnetic field strength

A = Area of the coil

θ = Angle between magnetic field and normal to the coil

The unit of magnetic flux is weber (Wb).

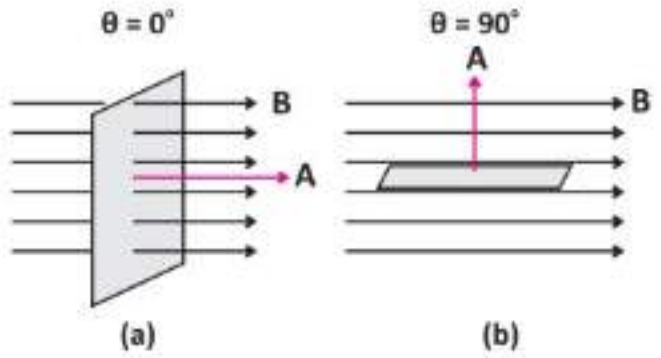


Fig. 18.3: Magnetic flux through a surface (a) Maximum (b) Zero

When a magnetic field of 1 tesla passes perpendicularly through an area of one square metre, the magnetic flux is equal to one weber.

Mathematically; 1 Wb = 1T m^2.

The magnetic flux is maximum when the angle between **B** and **A** is 0° (Fig. 18.3-a). However, when the angle between **B** and **A** is 90°, flux will be zero (Fig. 18.3-b).

Faraday's Law of Electromagnetic Induction

The average e.m.f. induced in a conducting coil of *N* loops is equal to the negative of the rate at which the magnetic flux is changing with time.

Mathematically; it is expressed as:

Where:

$$\varepsilon = -N \frac{\Delta\phi}{\Delta t} \quad \ldots\ldots\ldots \quad (18.2)$$

ε = induced e.m.f. (in volts, V)

N = number of turns in the coil

$\frac{\Delta\phi}{\Delta t}$ = rate of change of magnetic flux

Negative sign indicates that the induced emf opposes the change of magnetic flux that produce it.

Example 18.1: A coil with 25 turns experiences an induced emf of 2.5 V for 0.20 s. Assuming the e.m.f. is constant during this interval, calculate the total change in magnetic flux ($\Delta\phi$) through the coil.

Solution:

Given that;

Number of turns N = 25

Induced emf ε = 2.5 V

Time interval Δt = 0.20 s

To find; Change in flux $\Delta\phi$ = ?

Using the formula: $\varepsilon = (N \times \Delta\phi) / \Delta t$

Rearranging to solve for $\Delta\phi$:

$\Delta\phi = (\varepsilon \times \Delta t) / N$

Substituting the values $\Delta\phi = (2.5\ V \times 0.20\ s) / 25$

$\Delta\phi = 0.5 / 25 = 0.02\ Wb$

Magnitude and Direction of Induced e.m.f (Lenz's Law)

Lenz's Law is a fundamental principle in electromagnetism that describes the direction of the induced current resulting from a changing magnetic flux. It states that:

The direction of induced current is always such that it opposes the cause which produces it.

This law is a direct consequence of the conservation of energy. If the induced current were to reinforce the change instead of opposing it, it would lead to a perpetual increase in energy, which is impossible.

When a magnetic field near a conductor changes whether due to a moving magnet, a varying current, or a changing coil orientation an electromotive force (e.m.f.) is induced, driving a current. The direction of this current is not arbitrary; it must generate its own magnetic field that counteracts the original change in flux. For example, if a magnet is pushed toward a coil, the coil's induced current will produce a magnetic field that repels the magnet, resisting its motion (Fig. 18.4-a). Conversely, if the magnet is pulled away, the induced current will create a field that attracts the magnet, again opposing the movement (Fig.18.4-b).

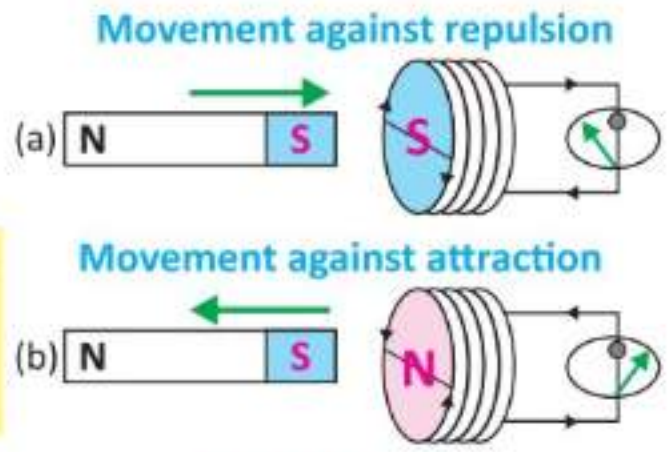


Fig. 18.4: Lenz's law

Do You Know?

- Simply moving a magnet through a coil can generate current. This is the same principle used in wind turbines and bicycle dynamos.
- The faster you change the magnetic field in a coil, the greater the current it produces, this is why fast-rotating generators make strong current.

Brain Teaser

If we stop moving a magnet near a coil, what happens to the induced current?

Tidbit

The faster we move a magnet through a coil, the greater the voltage (e.m.f.) is induced.

18.2 A.C. Generator

An alternating current (A.C) generator is a device that converts mechanical energy into electrical energy using electromagnetic induction. The most basic type includes a rectangular coil placed between the poles of a permanent magnet, as shown in Fig. 18.5(a). The coil is connected to two slip rings, which rotate along with the coil, while carbon brushes remain fixed and maintain contact with the slip rings to transfer the generated current.

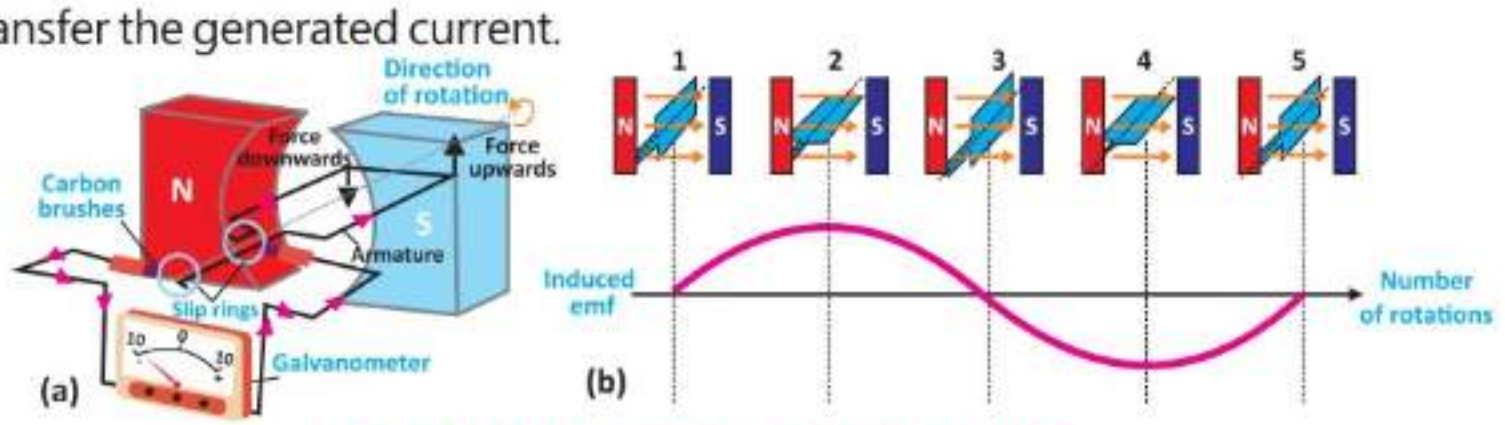


Fig. 18.5: An A.C generator and graph of current

As the coil rotates, it moves through the magnetic field, cutting the magnetic lines of force. This motion induces a voltage across the ends of the coil. The faster the coil rotates, the faster it cuts the magnetic field, resulting in a larger induced voltage. The induced voltage (or e.m.f.) changes throughout the rotation, as shown in Fig. 18.5(b). When the coil is vertical, it moves along the field lines, and no magnetic flux is cut. So, the induced voltage is zero. As the coil rotates and becomes horizontal, it cuts the magnetic field lines at the maximum rate, producing the maximum voltage. After a half-turn, the direction of the coil's movement through the field reverses, causing the polarity of the voltage to switch, resulting in an alternating voltage. This continuous change in direction creates an alternating current (A.C), which flows back and forth in the external circuit. The shape of the voltage graph is a sine wave, completing one full cycle in each full rotation of the coil. The number of such cycles per second is called the frequency, measured in hertz (Hz).

Tidbit

A generator works by spinning a coil in a magnetic field, creating electricity powering cities.

Do You Know?

In an A.C. generator, the voltage reverses direction with every half-turn of the coil that is why it is called alternating current.

Slip rings in an A.C. generator help to maintain continuous electrical contact with the rotating coil while allowing current to alternate naturally.

For example; if the coil rotates once per second, the frequency is 1 Hz, and if it

rotates 50 times per second, the frequency is 50 Hz (which is the frequency of A.C mains in many countries like Pakistan). According to Faraday's law of electromagnetic induction, an e.m.f. is produced in a coil when there is a change in magnetic flux through it. The amount of e.m.f. generated depends on how fast the magnetic field is being cut by the coil. Figure 18.6 shows how the e.m.f. varies with time during the rotation of a coil in a simple A.C generator. The graph clearly displays a sinusoidal pattern, which represents the alternating nature of the generated voltage.

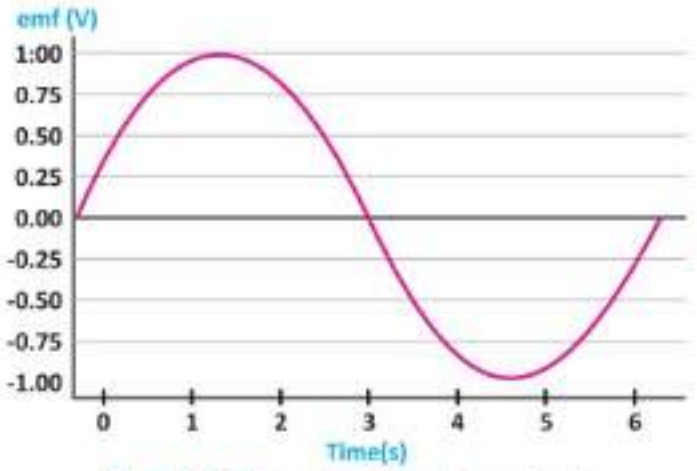


Fig. 18.6: Graph of e.m.f. against time for simple A.C generator

The e.m.f. reaches its maximum value when the coil is horizontal, as this is when it cuts the magnetic field lines at the highest rate. The e.m.f. becomes zero when the coil is vertical, since no magnetic flux is being cut at that position. As the coil continues to rotate, the direction of the e.m.f. reverses every half-turn, producing alternating current.

- At 0 and π radians (or 0° and 180°), the coil is vertical, and the e.m.f. is zero.
- At $\pi/2$ and $3\pi/2$ radians (or 90° and 270°), the coil is horizontal.
- At $\pi/2$, the e.m.f. is positive maximum.
- At $3\pi/2$, it reaches the negative maximum due to the reversal in direction of motion.

This repeating cycle creates the familiar A.C waveform, which alternates between positive and negative values over time.

18.3 Transformer

A transformer is a device used to increase or decrease the voltage in an alternating current (A.C) circuit. It works without any electrical connection between its input and output coils. Figure 18.7 shows a simple transformer. It has two coils of wire: the primary coil with N_P turns and the secondary coil with N_S turns. Both coils are wound on a soft iron core, which

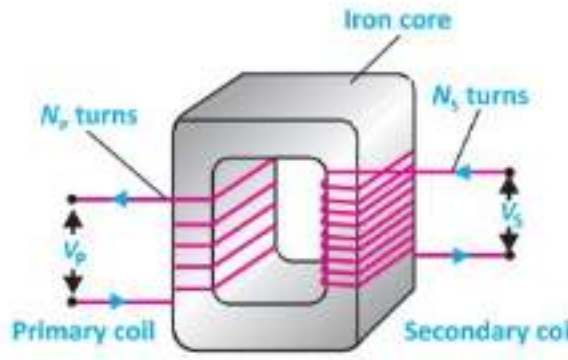


Fig. 18.7: Structure of a simple transformer showing primary and secondary coils wound around an iron core

helps carry the magnetic field from one coil to the other.

When an alternating voltage V_p is applied to the primary coil, it causes an alternating current I_p to flow. This current produces a changing magnetic field in the iron core. The magnetic field passes through the secondary coil, where it induces an alternating voltage V_s. This causes an alternating current I_s to flow in the secondary circuit. There is no direct electrical connection between the two coils. Energy is transferred from the primary coil to the secondary coil through the magnetic field in the core.

Do You Know?

The buzzing sound in transformers is due to the iron core vibrating at 50 or 60 Hz This vibration is caused by varying magnetic field and not by the current directly.

Step-up and Step-down Transformers

Transformers are used to either increase or decrease voltage in A.C circuits. When the secondary coil has more turns than the primary coil, the transformer increases the output voltage, it is called a step-up transformer (Fig. 18.8-a). Conversely, when the secondary coil has fewer turns than the primary, the output voltage is reduced, and it is known as a step-down transformer (Fig. 18.8-b).

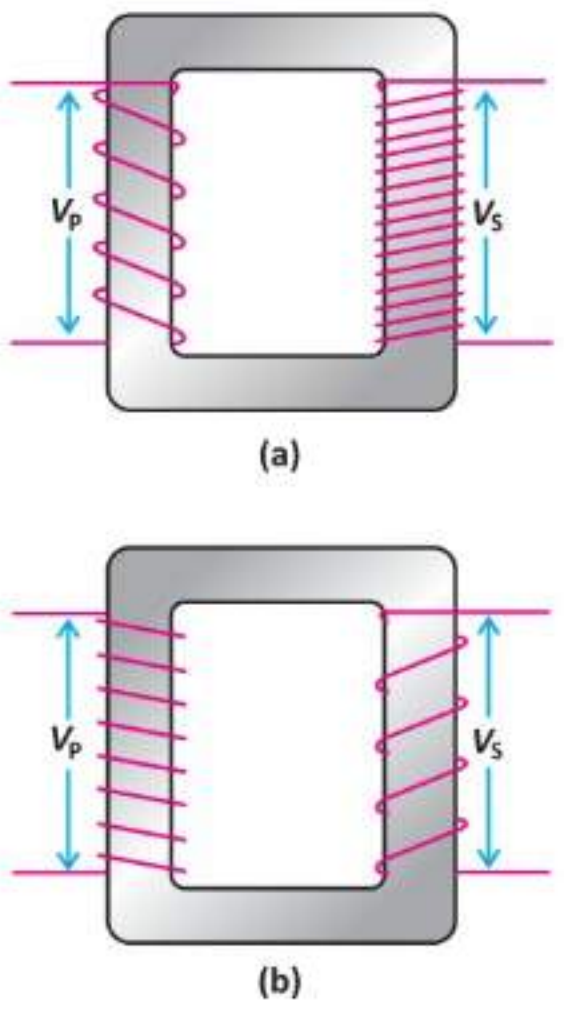


Fig. 18.8: (a) Step-up transformer
(b) Step-down transformer

This relationship between coil turns and voltages is described by the equation:

$$\frac{V_S}{V_P} = \frac{N_S}{N_P} \quad \text{.....} \quad (18.3)$$

This equation is known as the turns-ratio equation for a transformer.

where

V_P is the voltage across the primary coil

V_S is the voltage across the secondary coil

N_P is the number of turns in the primary coil

N_S is the number of turns in the secondary coil

This equation shows that the voltage ratio is directly proportional to the number of

turns in the coils. For example, if the primary has 5 turns and the secondary has 10 turns, the output voltage will be twice the input voltage.

Tidbit

Step-up transformers increase voltage for long-distance transmission, while step-down transformers reduce it to safe levels in our home.

Example 18.2: Electricity is transmitted at a voltage of 20,000 V with a current of 5 A through power cables that have a resistance of 10 Ω. Calculate the power loss in the cables?

Solution:

Given that;

$$\text{Voltage } V = 20{,}000 \text{ V}$$
$$\text{Current } I = 5 \text{ A}$$
$$\text{Resistance } R = 10 \ \Omega$$

To find;

$$\text{Power loss } P = ?$$

We know that;

$$\text{Power loss } P = I^2 R$$

Substituting the values

$$P = (5)^2 \times 10$$
$$P = 25 \times 10$$
$$P = 250 \text{ W}$$

The power loss in the cables is 250 W.

18.4 Deflection of Electron Beam in Electric and Magnetic Fields

The direction of electron beam or cathode rays can be changed by electric and magnetic field.

Deflection by Electric Field

The cathode rays generated from an electron gun are negatively charged electrons moving with high speed. Each negatively charged electron in cathode ray beam is attracted by the positive electrode and is repelled by the negative electrode. Thus, we can say that

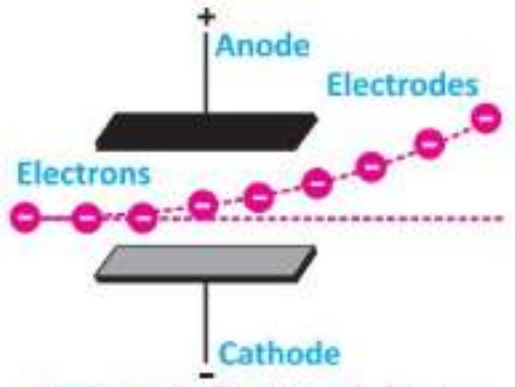


Fig. 18.9: Deflection of electron beam in an electric field

cathode rays are deflected toward positive electrode in the presence of electric field, as shown in Fig. 18.9.

Deflection by Magnetic Field

A magnetic field exerts force on electrically charged particles that are in motion. Cathode rays generated from an electron gun are a stream of negatively charged electrons. Electrons, while passing through the magnetic field, are deflected as shown in Fig. 18.10. To determine the direction of force and thus the deflection of the electron beam, the Fleming's left-hand rule can be used.

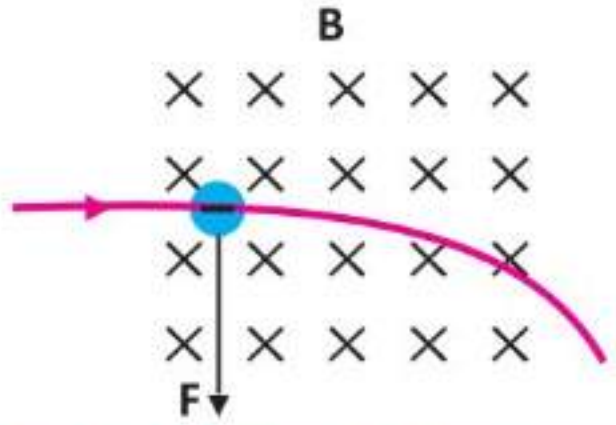


Fig. 18.10: Deflection of electron passing through uniform magnetic field

18.5 Waveform on Oscilloscope

A Cathode Ray Oscilloscope (CRO) is a widely used electronic instrument designed to display, observe, and measure how electrical signals change with time. The main component of the CRO is a cathode ray tube (CRT), as illustrated in Fig. 18.11(a), which includes an electron gun, deflecting system, and a fluorescent screen.

Brain Teaser

Which travels faster radiowaves or gamma rays? Why?

The electron gun generates a focused beam of electrons. It contains a heated filament F that heats the cathode C, causing it to emit electrons. These electrons are then accelerated and focused by three anodes placed at high positive potential. A control grid G, kept at a negative potential, controls how many electrons reach the screen and thus adjust the brightness of the spot formed. Once accelerated, the electron beam enters the deflecting system. The deflection system consists of two pairs of plates: the Y-plates, which control vertical movement (up and down) based on the input signal, and the X-plates, which control horizontal movement (left to right).

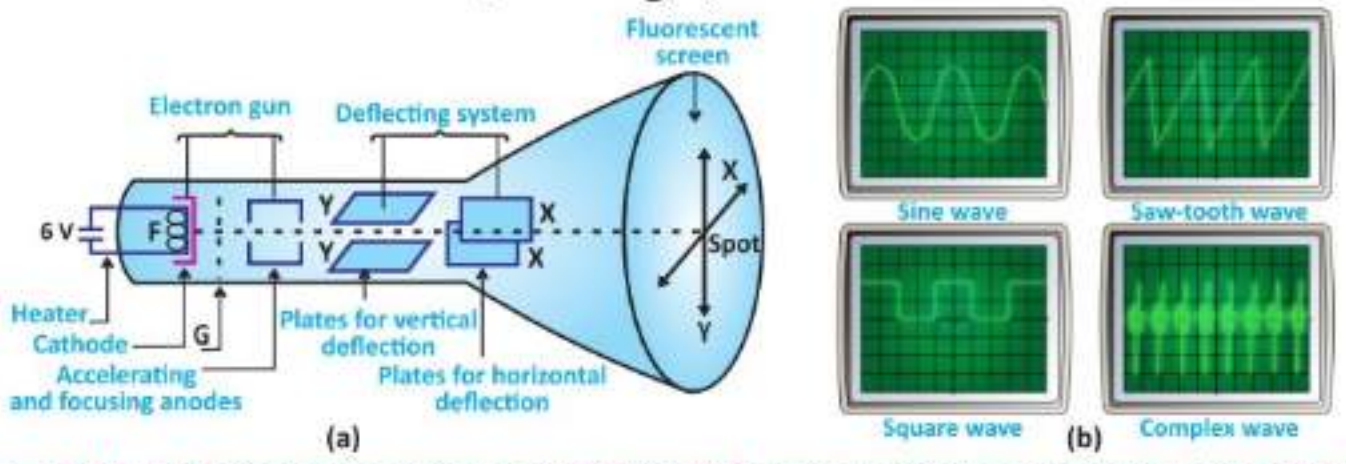


Fig. 18.11: (a) Schematic diagram of CRO (b) Different waveforms displayed on a CRO screen

The fluorescent screen is coated with a material that glows when the electron beam strikes it. As the beam strikes different points on the screen, it leaves a visible trace, allowing the waveform of the signal to be seen. To move the spot horizontally across the screen in a regular time-based manner, the CRO uses a saw-tooth waveform, which is applied to the X-plates. This waveform (Fig. 18.12) increases steadily over time and then rapidly drops to its starting value, repeating this cycle continuously. This pattern of voltage, called a saw-tooth wave, causes the electron beam to sweep from left to right and then drops to zero. This motion creates a time axis on the screen, enabling the CRO to display how the signal changes over time.

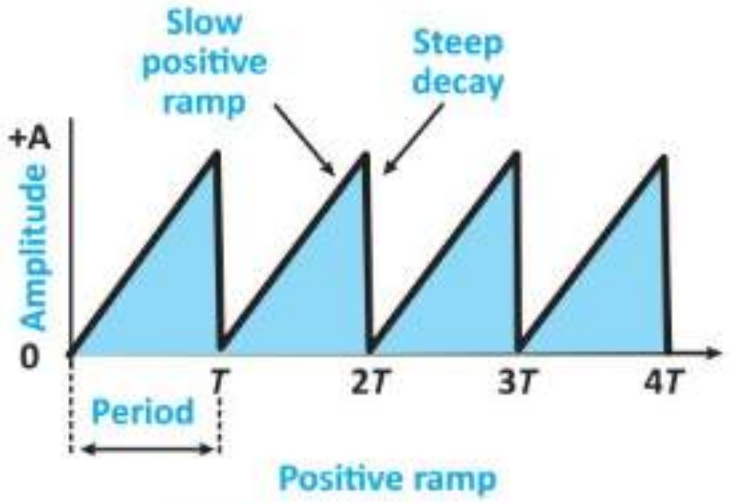


Fig. 18.12: Schematic diagram of a saw-tooth wave

When a sine wave is applied to the Y-plates and a saw-tooth voltage to the X-plates, the beam moves both up and down and side to side, tracing the waveform of the signal on the screen. The result is a clear, real-time display of the signal's shape. The display appears stable only when the frequency of the sawtooth wave (time base) is equal to or a multiple of the input signal's frequency. This synchronization can be adjusted using controls on the CRO.

CROs are extremely useful for measuring and analyzing electrical signals. They can show the waveform of a signal, measure its amplitude, determine its time period and frequency, and even allow comparison of two signals to measure their phase difference. For instance, if two waveforms are displayed together and one rises while the other falls, they may be out of phase by 180°, which can be easily observed on the screen.

A cathode ray oscilloscope is an essential tool in electronics, physics, and medical diagnostics. It uses electron beams, deflecting plates, and a fluorescent screen to visually represent electrical signals. The inclusion of a saw-tooth wave in its time base is important, as it ensures that the electron beam sweeps across the screen at a constant rate, making accurate and stable signal display possible.

18.6 Scattering of Light in the Atmosphere

Have you ever wondered why the sky is blue during the day and turns reddish at sunset? This beautiful phenomenon is caused by scattering of sunlight in the Earth's atmosphere. Sunlight is made up of all the colours of the visible spectrum; red, orange, yellow, green, blue, indigo, and violet. As this light passes through the atmosphere, it interacts with tiny gas molecules. Blue light, having a shorter wavelength, scatters more easily than red or green light. As shown in Fig. 18.13, during daytime, this scattered blue light reaches us from all directions, making the sky appear blue.

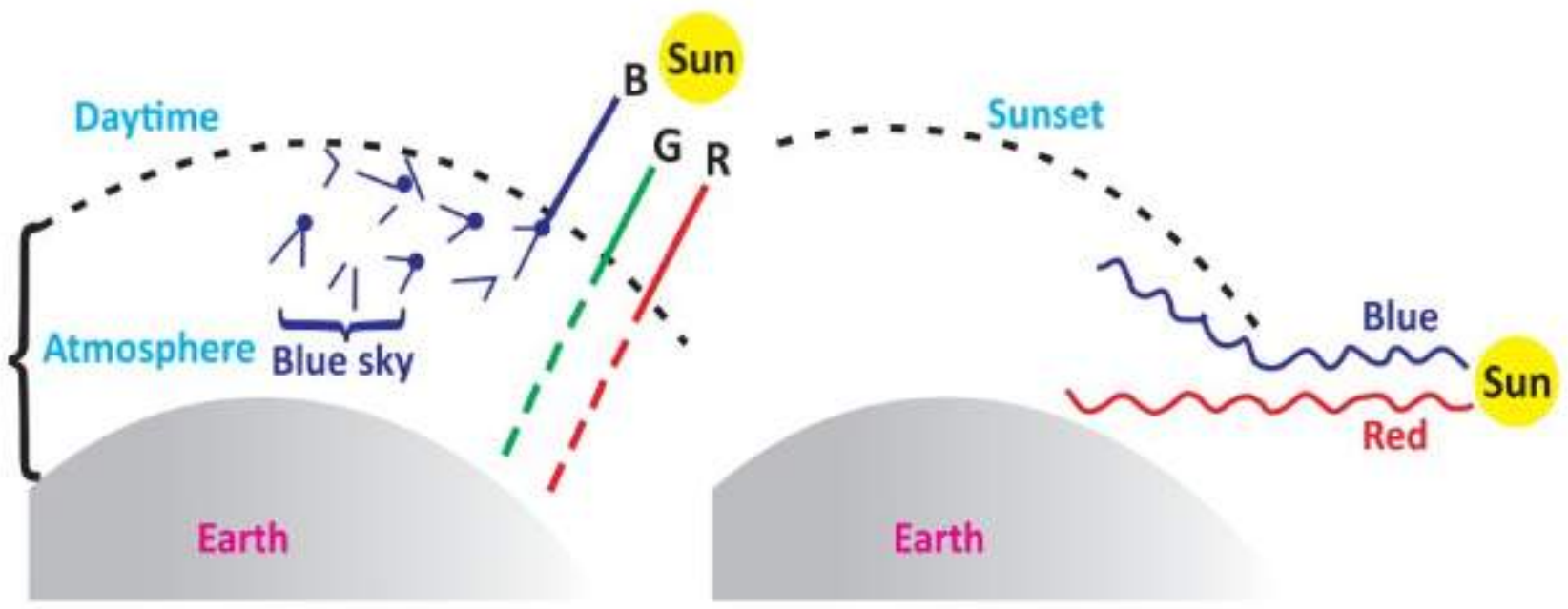


Fig. 18.13: Scattering of sunlight during daytime and sunset

During sunrise or sunset, the sunlight has to pass through a longer path in the atmosphere. By the time the light reaches us, much of the blue light has already been scattered out of the path. What remains are the longer wavelengths like red and orange, which scatter less. These colours dominate the sky near the horizon, giving it the warm, reddish hues we often see in the evening. Factors such as dust, pollution, and water droplets in the atmosphere can make the sunset even more dramatic by enhancing the scattering of certain colours, leading to deep reds and purples.

Tidbit

The sky is not blue, it is violet. But our eyes perceive scattered violet + blue as blue. Sunsets are red because blue light gets scattered away over long distances.

Brain Teaser

Why does the sky appear blue during the day but red at sunset?

18.7 Particle Nature of Light

Light is commonly known to behave as a wave, but it also has a particle-like nature. According to modern physics, light can be viewed as a stream of massless particles known as photons. These photons carry energy and momentum, even though they have no rest mass. This idea helps explain how light interacts with matter in situations where wave theory falls short.

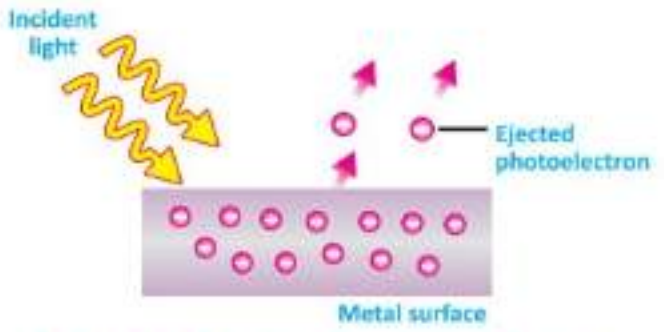


Fig. 18.14: Particle nature of light

One important piece of evidence for the particle nature of light is the photoelectric effect, shown in Fig. 18.14. When light shines on a metal surface, it can transfer energy to electrons. If the energy is high enough, electrons are ejected from the surface, these are called photoelectrons. This effect proves that light energy comes in packets (photons), and not as a continuous wave. Another example is radiation pressure light can exert a tiny force when it hits an object. Though the force is very small, it has real-world applications. For instance, solar sails on some spacecrafts are designed to reflect sunlight. The momentum of the photons gradually pushes the sail forward, allowing the spacecraft to move through space without using any fuel.

This concept demonstrates the dual nature of light it behaves like both a wave and a particle, depending on how it interacts with materials. It is one of the most fascinating ideas in modern physics.

EXERCISE

A. Multiple Choice Questions

Tick (✓) the correct answer.

18.1 What happens to the induced e.m.f. in a coil if the rate of change of the magnetic field increases?
(a) Decreases
(b) Remains the same
(c) Increases
(d) Becomes zero

18.2 In an A.C generator, slip rings are used to:
(a) reverse current direction periodically
(b) convert A.C to D.C
(c) prevent induced current
(d) increase magnetic flux

18.3 The sky appears blue during the day due to:
(a) reflection of light
(b) scattering of shorter wavelengths
(c) absorption of blue light
(d) refraction of light

18.4 Light can be considered as massless particles called:
(a) electrons (b) protons
(c) photons (d) neutrons

18.5 In a transformer, energy is transferred from the primary coil to the secondary coil through:
(a) direct electrical connection (b) a magnetic field in the iron core
(c) electrons flowing through the core (d) heat conduction

B. Short Answer Questions

18.1 What is the direction of induced current in Lenz's law?

18.2 Why are slip rings used in an A.C generator?

18.3 When is induced e.m.f. zero in an A.C generator?

18.4 Why is the sky red at sunset?

18.5 What is a transformer and on what principle does it work?

C. Constructed Response questions

18.1 If a magnet is moved quickly into a coil, a larger e.m.f. is induced. Why does speed affect the magnitude of the induced current?

18.2 Why is an iron core used in transformers instead of wood or plastic? Explain briefly.

18.3 How does the concept of photons help explain the working of solar sails in space?

18.4 Why can a transformer work only on alternating current and not on direct current ?

D. Comprehensive Questions

18.1 Describe how Lenz's Law supports the law of conservation of energy. Give one real-life example to support your explanation.

18.2 Compare step-up and step-down transformers. Include the difference in number of turns, voltage output, and where is each used.

18.3 How does the scattering of sunlight cause the sky to appear blue during the

day and red at sunset? Explain.

18.4 What is an oscilloscope, and how does it help in analyzing electrical signals? Describe its main components.

18.5 What is the shape of the path followed by an electron when it moves at right angles to a uniform magnetic field? Explain why.

D. Numerical Problems

18.1 A coil consisting of 50 tightly wound turns experiences a change in magnetic flux from 0.3 Wb to 0.8 Wb over a time interval of 0.4 s. Determine the average induced electromotive force (e.m.f.) generated in the coil during this time. **[Ans: -62.5 V]**

18.2 A circular loop of radius 0.2 m and resistance 5 Ω is placed perpendicular to a magnetic field of 0.5 T. If the field drops to zero in 0.1 s, calculate:
(a) the induced emf
(b) the induced current and its direction (assuming the field points into the page) **[Ans: 0.63 V, 0.126 A]**

18.3 A transformer has 500 primary turns and 100 secondary turns. If the primary voltage is 220 V, find: (a) secondary voltage (b) is this a step-up or step-down transformer? **[Ans: 44 V, Step-down ($V_s < V_p$)]**

18.4 A step-up transformer has a turns ratio of 2:100. If an alternating voltage of 25 V is applied to the primary coil, what will be the secondary voltage? **[Ans: 1250 V]**

18.5 A step-down transformer has a turns ratio of 100:5. If an A.C voltage of 190 V is applied to the primary coil, what is the voltage across the secondary coil? **[Ans: 9.5 V]**

CHAPTER 19

ELECTRONICS

Student's learning outcomes (SLOs)

After studying this chapter, students will be able to:

- describe the working of a diode.
- describe the action of a light-emitting diode in passing current in one direction only and emitting light.
- compare analog and digital electronics.
- explain that electronic devices are built from digital logic circuits (that can act as switches that can convert incoming voltage into binary electrical pulses of high and low (1 or 0).
- explain that Boolean logic is the basis for converting analog data to digital data (this includes knowing that 'bit' is the smallest unit of data in computing; either 1 or 0. Eight bits make up a byte).
- state in words and in truth table form, the action of logic gates (specifically of AND, OR, NAND, NOR, and NOT).
- identify the use of logic gates for security purposes (e.g: burglar alarm, fire extinguisher etc.).
- use circuit symbols for the logic gates.
- identify in given problems how Boolean switches can be put into combinations that then allow them to achieve logical operations.

Electronics is a branch of science that deals with the study and control of the flow of electrons in devices and circuits. It blends technical precision with innovative thinking, giving rise to advancements in areas such as artificial intelligence, renewable energy, and space exploration. From simple components like resistors to sophisticated microprocessors, each element contributes to the ever-evolving landscape of technology, providing many possibilities for innovation and shaping the future.

19.1 Semiconductors

Semiconductors are materials whose electrical conductivity lies between that of conductors and insulators. They are widely used in electronic devices because their conductivity can be controlled. The most common semiconductors are silicon (Si) and germanium (Ge). Their conductivity can be increased by adding a small amount of impurity, a process known as doping. There are two main types of doped semiconductors (N-type and P-type). In an N-type semiconductor, a small amount of a pentavalent impurity such as phosphorus or arsenic is added to silicon (Fig.19.1-a). These elements have five valence electrons; four form covalent bonds with silicon, while the fifth remains free to move. These free electrons are the majority charge carriers, which increase the conductivity of the semiconductor.

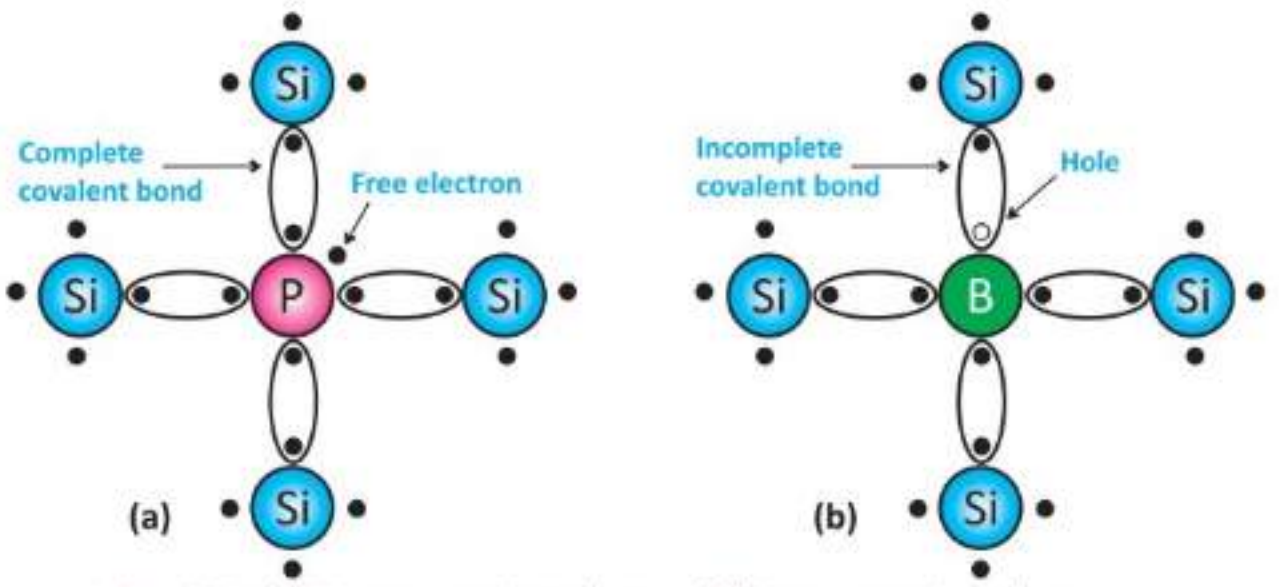


Fig. 19.1: (a) N-type semiconductors (b) P-type semiconductors

In a P-type semiconductor, a trivalent impurity such as boron or gallium is added to silicon (Fig. 19.1-b). These atoms have only three valence electrons, so one bond remains incomplete, creating a hole (a missing electron). Holes act as positive charge carriers, moving through the crystal and helping in current conduction.

PN Junction

When an N-type and a P-type semiconductors are joined together, they form a PN junction semiconductor diode. At the junction, electrons from the N-side and holes from the P-side recombine, creating a region without free charge carriers called the depletion region. This region acts as a barrier that prevents further movement of charges. To allow current to flow, an external voltage is applied to overcome this barrier. For silicon based diodes, the required voltage is about 0.7 V, and for germanium based diodes, it is about 0.3 V.

Tidbit

A diode is like a one-way road for current allowing it to flow in only one direction and blocks in the opposite direction.

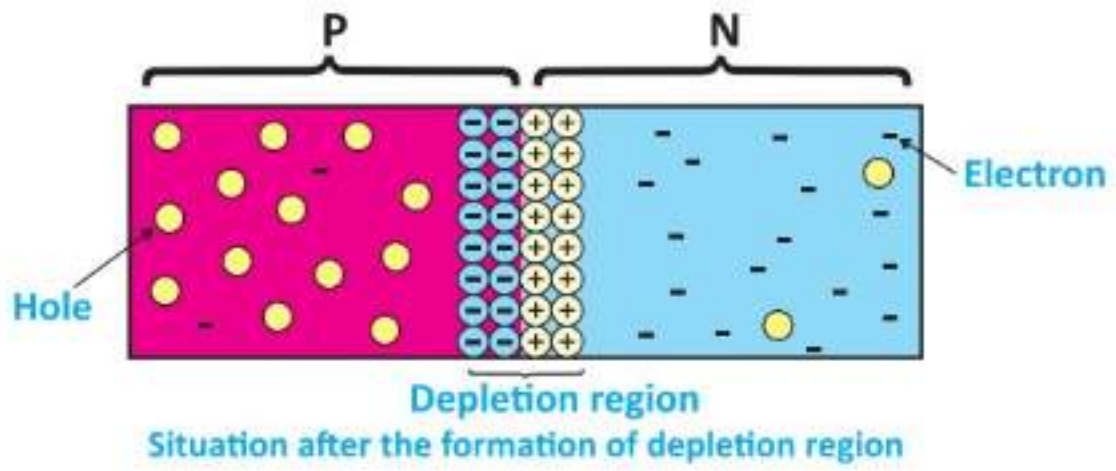


Fig.19.2: Schematic diagram of formation of PN junction

Working of Semiconductor Diode

A semiconductor diode (also known as a PN junction) allows current to flow in only one direction. Its symbolic representation is shown in Fig. 19.3. The diode conducts current when the P-side is connected to the positive terminal and the N-side to the negative terminal of a battery (Fig. 19.4-a). This condition is known as forward bias. In forward bias, the applied voltage reduces the potential barrier at the junction and narrows the depletion region. This enables charge carriers (electrons and holes) to easily cross the junction, causing the flow of current through the diode. In contrast, when the P-side is connected to the negative terminal and the N-side to the positive terminal of a battery, the diode is said to be in reverse bias (Fig. 19.4-b). In this condition, the depletion region widens, increasing the potential barrier and

Fig. 19.3: A semiconductor diode

preventing the flow of majority charge carriers. However, a very small current, known as leakage current, still flows due to the movement of minority carriers from both sides of the junction.

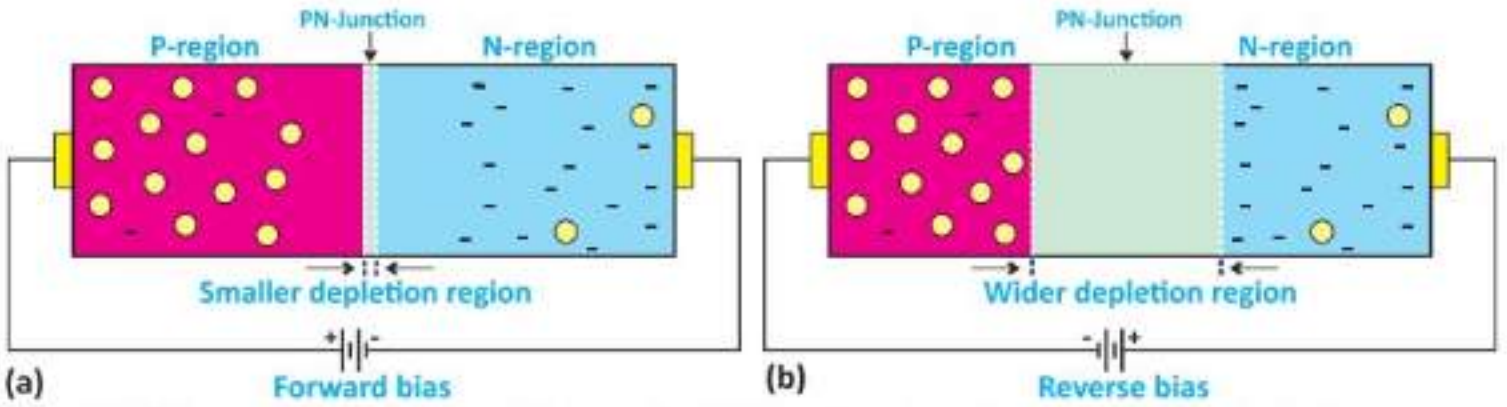


Fig. 19.4: Forward and reverse biasing of a PN junction showing changes in depletion region

The typical current-voltage (*I*–*V*) characteristic curve of a diode is shown in Fig. 19.5. In this graph, the diode conducts a significant current only in forward bias, whereas in reverse bias, it blocks the current almost completely. This property of diodes is important for their use in circuits such as rectifiers, voltage regulators, and electronic switches.

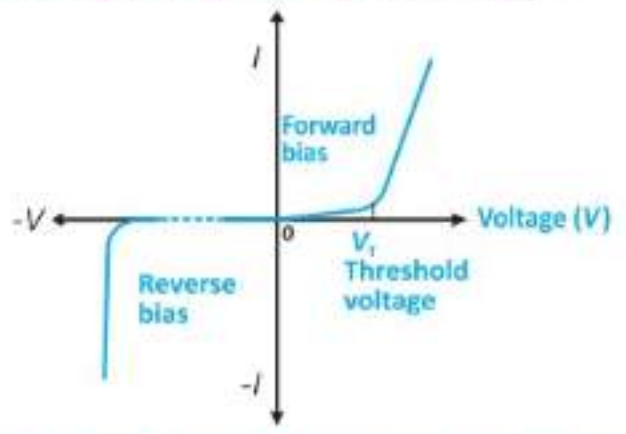


Fig. 19.5: *I-V* graph of a semiconductor diode

Light -Emitting Diode (LED)

A Light-Emitting Diode (LED) is a semiconductor device that allows electric current to flow in one direction, like a typical diode, and emits light when electrons recombine with holes. The symbol of LED is shown in Fig. 19.6. It consists of a PN-junction made from P-type and N-type materials. When the LED is connected in a forward bias, the applied voltage reduces the depletion region and allows the flow of charge carriers across the junction. As electrons from the N-type material move across and recombine with holes in the P-type material, energy is released in the form of photons, creating visible light.

Fig.19.6: LED symbol

The working of an LED under forward bias condition is shown in Fig. 19.7(a). Here, a simple circuit diagram demonstrates the LED setup with a resistor *R* to limit the current, a voltmeter V for the measurement of voltage across the LED, and an ammeter (mA) in series to measure the current flowing through the circuit.

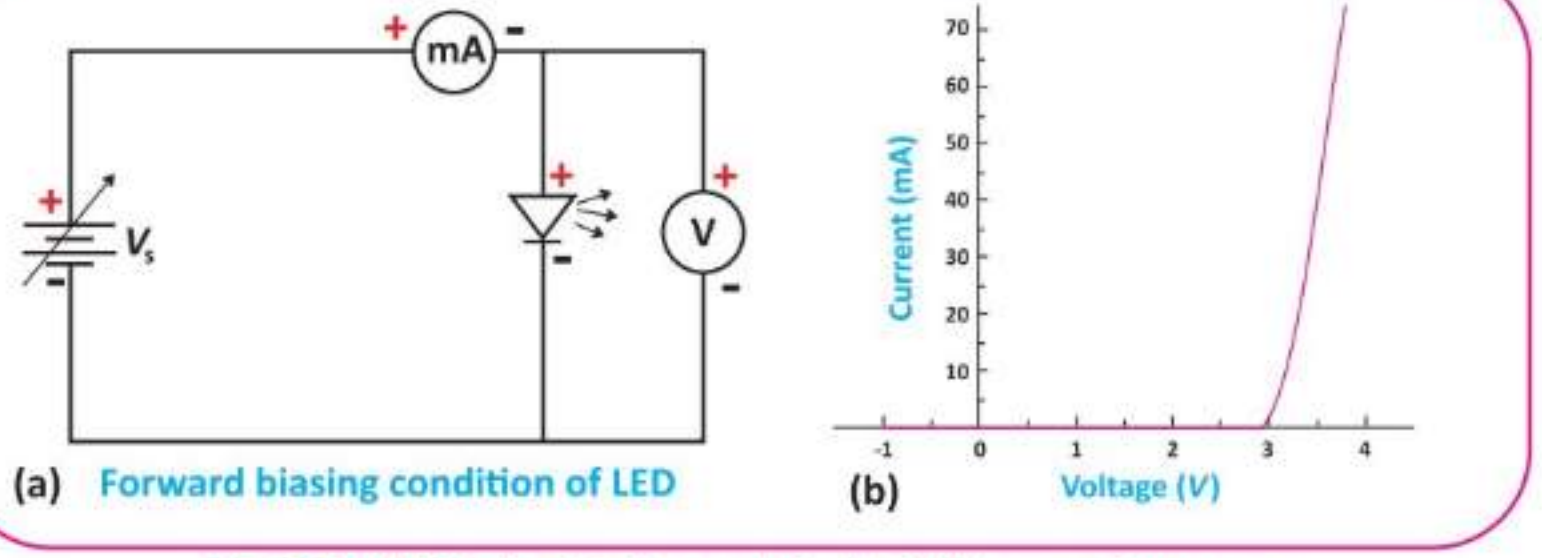


Fig. 19.7: (a) LED circuit in forward bias (b) *I–V* characteristic curve

In the reverse bias condition (positive to N-side and negative to P-side), the depletion region widens, preventing the flow of current, and as a result, no light is emitted. Therefore, LEDs are designed to function only under forward bias condition.

The behaviour of the LED can also be understood using a current-voltage (*I–V*) characteristic graph as shown in Fig. 19.7-b. In this graph, it is observed that initially small current flows as voltage increases. However, after a certain threshold voltage, a sudden sharp increase in current occurs, resulting in light emission.

The colour of the light produced by an LED depends on the materials used during its manufacture, affecting the wavelength (and thus the colour) of the emitted light. LEDs are highly efficient, durable, energy-saving, and are extensively used in a variety of applications including radios, lamps, digital clocks, calculators, video displays, remote controls, and modern lighting systems.

Thus, LEDs play an important role in both everyday life and advanced technologies by efficiently converting electrical energy directly into light.

Do You Know?

Diodes are Important

- The silicon diode is the simplest of all the semiconductor devices. It is also one of the most important. Without diodes, one can not build electronic equipment.
- Applications for diodes range from power supplies to cell phones and everything in between.

Tidbit

Unlike normal bulbs, LEDs do not waste much energy as heat. They instantly glow by simply letting current flow across a special junction.

Brain Teaser

In an LED, electrons meet holes and produce something surprising. What is released during this encounter heat, light, or sound?

19.2 Analog and Digital Electronics

Electronic circuits, devices, or systems are mainly divided into analog and digital types.

In analog circuits, voltages and currents can vary smoothly and continuously within a certain range (Fig. 19.8-a). For example, an analogue meter uses a pointer moving over a continuous scale to display readings. These circuits are used in devices like amplifiers and variable resistors, which allow for a wide range of adjustments, such as dimming a lamp to various brightness levels. In digital circuits, voltages have only two values: "high" (e.g., 5 V) or "low" (e.g., near 0 V) (Fig. 19.8-b). These circuits are used in switching systems, like a simple ON/OFF switch for a lamp. While digital electronics were once limited to computers, these are now widely used in modern telephones, radar systems, industrial machines, medical equipments, and household appliances. However, the quantities we perceive in daily life, such as sound or light, are analog and cannot be directly processed by digital circuits. To bridge this gap, an analog-to-digital converter (ADC) is used. It converts analog signals into digital binary form for processing by computers (Fig. 19.9). The ADC works by sampling the analog signal at regular intervals and converting each sample into a binary number that represents its voltage level.

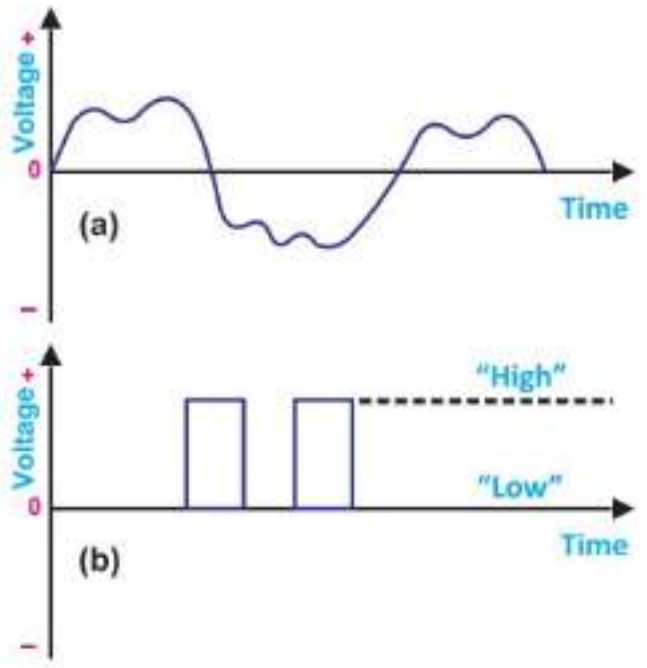


Fig. 19.8: Comparison of analog and digital signals: (a) analog signal varies continuously over time, while (b) digital signal switches between discrete "high" and "low" levels

Tidbit

Analog signals are continuous like ocean waves. Digital signals are sharp like stair steps just highs and lows (1's and 0's).

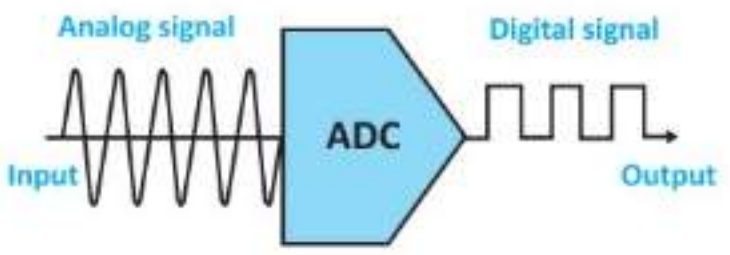


Fig. 19.9: Analog-to-digital converter (ADC)

Conversion from Analog to Digital Data

Analog data, such as sound or light, is continuous and can take any value within a range. In contrast, digital systems use binary data (0s and 1s), which is discrete. To convert analog data into a digital format, an analog-to-digital converter (ADC) is used. The process works as follows (Fig. 19.10).

1. **Sampling:** The continuous analog signal is measured at regular intervals.

2. **Quantization:** Each sampled value is rounded to the nearest predefined level.

3. **Encoding:** The quantized values are then converted into binary numbers (0s and 1s).

For example, a sound wave (analog) is measured at regular intervals, each value is quantized to the nearest level, and then encoded into a series of binary numbers. This process makes the sound wave usable by digital devices, such as computers. Once processed, a digital-to-analog converter (DAC) can convert the binary data back into an analog signal for output, such as playing sound through a speaker. This process enables digital systems to handle real-world, continuous data efficiently.

Fig. 19.10: Basic steps of analog-to-digital conversion

19.3 Boolean Logic

A binary variable has only two possible states, like a switch that is either ON (closed) or OFF (open). These states are represented by 1 and 0 respectively. For example, in a circuit with a battery, lamp, and switch, the state of the switch (open or closed) is the input, and state of the lamp (OFF or ON) is the output. When the switch is open (input = 0), no current flows, and the lamp is OFF i.e; the output is zero. However, when the switch is closed (input = 1), the lamp turns ON and the output is 1 (Fig. 19.11).

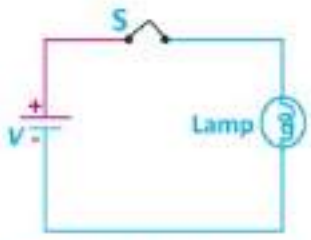
Brain Teaser

In Boolean logic, what is the output of an AND gate if one input is 0 and the other is 1?

To understand how inputs affect outputs, George Boole developed Boolean algebra, the foundation of digital electronics and computing, which uses binary values (bits), where each bit is either 0 or 1. A byte is formed using eight bits, which represents data in computers. Boolean algebra is used in ADC which converts analog data (continuous signals) into digital data (discrete binary values). It also forms the basis for designing digital systems.

Boolean algebra uses three basic logic operations: AND, OR, and NOT. These operations are implemented using logic gates, which are digital circuits with binary inputs and outputs. A logic gate's output can only be high (1) or low (0), depending

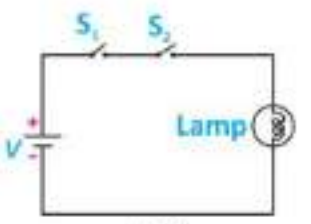
on the conditions at its input. For example; AND gate gives an output of 1 only if all its inputs are 1. An OR gate gives an output of 1 if at least one input is 1. A NOT gate inverts the input (1 becomes 0, and 0 becomes 1). AND and OR circuit symbols and truth tables are shown in Fig. 19.12 and Fig. 19.13, respectively.



S	Lamp	State
Open	OFF	0
Closed	ON	1

Fig. 19.11: Binary logic in a circuit (The switch (S) controls the lamp based on boolean logic—Open (0) = OFF, Closed (1) = ON)

In the case of the AND gate, a lamp is connected in series with two switches, S_1 and S_2, along with a battery. In this configuration, the lamp only lights up when both switches are closed, forming a complete path for current to flow. If either switch is open, the current is interrupted, and the lamp remains OFF. This setup models the logic AND operation, where the output is 1 only if both inputs are 1. The circuit, switching combinations (Fig.19.12(a), and truth table are illustrated in Fig. 19.12(b).

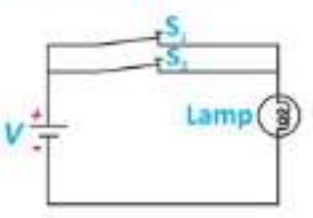


(a)

S_1	S_2	Lamp
Open	Open	OFF
Open	Closed	OFF
Closed	Open	OFF
Closed	Closed	ON

(b)

Fig. 19.12: (a) Circuit representation of AND logic using switches (b) Truth table for AND logic



(a)

S_1	S_2	Lamp
Open	Open	OFF
Open	Closed	ON
Closed	Open	ON
Closed	Closed	ON

(b)

Fig. 19.13: (a) Circuit representation of OR logic using switches (b) Truth table for OR logic

For the OR gate, the lamp is connected in a circuit where switches S_1 and S_2 are placed in parallel (Fig. 19.13-a). In this arrangement, the lamp glows if either or both switches are closed, as current can flow through at least one path. The lamp remains OFF only when both switches are open. This models the logic OR operation, where the output is 1 if any one or both inputs are 1. The complete explanation and truth table for the OR operation are provided in Fig. 19.13(b) .

Tidbit

Tiny circuits called logic gates act like smart switches, making decisions inside our computers, watches, and phones.

These simple logic gates can be combined to perform complex operations, forming the backbone of modern digital systems, from computers to smartphones. By using Boolean algebra and logic gates, we can systematically design circuits that process binary data efficiently and reliably.

19.4 Logic Gates

A logic gate is a basic component of digital circuits that performs logical operations like AND, OR, and NOT. Most logic gates have two inputs and one output. However, in the NOT gate, there is only one input and one output. These gates enable digital devices to process binary data and make decisions.

Logic gates are used in everyday devices like smartphones, computers, calculators, and digital watches.

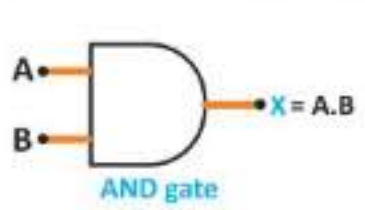
Do You Know?

The Meaning of Logic Gates

- A **gate** is a device that performs a basic operation on electrical signals.
- Gates are combined into **circuits** to perform more complicated tasks.
- **Logic Gates** are the circuits that are designed to perform these basic logic functions.
- Actually, the term logic is applied to digital circuits used to implement logic functions.

AND GATE

The AND gate has two inputs. The output of the AND gate will only be 1 (high) if both inputs are 1 (high). In other words, if A and B are two inputs of the AND gate, then output X will be 1 if A=1 and B=1. The logic equation for the AND gate is written as $X=A \cdot B$ (X equals A AND B). The circuit symbol for AND gate and its truth table are shown in Fig. 19.14 (a) and Fig. 19.14 (b), respectively.



(a)

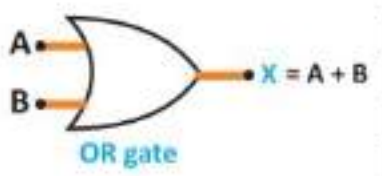
A	B	X = A.B
0	0	0
0	1	0
1	0	0
1	1	1

(b)

Fig. 19.14: (a) The circuit symbol and (b) Truth table for an AND gate

OR GATE

The OR gate has two inputs. The output of OR gate will be 0 (low) if both the inputs are 0 (low). In other words, if A=0 and B=0, then X=0, otherwise X=1. The logic equation for OR gate is written as X=A+B (X equals A OR B). The circuit symbol for OR gate and its truth table are shown in Fig. 19.15 (a) and Fig. 19.15 (b), respectively.



(a)

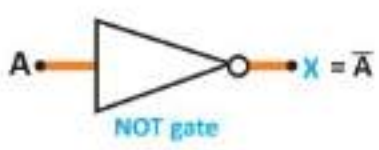
A	B	X = A+B
0	0	0
0	1	1
1	0	1
1	1	1

(b)

Fig. 19.15: (a) The circuit symbol and (b) Truth table for an OR gate

NOT GATE

NOT gate has single input. It is also called an inverter as it inverts the input signal, i.e; if its input is 1, then the output will 0 and vice



(a)

A	X = $\overline{A}$
0	1
1	0

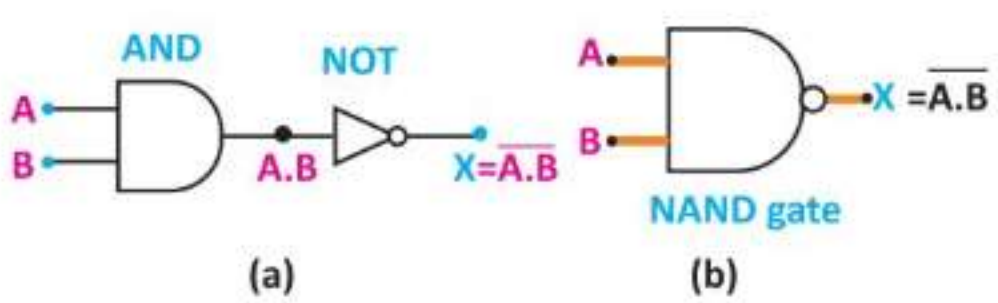
(b)

Fig. 19.16: (a) The circuit symbol and (b) Truth table for NOT gate

versa. The Logic equation for the NOT gate is $X=\overline{A}$ (equals NOT A). The symbol of NOT gate (Fig. 19.16-a) and the truth table is shown in Fig. 19.16 (b).

NAND GATE

A NAND gate is a combination of AND gate and NOT gate. The symbol for a NAND gate is made from an AND gate along with the bubble circle at its output as shown in Fig. 19.17 (b). The logic equation for the NAND gate is written as $X=\overline{A \cdot B}$ (read as X equals NOT A AND B). From truth table (Fig.19.17-c), we can see that the output is 0 when both inputs A and B are 1, otherwise output is 1.



(a) (b)

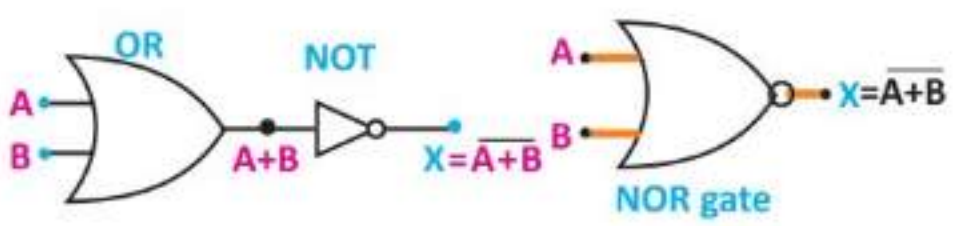
A	B	$X = \overline{A.B}$
0	0	1
0	1	1
1	0	1
1	1	0

(c)

Fig. 19.17 (a,b): The circuit symbol (c) Truth table for NAND gate

NOR GATE

A NOR gate is an OR gate with a NOT gate at its output (Fig. 19.18-a). The symbol for a NOR gate is made from an OR gate with the inversion circle (bubble) at its output as shown in Fig. 19.18 (b). The logic equation for the NOR gate is written as $X=\overline{A+B}$ (read as X equals not A OR B). From truth table (Fig. 19.18.-c), we can see that the output is 1 when both inputs A and B are 0, otherwise output is 0.



(a) (b)

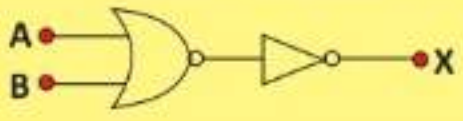
A	B	$X = \overline{A+B}$
0	0	1
0	1	0
1	0	0
1	1	0

(c)

Fig. 19.18 (a,b): The circuit symbol (c) Truth table for NOR gate

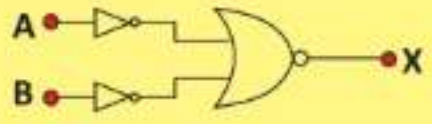
Brain Teaser

Show that the circuit given below acts as OR gate.



Brain Teaser

Show that the circuit given below acts as AND gate.



19.5 Applications of Logic Gates

Burglar Alarm

We can create a simple burglar alarm using a single NAND gate, an LDR (Light-Dependent Resistor), a push-button switch (S), and an alarm. The LDR is connected between one input (B) of the NAND gate and the positive terminal of the battery, while the push-button switch (S) is connected to the other input (A). The alarm is connected to the output of the NAND gate (Fig. 19.19). When light falls on the LDR, its resistance is low, causing input B to be high (1). However, if the burglar interrupts the light (e.g., by blocking it), the LDR's resistance becomes high, causing input B to be low (0). Similarly, if the burglar steps on the push-button switch (S), input A becomes low (0). The NAND gate outputs low (0) only when both inputs are high (1); otherwise, it outputs high (1). This means the alarm will sound if either the light is blocked (B = 0), the switch is pressed (A = 0), or both events occur simultaneously. This simple yet effective circuit ensures the alarm is triggered in response to unauthorized entry, making it a practical burglar alarm system.

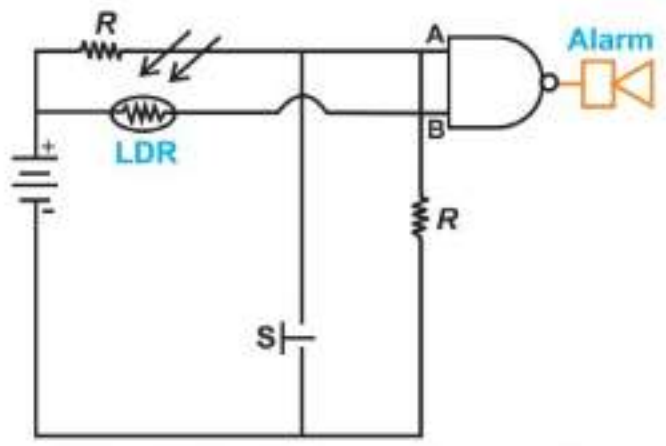


Fig. 19.19: Burglar alarm circuit using NAND gate

Fire Alarm System

A fire alarm system detects fire at an early stage by sensing smoke and heat, triggering an alarm to warn people and provide time to take action. It consists of alarm-starting devices (like smoke detectors and heat sensors), alarm devices (such as sirens), fire control systems (like sprinklers), and power supplies (Fig. 19.20). The alarm can be triggered by sensors such as smoke detectors or heat sensors, which are designed to detect certain levels of smoke or heat that may indicate a fire. While there are advanced and high-cost fire alarm systems available, it is also

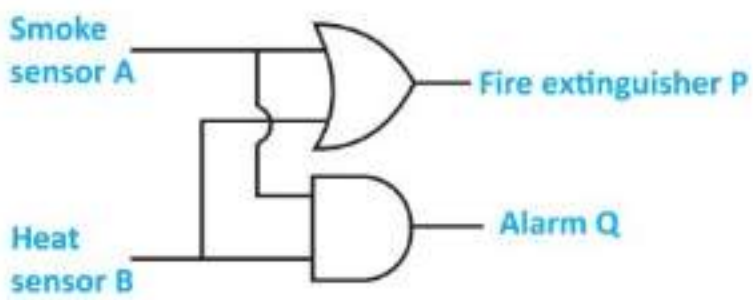


Fig. 19.20: Circuit diagram of fire alarm using basic logic gates

Brain Teaser

A fire alarm must go OFF when either smoke is detected or heat is detected. Which logic gate fits this setup?

possible to make a basic fire alarm using simple components like thermistors, LM358 (Operational amplifier), germanium diodes, LM341 (Voltage regulator), and NE555 (Timer IC). Furthermore, a fire alarm system can be constructed using basic logic gates. For instance, a circuit with logic gates can process inputs from smoke and heat sensors, triggering the alarm when either of the conditions is met, providing an affordable and efficient fire detection solution.

For Your Information

How Fire Alarms Can Save Lives?

1. Early detection saves lives
2. Fire alarms can detect fires before they become large
3. Fire alarms can alert the authorities
4. Fire alarms can be connected to a monitoring service
5. There are different types of fire alarms
6. Fire alarms should be tested regularly

EXERCISE

A. Multiple Choice Questions

Tick(✓) the correct answer.

19.1 A diode allows current to flow in:
(a) both directions (b) neither direction
(c) one direction only (d) random directions

19.2 What is the primary function of a light-emitting diode?
(a) To block current in both directions
(b) To emit light when current passes in one direction
(c) To amplify electrical signals
(d) To convert light into electrical energy

19.3 The output of a two inputs NOR gate is '1', when:
(a) A is '1' and B is '0' (b) A is '0' and B is '1'
(c) both A and B are '0' (d) both A and B are '1'

19.4 The output of a NAND gate is '0', when:
(a) both of its inputs are '0' (b) both of its inputs are '1'
(c) any of its inputs is '0' (d) any of its inputs is '1'

19.5 How many bits make up a byte in Boolean logic?
(a) 2 (b) 4 (c) 6 (d) 8

B. Short Answer Questions

19.1 What is the function of a semiconductor diode?

19.2 What happens when a diode is forward biased?

19.3 What is the function of an LED?

19.4 Why does an LED emit light when current passes through it?

19.5 What does an analog-to-digital converter (ADC) do?

19.6 What is the difference between analog and digital signals?

19.7 What is Boolean logic in digital electronics?

19.8 What does a NOT gate do in a digital circuit?

19.9 What is the role of an AND gate in digital circuits?

C. Constructed Response Questions

19.1 Why would a diode be damaged if it is connected in reverse bias with a very high voltage? What does this tell us about the diode's physical limits?

19.2 What makes an LED glow brighter or dimmer depending on the voltage applied? How is this property used in adjustable display brightness?

19.3 Why are digital systems more reliable than analog systems when transmitting signals over long distances?

19.4 Why is the NOT gate also called an inverter, and how can such a simple function have a major role in digital decision-making?

19.5 Why would a security system use NAND gates instead of OR or AND gates for certain logical conditions?

D. Comprehensive Questions

19.1 Explain how the depletion region of a diode changes in forward and reverse bias. What effect does this have on current flow?

19.2 Describe how an LED produces light. Also explain how the type of semiconductor material affects the colour of the light.

19.3 What is Boolean logic? Discuss its importance in solving complex digital problems with examples.

19.4 What are logic gates? Describe the working of NAND and OR gates with the help of truth tables and circuit symbols.

19.5 How does a NOR gate work, and how can it be used to build other basic logic gates?

19.6 How can a burglar alarm be designed using a NAND gate and an LDR? Explain.

CHAPTER 20

ATOMIC AND NUCLEAR PHYSICS

Student's learning outcomes (SLOs)

After studying this chapter, students will be able to:

- describe the structure of the atom [in terms of a positively charged nucleus and negatively charged electrons that go around the nucleus. This should include an understanding of the big ideas: These electrons do not go around in predictable circular paths in the way that planets go around the sun. The electrons behave as 'quantum particles' and their location and momentum at any point in time is governed by probability; one cannot predict the motion of an electron. The 'shells' in which electrons 'orbit' refer to the level of kinetic energy the electrons possess; the further the shell is from the nucleus, the more energy the electron has. If one were to 'look' at an atom, one would see a fuzzy 'cloud' of electrons with a very small nucleus in the centre.
- justify the findings of the alpha-particle scattering experiments, specifically that it provides evidence for: (a) a very small nucleus surrounded by mostly empty space, (b) a nucleus containing most of the mass of the atom, (c) a nucleus that is positively charged.
- define the terms proton number (atomic number) Z and nucleon number (mass number) A and be able to calculate the number of neutrons in a nucleus.
- recall the term nuclide and use the nuclide notation ${}^{A}_{Z}X$.
- explain what is meant by an isotope and state that an element may have more than one isotope.
- describe the emission of radiation from a nucleus as spontaneous and random.
- describe alpha-particles, beta-particles, and gamma-radiation.
- justify qualitatively the order of strength for alpha-particles, beta-particles, and gamma-radiation in terms of their (a) relative ionizing effects and (b) relative penetrating powers.
- describe the deflection of alpha-particles, beta-particles, and gamma-radiation in electric fields and magnetic fields.
- explain that radioactive decay is a change in an unstable nucleus that can result, most commonly, in the emission of alpha-particles or beta-particles and/or gamma-radiation.

(Other types exist but are not required at this level.)

- use decay equations, using nuclide notation, to show the emission of alpha-particles, beta-particles, and gamma-radiation.
- describe nuclear reactions (fission and fusion) with examples. (Fusion as the formation of a larger nucleus by combining two smaller nuclei with the release of energy, and recognize fusion as the energy source for stars.)
- recognize that matter can be converted to energy and vice versa (in this way the law of conservation of energy still holds).
- apply the equation; $E = mc^2$ to calculate the energy released in the process of nuclear reactions.
- describe the activity of a radioactive material in terms of counts per unit time.
- define and infer the half-life of materials. (Half-life is the time taken for half the nuclei of an isotope in any sample to decay. Use this definition in calculations, which may involve tables or decay curves.)
- explain and apply the concept of Carbon dating to solve problems.
- explain how the type of radiation emitted and the half-life of the isotope determine which isotope is used for applications, including: (a) household fire (smoke) alarms, (b) irradiating food to kill bacteria, (c) sterilization of equipment using gamma rays, (d) measuring and controlling thicknesses of materials using appropriate radiation, (e) diagnosis and treatment of cancer using gamma rays.
- state the effects of ionizing nuclear radiations on living things, including cell death, mutations, and cancer.

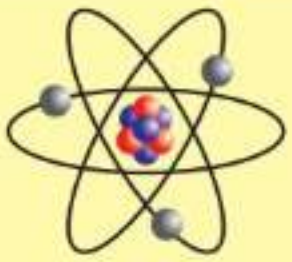
Atomic and nuclear physics are branches of science that help us to understand the smallest building blocks of matter. Atomic physics deals with the study of the structure of atoms, their constituents (electrons, protons, and neutrons), and how they interact with light and energy. Scientists have developed different models of the atom over time, from simple ideas to more advanced ones like the quantum model. Nuclear physics, on the other hand, focuses on the nucleus of the atom, which contains protons and neutrons. It explains important concepts like radioactivity, nuclear reactions, and how energy is released in nuclear power plants. Researches in these fields have led to important applications in medicine, energy, and technology. In this chapter, we will explore these basic ideas and understand how they shape the world around us.

20.1 Atomic Structure

All matter is made up of tiny particles called atoms, was first suggested by Dalton. In 1897, J. J. Thomson proposed that atoms contain positively charged matter and negatively charged electrons.

Do You Know?

Atom is 99.9999999% empty space!



Rutherford's Alpha Particle Scattering Experiment

In the early 20th century, scientists were studying radioactivity, a process in which unstable atoms release radiation. One type of radiation they discovered was alpha (α) particles. These particles were positively charged and have a small mass, similar to atoms like helium. They moved with high velocities. In 1911, Rutherford, along with Hans Geiger and Ernest Marsden, conducted another experiment using a thin sheet of gold foil as shown in Fig.20.1.

They directed a beam of alpha particles at the foil and noticed that most particles passed through without any deflection, suggesting that the atom is mostly empty space. Some particles were slightly deflected, indicating the presence of a small, positively charged region. A few particles bounced back at large angles, meaning that all the positive charge and most of the mass of atoms was concentrated in a tiny central part called nucleus.

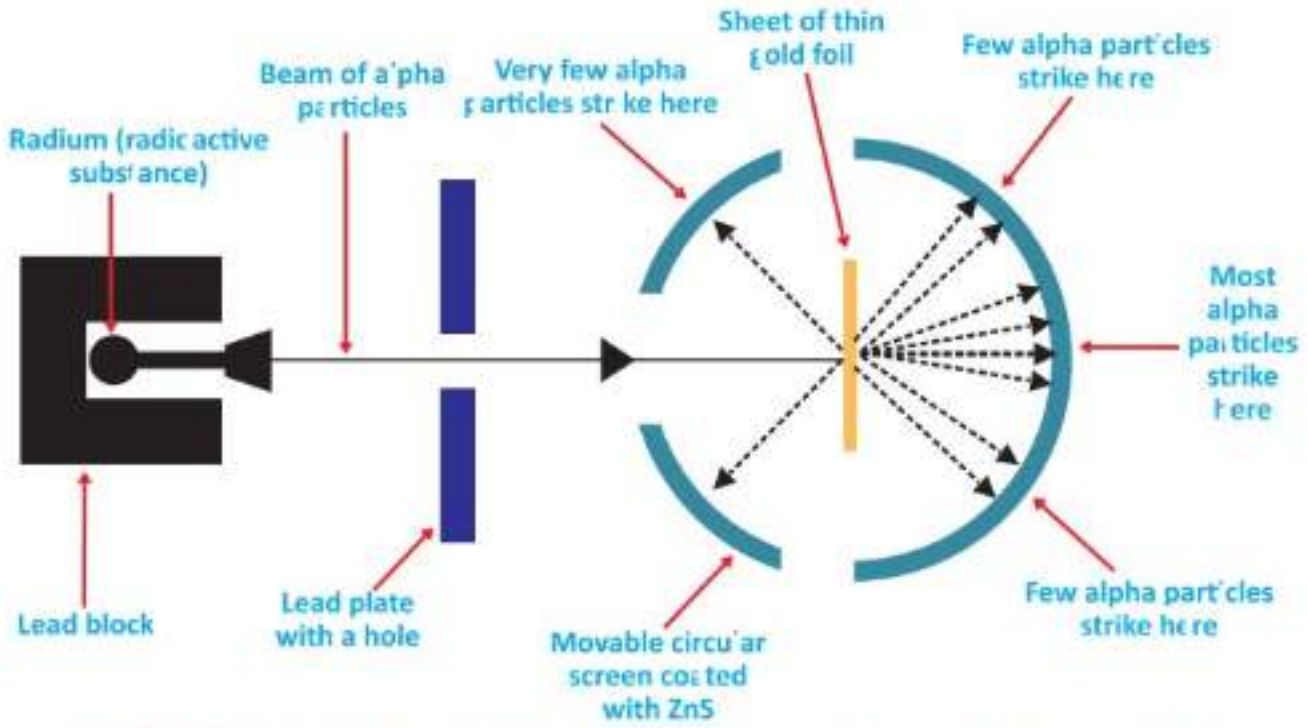


Fig. 20.1: Rutherford's gold foil experiment: scattering of alpha particles

Findings of Rutherford's Experiment

1. Atoms have a small, dense, and positively charged core called the nucleus.
2. The nucleus contains most of the mass of atoms.
3. Electrons orbit the nucleus at large distances, and the atom is mostly empty space.
4. The nucleus is extremely small, about 10,000 times smaller than the entire atom.

Later studies revealed that electrons do not follow fixed orbits like planets around the Sun. Instead, they exist in regions called electron clouds, where their exact position cannot be known. This "fuzzy cloud" represents the probability of finding an electron in a certain area around the nucleus. The cloud is denser where the electron is more likely to be and thinner where it is less likely. This model reflects the quantum nature of electrons where they behave as both particles and waves, and their motion is uncertain.

20.2 Atomic Nucleus

Atomic nucleus is the central part of an atom which holds most of its mass (Fig. 20.2). It is made up of protons and neutrons, which together known as nucleons. Protons and neutrons are held together by the strong nuclear force. The size of the nucleus is very small in comparison to the entire size of the atom.

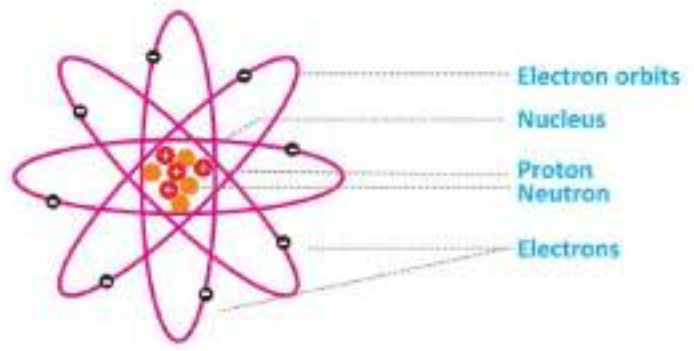


Fig. 20.2: Diagram of an atom showing the nucleus, protons, neutrons, and electron orbits

Charge Number and Mass Number

Atoms are made up of protons, neutrons, and electrons. The charge number Z tells us how many protons an atom has, which is unique for each element. It is also called atomic number. This number also determines an element's position in the periodic table and its chemical properties. The mass number A is the total count of protons and neutrons in an atom's nucleus. Since electrons have very little mass, they are not included in the mass number. Scientists use the mass number to understand an atom's size, stability, and structure. A nuclide is represented by ${}^{A}_{Z}X$, where X is its chemical symbol, the superscript is mass number A and subscript is charge number Z.

Do You Know?

The number of protons in the nucleus is what defines an element. Change the number of protons, and we change the element itself!

Tidbit

Electrons are nearly 1,836 times lighter than protons, yet they move extremely fast—almost at the speed of light in their orbitals.

Brain Teaser

If protons repel each other, how can so many of them stay packed in a tiny nucleus without flying apart? What holds them together?

To determine the number of neutrons in the nucleus of an atom, we use the formula:

$$N = A - Z$$

Example 20.1: Find the number of protons and neutrons in the nuclide defined by ${}^{15}_{7}X$.

Solution: From the symbol, we have atomic number Z = number of protons = 7
Mass number A = number of protons + number of neutrons = 15
But number of protons are 7, so number of neutrons will be 8. So, the element is an isotope of nitrogen-7, and is written as ${}^{15}_{7}N$.

20.3 Isotopes

Isotopes are atoms of an element that have the same number of protons but different numbers of neutrons.

Atoms are electrically neutral, meaning they have equal number of protons and electrons. If an atom gains or loses electrons, it becomes an ion and carries an electric charge. The number of protons and electrons determines an atom's chemical properties, while the number of neutrons affects its nuclear properties, like stability and radioactivity. A common example of isotopes is hydrogen, which has three isotopes as shown in Fig. 20.3.

- ${}^{1}_{1}H$ contains 1 proton and 0 neutrons
- ${}^{2}_{1}H$ contains 1 proton and 1 neutron.
- ${}^{3}_{1}H$ contains 1 proton, 2 neutrons

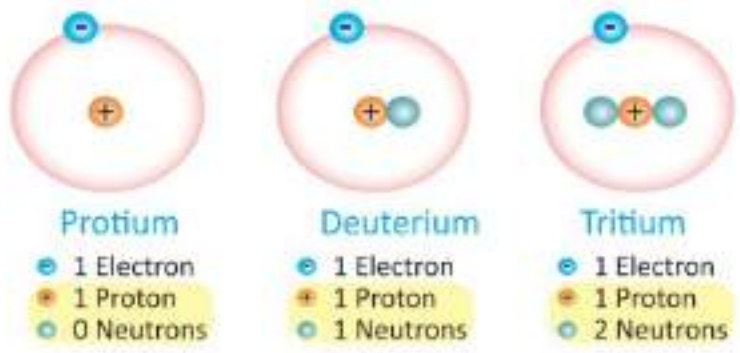


Fig. 20.3: Isotopes of hydrogen

Even though these hydrogen isotopes have different masses, they still behave chemically in the same way. Similarly, carbon has three isotopes ${}^{12}_{6}C$, ${}^{13}_{6}C$, ${}^{14}_{6}C$ containing 6,7 and 8 neutrons, respectively.

20.4 Radioactivity

Radioactivity is the process in which unstable atoms release energy to become stable. This energy is given off as radiation, which can be in the form of particles or waves. Some elements are naturally radioactive, while others can be made radioactive in laboratories. Henri Becquerel discovered radioactivity in 1896, and later, Marie Curie and Ernest Rutherford studied it further. Atoms have a nucleus made of protons and neutrons, surrounded by electrons. Some nuclei become unstable due to an imbalance of protons and neutrons or excess energy inside. To become stable, the nucleus breaks down and gives off radiation in a process called radioactive decay. This happens naturally and cannot be controlled. It is spontaneous and random. While we cannot predict when a single atom will decay, but in a large group of atoms, the decay follows a pattern.

Do You Know?

Marie Sklodowska-Curie, a French Physicist and chemist, was the first woman to receive a Nobel Prize and the only woman to receive two Nobel Prizes, while studying uranium's rays, she discovered new elements and named them polonium and radium.

Emission of α, β and γ Radiations

Radioactive decay releases three types of radiation: Alpha (α), Beta (β), and Gamma (γ) radiation, each with different properties.

Alpha particles (α) are helium nuclei, consisting of 2 protons and 2 neutrons each (Fig. 20.4). They carry a +2e charge ($e=1.6 \times 10^{-19}$ C), and are relatively large and

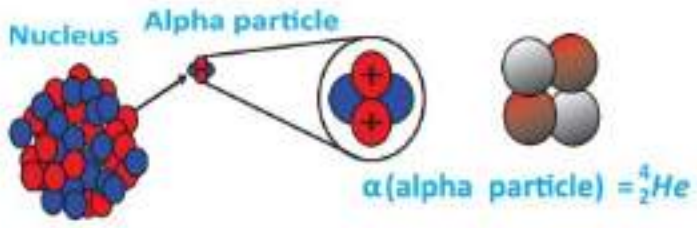


Fig. 20.4: Representing alpha particle

heavy [4 atomic mass units,u). Due to their size, alpha particles have low penetration power and can be stopped by a sheet of paper or a few centimetres of air. However, they have high ionizing power, meaning they strongly affect other atoms they come in contact with.

Beta particles (β) are high-energy electrons ($_{-1}^{0}e$) or positrons ($_{+1}^{0}e$) emitted from the nucleus (Fig.20.5) They carry a -1e charge (electrons) or +1e charge (positrons) and have a very small mass. Beta radiation has moderate penetration power. It can pass through paper but is stopped by a few millimetre of aluminum. Their ionizing power is moderate, meaning they cause less ionization than alpha particles but more than gamma rays.

Tidbit

Alpha particles are the heaviest and slowest of the three common radiation types. They can not penetrate a sheet of paper but can cause severe damage if inhaled or ingested.

Fig. 20.5: Representing beta particles

Gamma radiation (γ) consists of high-energy electromagnetic waves (photons), making them massless and neutral (0 charge). Gamma rays are emitted out due to de-excitation of nucleus (Fig. 20.6). Gamma rays have very high penetration power, allowing them to pass through thick materials like lead or concrete. However, they have low ionizing power, meaning they cause much less ionization compared to alpha and beta particles.

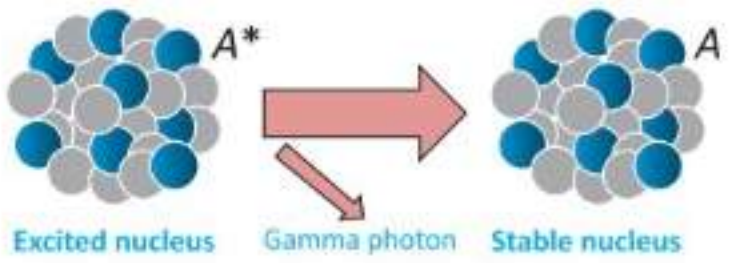


Fig. 20.6: Representing gamma radiation

Ionizing Effects and Penetrating Powers

Ionizing Effects

Ionization occurs when radiation removes electrons from atoms, turning them into ions. The ability of radiation to ionize atoms depends on its energy and charge.

Alpha (α) particles: Strongest ionizing power due to their large size and charge.

Beta (β) particles: Moderate ionizing

Do You Know?

Gamma rays are pure electromagnetic energy with no mass or charge. They are the most penetrating and require thick lead or concrete to shield against.

power, as they are smaller and faster than alpha particles.

Gamma (γ) rays: Weakest ionizing power, as they have no charge and no mass.

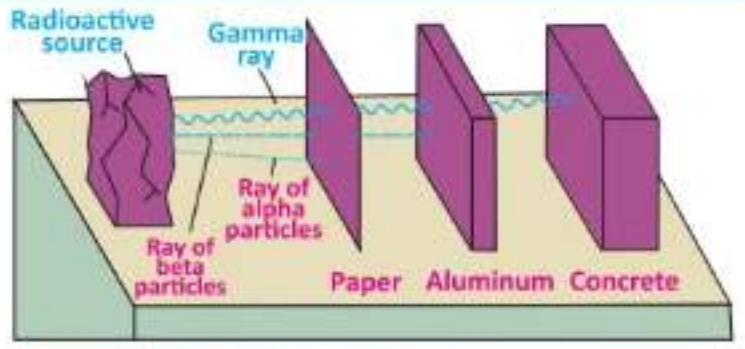


Fig. 20.7: Penetrating power of three types of radiations

Penetrating Powers

Penetration power refers to how far radiation can travel through materials before being absorbed. Penetration power of (α) ,(β) and (γ) rays are shown in Fig. 20.7.

Alpha (α) particles: Lowest penetration – stopped by a sheet of paper or a few centimetres of air.

Beta (β) particles: Moderate penetration – can pass through a sheet of paper but stopped by a few millimetres of aluminum.

Gamma (γ) rays: Highest penetration – can pass through paper, aluminum, and even thick lead or concrete slabs.

The other properties like composition, charge, mass, ionizing power, penetrating power and deflection in fields of these rays are shown in Table 20.1.

Table 20.1: Comparison of alpha, beta, and gamma radiation.

Property	Alpha particles (α)	Beta particles (β)	Gamma rays (γ)
Composition	Helium nuclei ($^{4}_{2}He$)	Electrons ($^{0}_{-1}e$) or positrons ($^{0}_{+1}e$)	Electromagnetic waves (photons)
Charge	+2e	-1e or +1e	0
Mass	4 atomic mass units	Very small	0
Ionizing power	High	Moderate	Low
Penetrating power	Low	Moderate	High
Deflection in fields	Slight both in electric and magnetic fields	Significant in electric and magnetic fields	No deflection

20.5 Radioactive Decay

Radioactive decay is the process in which unstable atoms release radiation to become stable. This radiation can be in the form of particles (alpha and beta) or waves (gamma rays). Some atoms have too many or too few neutrons in their nucleus, making them unstable. To become stable, they release energy in the form of radiation.

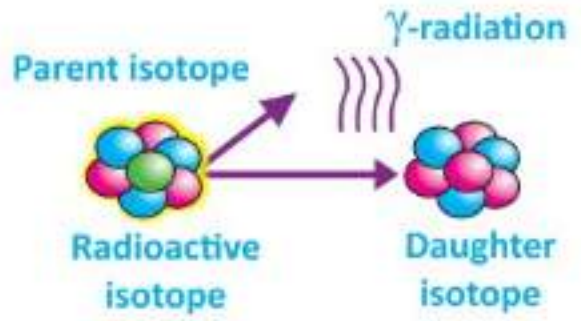


Fig. 20.8: Transformation of a parent isotope into a daughter isotope

Figure. 20.8 demonstrates a radioactive process in which transformation of parent isotope into daughter isotope takes place through the emission of radiations.

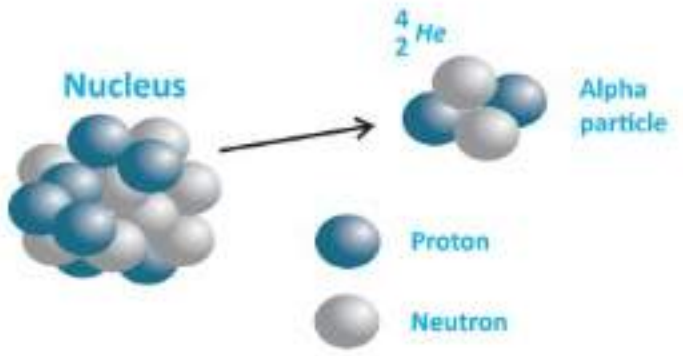


Fig. 20.9: Representing alpha decay

1. Alpha (α) Decay Equation

In alpha decay, an unstable nucleus emits an alpha particle (^4_2He), reducing its atomic number by 2 and mass number by 4 (Fig. 20.9)

General Equation: $^A_ZX \rightarrow {}^{A-4}_{Z-2}Y + {}^4_2He$ ..... (20.1)

Example (Decay of Uranium-238): $^{238}_{92}U \rightarrow {}^{234}_{90}Th + {}^4_2He$ +Energy

2. Beta (β) Decay Equations

In beta decay, a neutron converts into a proton and emits a beta particle (electron).

General Equation: $^A_ZX \rightarrow {}^A_{Z+1}Y + {}^0_{-}\beta$ +Energy ..... (20.2)

Example (Decay of Carbon-14): $^{14}_6C \rightarrow {}^{14}_7N + {}^0_{-}\beta$ + energy

3. Gamma (γ) Decay Equation

In gamma decay, the nucleus releases excess energy as a gamma ray (γ) without changing the number of protons or neutrons (Fig. 20.10).

General Equation: $^A_ZX^* \rightarrow {}^A_ZX + \gamma$ .....(20.3)

Example (Decay of Cobalt-60):

$$^{60}_{27}Co^* \rightarrow {}^{60}_{27}Co + \gamma$$

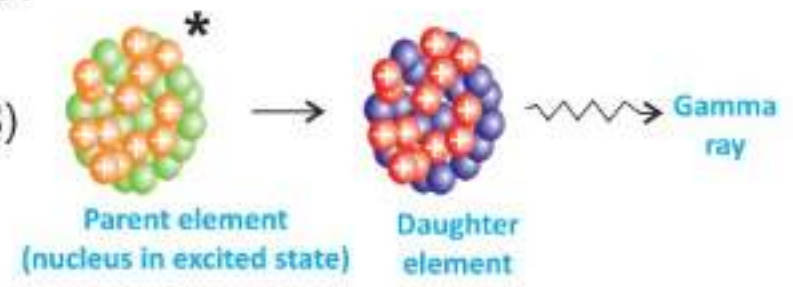


Fig. 20.10: Representing gamma decay

These equations represent the fundamental processes of radioactive decay, helping us to understand how unstable atoms transform into stable ones.

Example 20.2: Find the atomic mass and atomic number of the nuclei that come after alpha decay of Uranium (*U*-238).

Solution:

Alpha decay nuclear reaction is given by: $^A_ZX \rightarrow {}^{A-4}_{Z-2}Y + \alpha$ + Energy

For Uranium -238, the nuclear reaction will come: $^{238}_{92}U \rightarrow {}^{238-4}_{92-2}Y + {}^4_2He(\alpha)$ + Energy

or $^{238}_{92}U \rightarrow {}^{234}_{90}Y + {}^4_2He(\alpha)$ + Energy

So, atomic number of the required nucleus is 90 and mass number is 234.
Every element has a unique atomic number. From periodic table, the new element is to be Thorium (*Th*) with Z =90.
The finalized nuclear reaction can now be witten as: ${}^{238}_{92}U \rightarrow {}^{234}_{90}Th + {}^{4}_{2}He(a) +$ Energy

20.6 Nuclear Reactions

Nuclear reactions involve changes in the nucleus of an atom, leading to the transformation of elements and the release or absorption of energy. These reactions are different from chemical reactions, which only involve electrons.
We will discuss here two types of nuclear reactions:

1. Fission Reaction
2. Fusion Reaction

Fission Reaction

In fission reaction, a heavy nucleus (like Uranium-235) splits into two smaller nuclei when bombarded by a neutron. This process releases a large amount of energy and additional neutrons, which can cause a chain reaction. The fission reaction is the foundation of both nuclear power generation and atomic weapons. In fission, a tiny fraction of mass transforms into an enormous amount of energy. Nuclear fission was first discovered in 1939 by Otto Hahn and Fritz Strassman. They observed that a uranium nucleus splits into two nearly equal fragments after absorbing a slow-moving neutron (Fig. 20.11). This process also releases extra neutrons, typically two or three per fission event, with an average of 2.5 neutrons per reaction. This chain reaction plays an important role in nuclear power generation and atomic bombs.

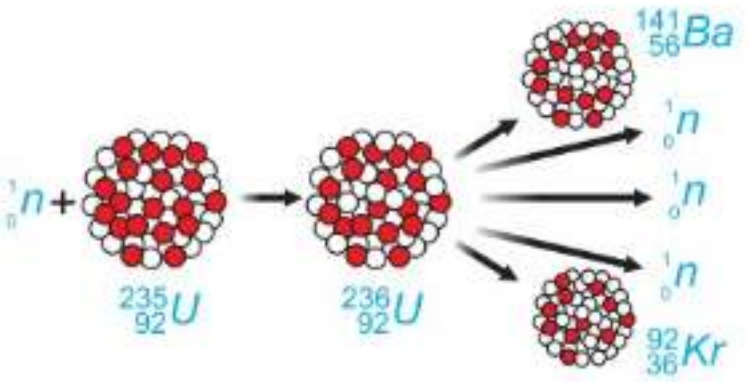


Figure 20.11: Nuclear fission reaction

$$ {}^{1}_{0}n + {}^{235}_{92}U \longrightarrow {}^{236}_{92}U^{*} \longrightarrow {}^{141}_{56}Ba + {}^{92}_{36}Kr + 3\,{}^{1}_{0}n + \text{Energy} \quad \ldots\ldots\ldots\ (20.4) $$

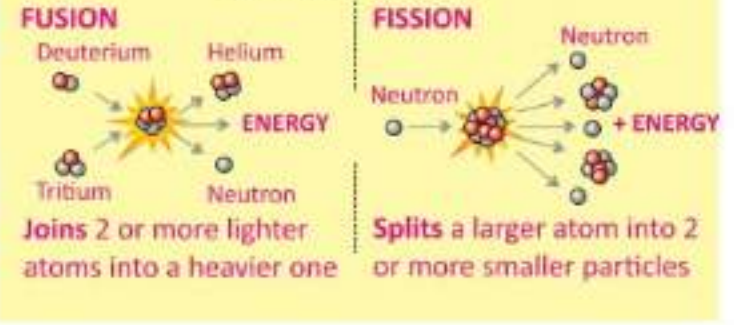
In nuclear fission reaction, the total mass of the products is slightly less than the original heavy nucleus. This lost mass is converted into energy, releasing about

200 MeV (1 eV = 1.6 x 10^{-19}J) per fission event, which is far greater than energy from chemical reactions. For instance, burning 1 ton of coal releases 3.6 × 10^9 J, while fission of 1 kg of *U*-235 produces around 6.7 × 10^{13} J. During fission, released neutrons can trigger further reactions, leading to a chain reaction. If uncontrolled, this can cause a rapid energy release, resulting in an explosion. However, in nuclear reactors, this reaction is carefully controlled by absorbing extra neutrons, allowing the energy to be used safely for power generation.

Do You Know?

Fusion vs fission

Nuclear reactions that produce massive amounts of energy, but have different processes



Nuclear Fusion

Nuclear fusion is a process where two or more light nuclei (like hydrogen isotopes) combine to form a heavier nucleus, releasing huge amount of energy (Fig. 20.12). This occurs at extremely high temperatures and speeds, where some mass is converted into energy. The final nucleus is always lighter than the total mass of the original nuclei, and the lost mass turns into energy.

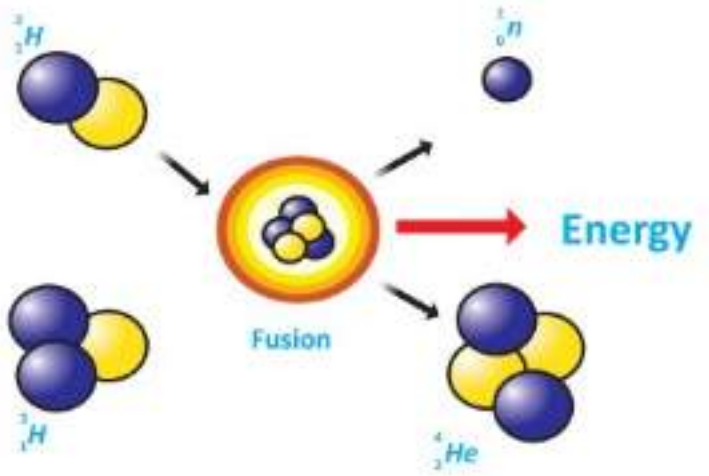


Fig. 20.12: Nuclear fusion reaction

For example, when deuterium and tritium fuse, they form helium (alpha particle) and release energy.

$$ {}_{1}^{2}H + {}_{1}^{3}H \longrightarrow {}_{2}^{4}He + {}_{0}^{1}n + \text{Energy} \quad \ldots\ldots\ldots\ldots \quad (20.5) $$

The Sun and stars shine because of fusion reactions, where four hydrogen nuclei fuse into one helium nucleus, releasing about 25.7 MeV of energy. The Sun's core, at nearly 20 million kelvin, provides the perfect conditions for fusion to occur.

20.7 Interconversion of Matter and Energy

Matter and energy can be converted into each other (Fig. 20.13), a concept explained by Einstein's equation ($E=mc^2$). This means that a small amount of mass can turn into a huge amount of energy, as seen in nuclear fission and fusion, which power nuclear reactors and the Sun. Similarly, energy can also transform into matter under extreme conditions, such as in particle accelerators, where high-energy photons create particle-antiparticle pairs (pair production). This process follows the law of conservation of energy, which states that total energy, including mass-energy, remains constant in an isolated system. The ability to convert matter into energy and vice versa is key to understanding the universe, stars, and atomic particles. Theoretically a single gram of matter can be converted into enough energy to power a city for days.

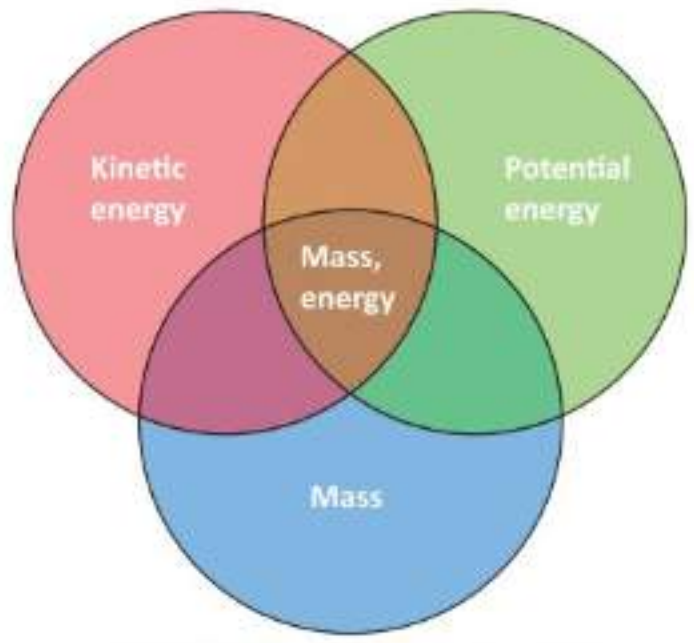


Fig. 20.13: Interconversion of different energies

Einstein's Equation and Energy Calculation

Einstein's equation $E = mc^2$ helps to calculate the energy released in nuclear reactions like fission and fusion. It states that a small amount of mass (m) converts into a large amount of energy (E), where: E = Energy (joules or MeV), m = Mass, c = Speed of light (3×10^8 m s^{-1}). In nuclear reactions, the total mass of the products is slightly less than the mass of the reactants. This missing mass is called mass defect (Δm). Using $E = mc^2$, we can find the energy released:

If $\Delta m = 1 \times 10^{-4}$ kg, then using $E = mc^2$:

$$E = (1\times10^{-4}\ \text{kg}) \times (3\times10^{8}\ \text{m s}^{-1})^2\ ;\ E = 9\times10^{12}\ \text{J}$$

Uniform Mass Scale (u)

The term uniform mass scale (u) refers to atomic mass unit (u) being used as a standardized unit to measure the mass of atoms and molecules.

1u = 1/12 the mass of carbon-12 atom $\approx$ 1.66605×10^{-27} kg

Example 20.3: Energy Released in Nuclear Fission Reaction:

$$^{235}_{92}U + ^{1}_{0}n \rightarrow ^{141}_{56}Ba + ^{92}_{36}Kr + 3^{1}_{0}n + \text{Energy}$$

Solution:

Consider the fission of uranium-235:

where,

- Mass of ($^{235}_{92}U$)= 235.0439 u
- Mass of neutron($^{1}_{0}n$) = 1.0087 u
- Mass of ($^{141}_{56}Ba$) = 140.9144 u
- Mass of ($^{92}_{36}Kr$) = 91.9262 u
- Mass of 3 neutrons = 3×1.0087=3.0261 u

Mass defect will be:

$$\Delta m = (\text{Mass of reactants}) - (\text{Mass of products})$$

$$\Delta m = (235.0439 + 1.0087) - (140.9144 + 91.9262 + 3.0261)$$

$$\Delta m = 236.0526 - 235.8667 = 0.1859 \text{ u}$$

Energy released will be:

$$E = \Delta m \times 931.5 \text{ MeV/ u}$$

$$E = 0.1859 \times 931.5 = 173.2 \text{ MeV}$$

Tidbit

Nuclear power plants use fission, where heavy nuclei like uranium split into smaller parts, releasing energy. Fusion is safer and cleaner, but hard to control.

20.8 Half-Life

Brain Teaser

What happens when a uranium nucleus splits during nuclear fission? Does it just break into two pieces, or is something else released?

The activity of a radioactive material is the rate at which its atoms decay, releasing radiation in the form of alpha, beta, or gamma particles. It tells us how many atoms break down in a given period and is measured in Becquerels (Bq), where 1 Bq = 1 disintegratoin per second, or in Curies (Ci), where 1 Ci = 3.7×10^{10} disintegration per second (dps). The activity of a substance depends on the number of radioactive atoms present and the decay constant (λ), which is linked to its half-life. A material with a shorter half-life decays faster and has higher activity, while one with a longer half-life decays slower and has lower activity. Scientists measure radioactivity using tools like Geiger counters and scintillation detectors, which help in monitoring radiation levels, ensuring safety, and studying radioactive decay in fields like medicine, archaeology, and nuclear physics.

The half-life of a radioactive isotope is the time it takes for half of the radioactive atoms in a sample to decay into a more stable form.

This concept helps scientists predict how long a radioactive substance remains active and is essential for its use in nuclear power, medical treatments, and radiocarbon dating (Table. 20.2).

Table 20.2: Half-life of isotopes

Istope	Symbol	Half-Life	Application
Carbon-14	${}^{14}_{6}C$	5,730 years	Radiocarbon dating of ancient artifacts and fossils.
Uranium-238	${}^{238}_{92}U$	4.5 billion years	Dating rocks and Earth's age; used in nuclear reactors.
Potassium-40	${}^{40}_{19}K$	1.25 billion years	Dating rocks and geological formations.
Thorium-232	${}^{232}_{90}Th$	14 billion years	Used in nuclear reactors and dating.
Radon-222	${}^{222}_{86}Rn$	3.8 days	Indoor air quality monitoring; health hazard.
Iodine-131	${}^{131}_{53}I$	8 days	Medical treatment for thyroid cancer and imaging.
Cobalt-60	${}^{60}_{27}Co$	5.27 days	Cancer treatment (radiotherapy) and industrial radiography.
Tritium (Hydrogen-3)	${}^{3}_{1}H$	12.3 days	Used in luminous paints and as a tracer in biological studies.
Polonium-210	${}^{210}_{84}Po$	138 days	Used in static eliminators and as a heat source in space probes.
Strontium-90	${}^{90}_{38}Sr$	28.8 days	Used in medical treatment and as a radioactive tracer.

The amount of radioactive isotope in the given sample decreases with time as shown in Fig. 20.14. .The number of nuclei present at time t=0 is $N = N_o$, and the number present at time $t = T_{½}$ is $N = N_o/2$. The number present at time $t = 2T_{½}$ is $N = N_o/4$ and so on. In this example the amount N of the radioactive substance left after sometime t is given by

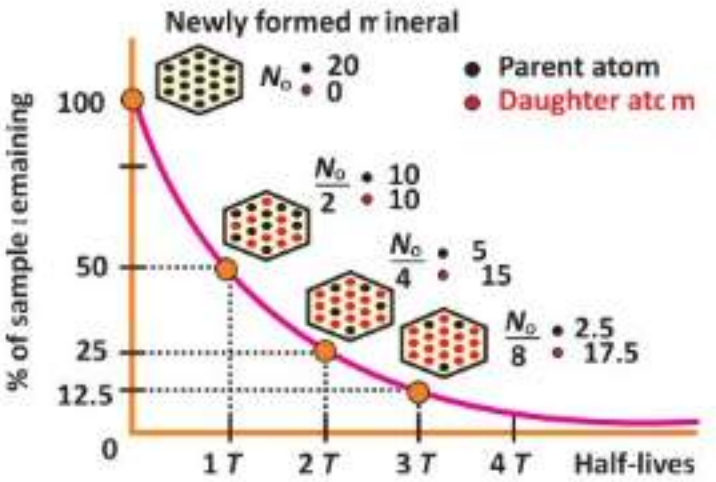


Fig. 20.14: Conversion of ${}^{99}_{43}Tc$ to ${}^{99}_{44}Ru$ by beta decay

After 1 half-Life: $N_1 = \frac{1}{2}N_0$

After 2 half-Life: $N_2 = \frac{1}{2} \times \frac{1}{2}N_0 = \left(\frac{1}{2}\right)^2 N_0$

After 3 half-Life: $N_3 = \frac{1}{2} \times \frac{1}{2} \times \frac{1}{2}N_0 = \left(\frac{1}{2}\right)^3 N_0$

After 4 half-Life: $N_4 = \frac{1}{2} \times \frac{1}{2} \times \frac{1}{2} \times \frac{1}{2}N_0 = \left(\frac{1}{2}\right)^4 N_0$

Number of half-lives (n) can be found by the following relation:

$$\text{Number of half-lives} = \frac{\text{Total time passed}}{\text{Half-life}}$$

Therefore $$n = \frac{\Delta t}{T_{1/2}} \quad \ldots\ldots\ldots\ldots \quad (20.6)$$

Half-Life of Radioactive Isotopes

The half-life of a radioactive isotope is the time it takes for half of its atoms to decay into a more stable form. Each isotope has a unique half-life that never changes, no matter how much of the substance is present or what ever may be the surrounding conditions.

For example, carbon-14, used in radiocarbon dating, has a half-life of 5,730 years, while *U*-238 takes 4.5 billion years to decay by half. Radioactive decay follows an exponential pattern, meaning that after each half-life, only half of the remaining material is left.

The concept of half-life is important in many fields, including archaeology (dating ancient artifacts), medicine (using radioactive isotopes for diagnosis and treatment), and nuclear energy (handling radioactive waste). By knowing the half-life of a substance, scientists can predict how long it will stay radioactive and how fast it will decay.

Carbon Dating

Carbon dating is a scientific method used to determine the age of ancient organic materials like wood, bones, and shells, up to 50,000 years old. This technique is based on the radioactive decay of carbon-14, a type of carbon found in the atmosphere. Living organisms constantly absorb carbon-14 while they are alive, maintaining a steady balance with carbon-12. However, when an organism dies, it stops absorbing carbon, and the carbon-14 starts to decay at a fixed rate, with a half-life of about 5,730 years. By measuring the remaining carbon-14 in a sample and comparing it to its original amount, scientists can estimate how long ago the organism died. Carbon dating is an essential tool in archaeology, geology, and anthropology, helping researchers determine the age of artifacts, fossils, and

Brain Teaser

If two fossils found in the same layer of rock have nearly the same amount of carbon-14 left, but one belong to a fast-living animal and the other to a slow-living one, which one is older or are they the same age?

Tidbit

Carbon-14 is constantly created in the upper atmosphere when cosmic rays hit nitrogen atoms — meaning the clock "starts ticking" the moment an organism dies.

Fun Fact

Carbon-14 is constantly being created in Earth's atmosphere!

ancient remains, giving important insights into human history and environmental changes. The radioactive decay of carbon-14 shown in Fig. 20.15.

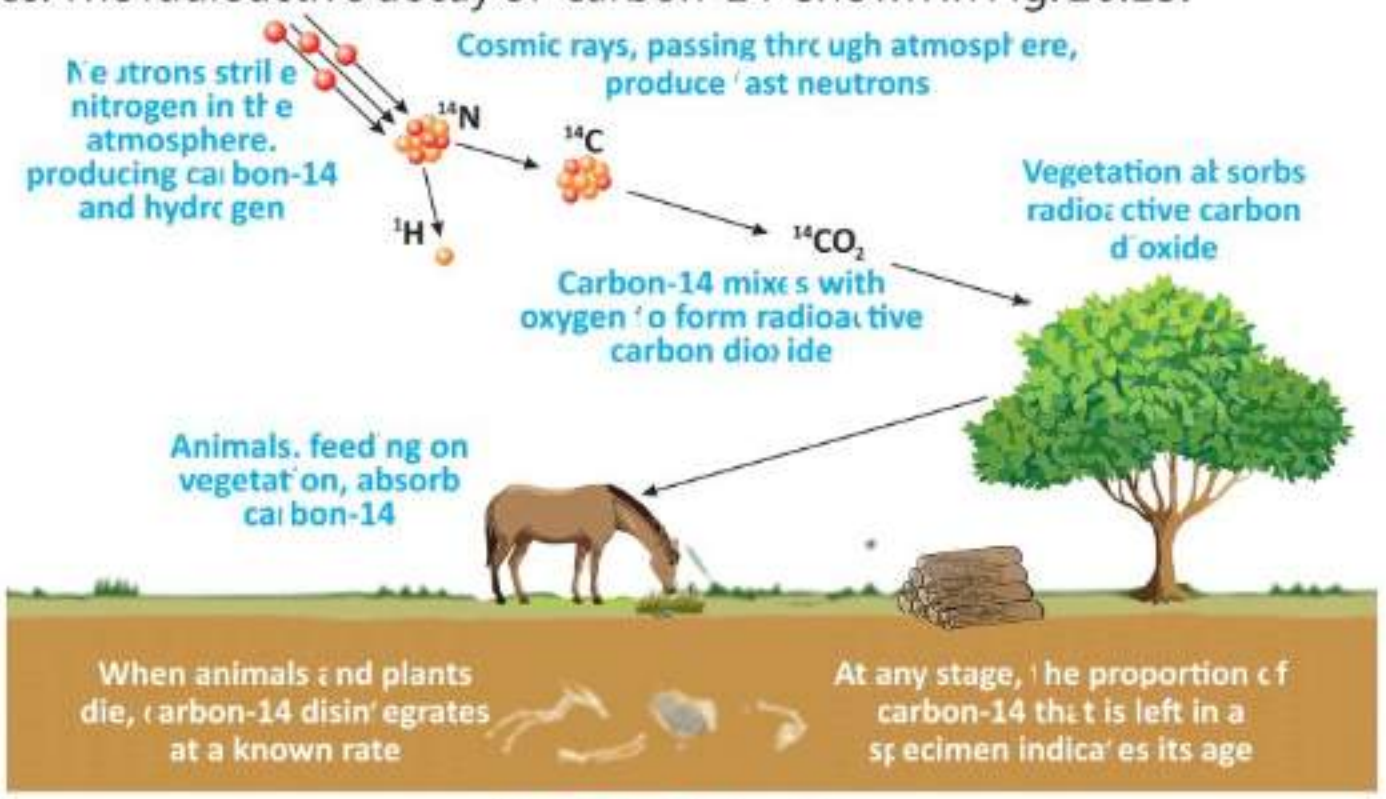


Fig. 20.15: Carbon dating

Example 20.4: We have a 50 mg sample of lead-212. it decays by beta and gamma emission with a half-life of 10.6 hours. How much of the pure sample is left after 53 hours?

Solution:

Given that;

initial quality of pure lead-212 N_0 = 50 mg

Half-life of lead - 212 T - 10.6h

Total elapsed time Δt = 53 hours

To find; Quantity to be left N = ?

The number of half-lives n is given by $n = \dfrac{\Delta t}{T_h}$

Substituting the values: $n = \dfrac{53\ \text{h}}{10.6\text{h}}$

Therefore $n = 5$

Original sample remaining after n number of half-lives: $N = \left[\dfrac{1}{2}\right]^n N_0$

Substituting the values: $N = \left[\dfrac{1}{2}\right]^5 \times 50\ \text{mg}$

Therefore $N = 1.56\ \text{mg}$

So, 1.56 mg of lead -212 will be present after 53 hours of 5 half-lives.

20.9 Effects and Uses of Nuclear Radiation

Ionizing radiation (such as alpha, beta, and gamma rays) can affect living organisms because it can alter or damage atoms and molecules, including DNA. The impact of radiation depends on the dose, exposure time, and type of radiation.

Effects of Nuclear Radiation

1. High doses can kill cells by damaging their DNA, which is why radiation is used in cancer treatment (radiotherapy) to destroy cancer cells.
2. Radiation can cause DNA mutations, breaking chemical bonds and altering genetic codes, which may lead to genetic disorders or hereditary diseases if reproductive cells are affected.
3. Long-term exposure to low doses increases the risk of cancer by mutating normal body cells. For example, too much UV radiation from the Sun can lead to skin cancer.
4. Severe exposure over a short time can cause radiation sickness, leading to nausea, vomiting, organ failure, and even death in extreme cases.

Do You Know?

High-energy gamma rays are used to target and destroy cancer cells in radiotherapy. Precision is key to avoid harming healthy cells.

Uses of Nuclear Radiation

The selection of a radioactive isotope depends on its type of radiation and half-life:

1. **Medical Uses:** Short-lived isotopes are used in radiotherapy and imaging to minimize long-term radiation risks.
2. **Industrial Uses:** Isotopes with long half-lives are used in power generation, radiation detectors, and material testing, where long-term stability is important.

   Nuclear radiation plays a major role in medicine, industry, and scientific research, but it must be handled carefully to avoid harmful effects.
3. **Cobalt-60 and Cesium-137 in Food Preservation:** Gamma rays from these isotopes kill bacteria in food, increasing shelf life without affecting quality. Cobalt-60, with a moderate half-life (5.27 years), is commonly used in the food industry.
4. **Cobalt-60 in Sterilization:** Gamma radiation is used to sterilize medical equipments, killing bacteria and viruses without damaging the materials.

Radiation Source

1. **Americium-241 ($^{241}_{95}Am$) in Smoke Detectors:** Used in fire alarms, where

alpha particles ionize air molecules, creating an electric current. When smoke enters, the current is disrupted, triggering the alarm. Its long half-life (432 years) makes it ideal for long-term use.

2. **Cobalt-60 and Iodine-131 in Medicine:**

Gamma rays from Cobalt-60 are used in radiotherapy to destroy cancer cells, while Iodine-131, with a short half-life (8 days), is used in thyroid diagnosis and treatment to minimize long-term radiation exposure.

Do You Know?

Even without nuclear power or medical scans, we are exposed to radiation from cosmic rays, rocks, and even bananas (which contain potassium-40).

EXERCISE

A. Multiple Choice Questions

Tick (✓) the correct answer.

20.1 What did Rutherford's alpha particle scattering experiment reveal about the structure of the atom?
(a) Electrons are distributed evenly throughout the atom
(b) Protons and electrons are located in the nucleus
(c) Atoms are indivisible and indestructible
(d) The nucleus is small, dense, and positively charged

20.2 The atomic number of an element represents:
(a) number of neutrons in the nucleus
(b) number of protons in the nucleus
(c) total number of protons and neutrons
(d) number of electrons and neutrons

20.3 Which type of radiation is positively charged and consists of two protons and two neutrons?
(a) Alpha (α) (b) Beta (β)
(c) Gamma (γ) (d) Neutron emission

20.4 The process by which an unstable nucleus emits radiation and transforms into a more stable nucleus is called:
(a) nuclear fusion (b) nuclear fission
(c) radioactive decay (d) isotopic exchange

20.5 Nuclear fission involves:
(a) combining light nuclei to form heavier ones
(b) splitting heavy atomic nuclei into smaller ones
(c) absorbing gamma radiation to increase stability
(d) none of the above

20.6 What does Einstein's equation; $E=mc^2$; explain?
(a) The energy released in chemical reactions
(b) The equivalence of mass and energy
(c) The rate of radioactive decay
(d) The conversion of mass into momentum

20.7 Which of the following is a practical application of nuclear radiations?
(a) Cooking food in microwave ovens
(b) Medical imaging and cancer treatments
(c) Solar energy generation
(d) Airplane navigation systems

20.8 What are the potential effects of ionizing nuclear radiation on biological tissues?
(a) Increased cellular regeneration
(b) DNA damage and cancer
(c) Enhanced immune system response
(d) Improved metabolic activity

B. Short Answer Questions

20.1 Define the atomic nucleus. What are its two main characteristics?
20.2 What is the structure of an atom according to Rutherford's model?
20.3 How does alpha radiation differ from beta radiation?
20.4 What is the primary energy source of the Sun and other stars?
20.5 Name the equation proposed by Einstein that relates energy and mass.
20.6 What is the principle behind carbon dating and its applications?
20.7 Define nuclear fusion with an example.
20.8 Americium-241 ($^{241}_{95}Am$) undergoes alpha decay and produces an alpha particle. Write down the chemical equation for it and name the nucleus formed.

C. Constructed Response Questions

20.1 If an atom is mostly empty space, why do not we fall through solid objects or pass through walls?
20.2 Imagine a new radioactive element is discovered. How could scientists estimate its half-life without waiting thousands of years?

20.3 If gamma rays do not change the number of protons or neutrons in a nucleus, why are they still considered dangerous?

20.4 If carbon-14 stopped forming in the atmosphere today, how would that affect the use of carbon dating in the future?

20.5 What is the difference between nuclear fission and nuclear fusion in terms of process and energy release?

D. Comprehensive Questions

20.1 How does the structure of an atom determine its chemical properties? Explain with reference to the arrangement of protons, neutrons, and electrons?

20.2 Explain Einstein's equation; $E=mc^2$, and its significance. How does this equation relate to nuclear reactions?

20.3 Describe the process of radioactive decay and how it leads to the emission of alpha, beta, and gamma radiation?

20.4 Why do different isotopes of the same element have similar chemical properties but different physical properties? Explain.

20.5 Explain how carbon dating uses carbon-14 to estimate the age of artifacts. Discuss its reliability, considering the influence of carbon-14's half-life?

E. Numerical Problems

20.1 Find the number of protons and neutrons in the nuclide defined by ${}^{21}_{9}X$.
[Ans: 9 protons and 12 neutrons]

20.2 A fossil is found to have 25% of the carbon-14 compared to a living sample. How old is the fossil? **[Ans: ≈ 11460 years]**

20.3 A sample initially contains 400 g of a radioactive isotope with a half-life of 10 years. How much remains after 30 years? **[Ans: 50 g]**

20.4 A radioactive substance has a half-life of 64 months. In how much time, one-eighth of the substance will be left? **[Ans: 192 months]**

20.5 In a nuclear reaction, 4 μg of mass is converted into energy. Find the energy. **[Ans. 360 MJ]**

20.6 In 420 days, one-eighth of polonium (Po) remains un-decayed. Calculate the half-life of polonium? **[Ans: 140 days]**

20.7 Three-fourth of the initial mass of a certain radioactive isotope decay after one hour. Find half-life of isotope in minutes? **[Ans: 30 min]**

CHAPTER 21

SPACE AND ENVIRONMENT

Student's learning outcomes (SLOs)

After studying this chapter, students will be able to:

- explain the nature of the Sun [as a star of medium size, it consists mostly of hydrogen and helium, and that it radiates most of its energy in the infrared, visible and ultraviolet regions of the electromagnetic spectrum].
- interpret and compare given planetary data [about orbital distance, orbital period, density, surface temperature and uniform gravitational field strength at the planet's surface].
- use ideas of convection to explain how cyclones are formed.
- explain how global warming contributes to extreme weather events [specifically in the case of hurricanes, heat waves, flooding, rainfall, wildfires, droughts, winter storms].
- explain what is meant by background radiation.
- state the sources that make a significant contribution to background radiation [including:
  (a) radon gas (in the air)
  (b) rocks and buildings
  (c) food and drink
  (d) cosmic rays].

Space and the environment are closely connected to each other. In order to understand and solve problems on the Earth, it is essential to explore the space. In the space, information regarding the environmental changes are collected by the satellites, orbiting around the Earth. This enables scientists to make efforts to protect the Earth using the data obtained from the satellites. New ideas have been created due to advancements in the space technology which help in obtaining renewable energy with better and efficient utilization of the materials. The study of space also enables us to understand the origin and evolution of the universe and to make the technological advancements. In this chapter, we will study the nature of the Sun, planetary data, formation of cyclones, phenomena of global warming, geothermal activity and background radiations.

21.1 Sun and Planetary Data

The Sun is the greatest source of light, heat and other forms of electromagnetic (E.M) waves. The gravitational pull of the Sun keeps planets, including the Earth to orbit around it. The Sun is located at the centre of our solar system. The Sun contains 74 % of hydrogen and 24 % of helium along with few other elements. Nuclear fusion takes place at the core of the Sun (Fig. 21.1), in which hydrogen atoms are fused together to form helium, resulting in a tremendous increase in the temperature of the Sun (in millions of degree celsius). This releases a massive amount of energy which reaches the Earth in the form of light and heat. The energy released from the Sun travels through space in the form of various types of radiations such as infrared, heat, sunlight and ultraviolet radiations. These radiations have a considerable impact on the people living on the Earth and other form of lives. The energy obtained from the Sun plays an essential role in making weather patterns, changing the climate and supporting the ecosystems. For the study of planets, it is necessary to focus on different factors such as orbital distance, orbital period, density, surface temperature, gravitational field strength, etc. which makes each planet unique.

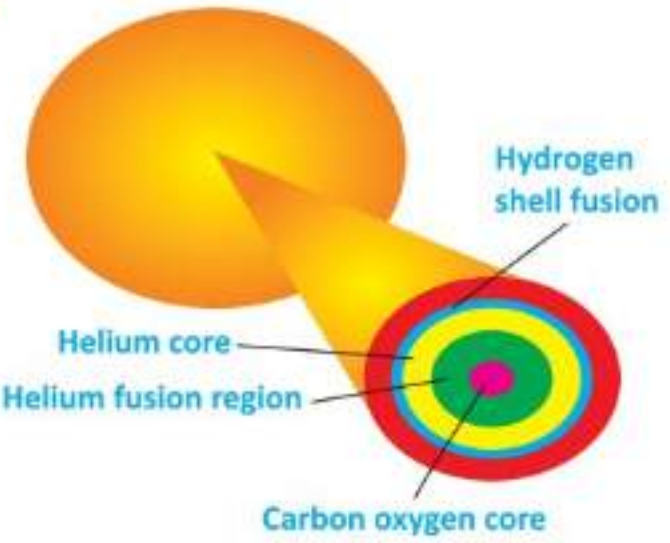


Fig. 21.1: Formation of the Sun

Tidbit

Even though it looks like a burning ball, the Sun does not burn like wood or coal. It fuses hydrogen into helium in its core, releasing immense energy through nuclear fusion, not combustion.

Orbital Distance

The solar system is shown in Fig. 21.2. Those planets that are closer to the Sun have smaller orbital distance and those located at a far away distance from the Sun have large orbital distances. Orbital distance plays a vital role in determining the amount of solar energy received by each planet.

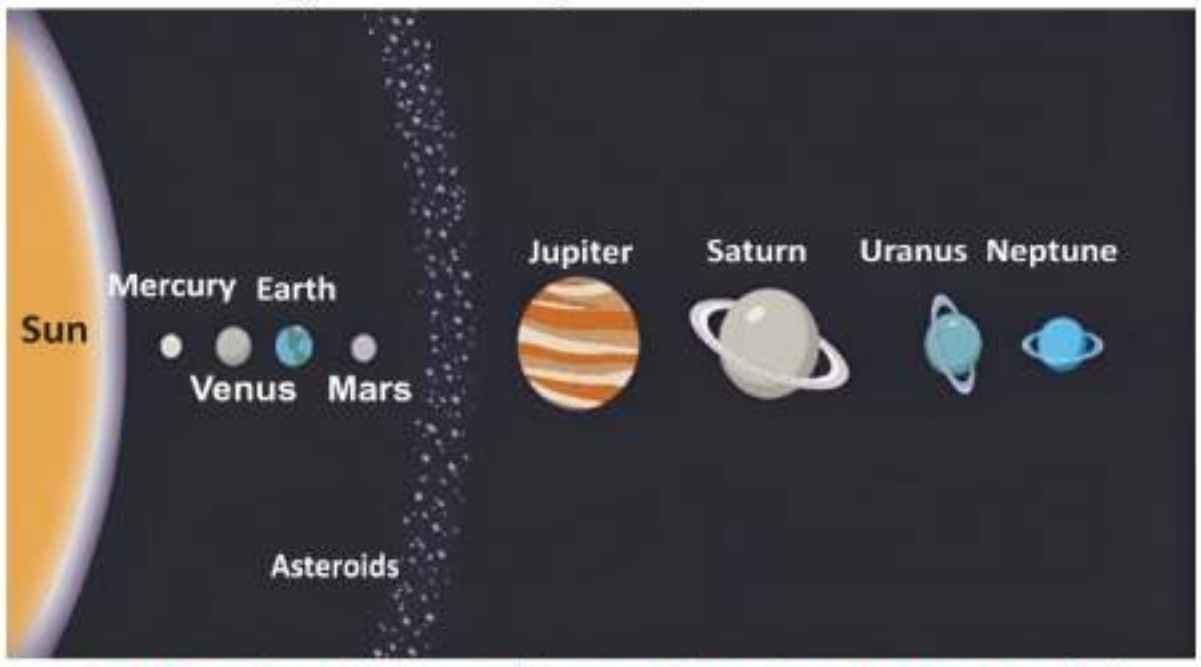


Fig. 21.2: The solar system (distance from the Sun is not to scale)

Orbital Period: This is the time a planet takes to complete one orbit around the Sun. Planets closer to the Sun have shorter orbital periods.

Density: Density reflects a planet's composition. Rocky planets like Earth and Mars have higher densities due to their solid, metallic cores, while gas giants like Jupiter and Saturn have lower densities because they are composed mostly of hydrogen and helium.

Surface Temperature: This depends on factors like distance from the Sun, atmospheric composition, and greenhouse effects. For example, Venus has an extremely high surface temperature due to its thick, heat-trapping atmosphere, while Mars is much colder due to its thin atmosphere and greater distance from the Sun.

Gravitational Field Strength: For a planet, the gravitational field strength at its surface depends on its mass, and is nearly uniform across its surface. The strength of the gravitational field decreases as the distance from the planet increases. Smaller

Do You Know?

Planets have different orbital periods. While Earth takes 365.25 days to orbit the Sun, Mercury takes just 88 days, and Neptune takes 165 Earth years!

Tidbit

Even after 4.5 billion years, the Earth's core remains molten, partly due to radioactive decay and the heat leftover from planetary formation.

planets (like Mars) have weaker gravitational force, while larger planets (such as Jupiter) have stronger gravitational relative to the Earth.

Formation of Cyclones

Cyclones refer to heavy storms containing fast and spinning winds forming around low air pressure area (Fig. 21.3). The phenomenon of convection is responsible to develop these cyclones. The convection takes place due to rise of the warm air (being lighter) as compared to the (heavier) cool air that moves down. Due to rise in the warm air, more air rushes in to take its place, which creates the spinning effect. The cyclone grows stronger and bigger due to the movement of air (Fig. 21.4).

Fig. 21.3: Cyclone

The convection contributes to cyclone formation in the following ways:

1. Warm Ocean Waters: Formation of cyclones occurs (over warm oceans) where temperature of the sea surface is very high (27 °C or 300 K). The air above the warm water is heated, becomes less dense and rises rapidly. This movement of the warm air in the upward direction creates an area of low pressure at the surface.

2. Rising Air and Condensation: The rising warm air moves to low air pressure areas, causing the air to expand. The clouds are formed due to the moisture in the air and as a result, heat is released into the surrounding air. Due to this heat, the air becomes even warmer and it rises even faster. As this process continues, the warm air further rises, forms more clouds and increases the release

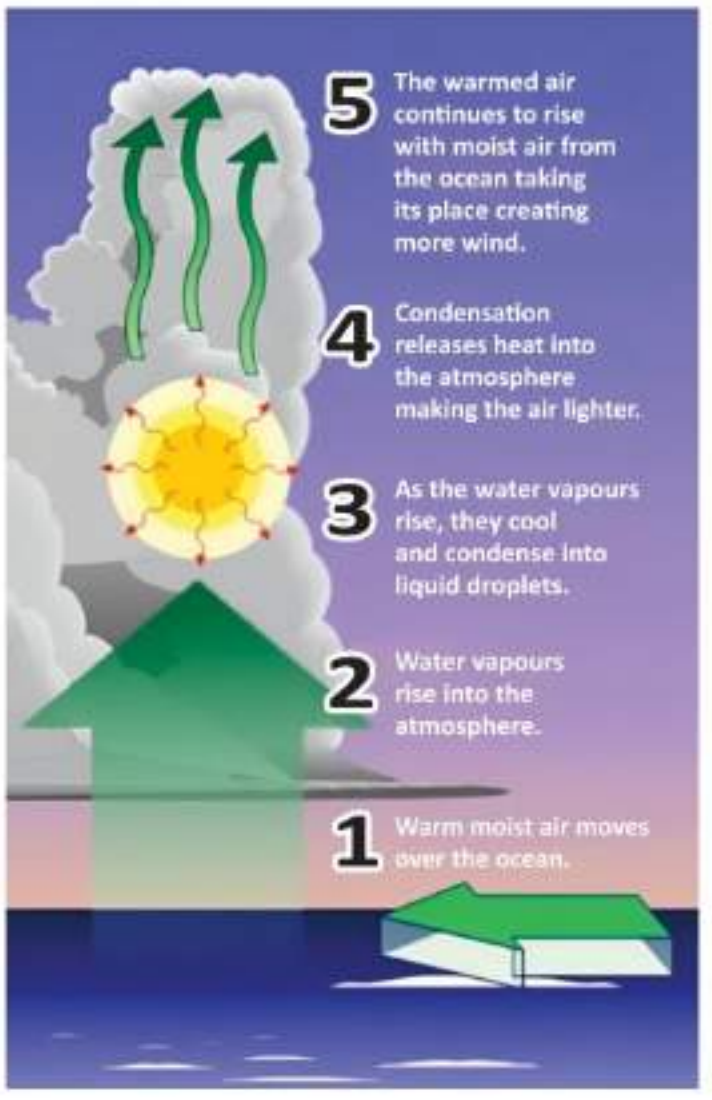


Fig. 21.4: Formation of cyclone

of more heat in the surroundings. This cycle keeps going, making the cyclone stronger and helping it grow bigger.

3. Formation of a Low-pressure Centre: As the warm air keeps rising, it leaves behind empty space near the surface, like a small vacuum. To fill this space, warmer, moist air from the surrounding areas rushes in. Because the Earth is spinning, this moving air does not go in a straight line. Instead, it starts to spin around the low-pressure area. This effect is called the Coriolis effect. In the northern hemisphere, the air spins anticlockwise, while in the southern hemisphere, it spins clockwise. This spinning motion helps shape the cyclone and keeps it growing stronger.

Tidbit

Earth-observing satellites can detect heat patterns, water vapour, and storm movement, helping scientists predict cyclones and track climate change with astonishing precision.

4. Development of a Cyclonic System: As more warm air keeps getting pulled into the storm, the rising and spinning of the air becomes even stronger. The cyclone keeps growing as long as it has warm, moist air from the ocean. In the middle of the cyclone, a special area called the eye forms, where the air moves downward, making it calm and clear. However, just outside this calm centre is the eye wall, which is the most dangerous part of the cyclone. Here, the winds are extremely strong, and heavy rain falls, making this the most powerful part of the storm.

5. Energy Dissipation: Cyclones start to weaken when they move over land or colder water because they can no longer get warm, moist air, which acts like fuel for the storm. Over the ocean, this warm air keeps the cyclone strong by helping the air rise and spin. But when the cyclone moves away from the warm ocean, the air stops rising as much, and the spinning slows down. Without this energy, the storm loses its strength, the winds become weaker, and the cyclone slowly fades away.

21.2 Global Warming and Geothermal Activity

Global warming is a long term increase in the average surface temperature of the Earth due to burning of fossil fuels, release of gases like methane, carbon dioxide, nitrous oxide, cutting down forests, and using certain industrial and farming methods. The gases trap the heat coming from the Sun and causes an increase in

the temperature. The global warming has a great impact on the weather, sea level and disruptions to ecosystems. Similar to global warming, the inner heat of the Earth (Geothermal Activity) causes volcanic eruptions, geysers, hot springs, and the movement of tectonic plates. Geothermal energy is considered as renewable resource of energy due to its sustainability as long as the Earth's internal heat remains active. Global warming has been illustrated in Fig. 21.5.

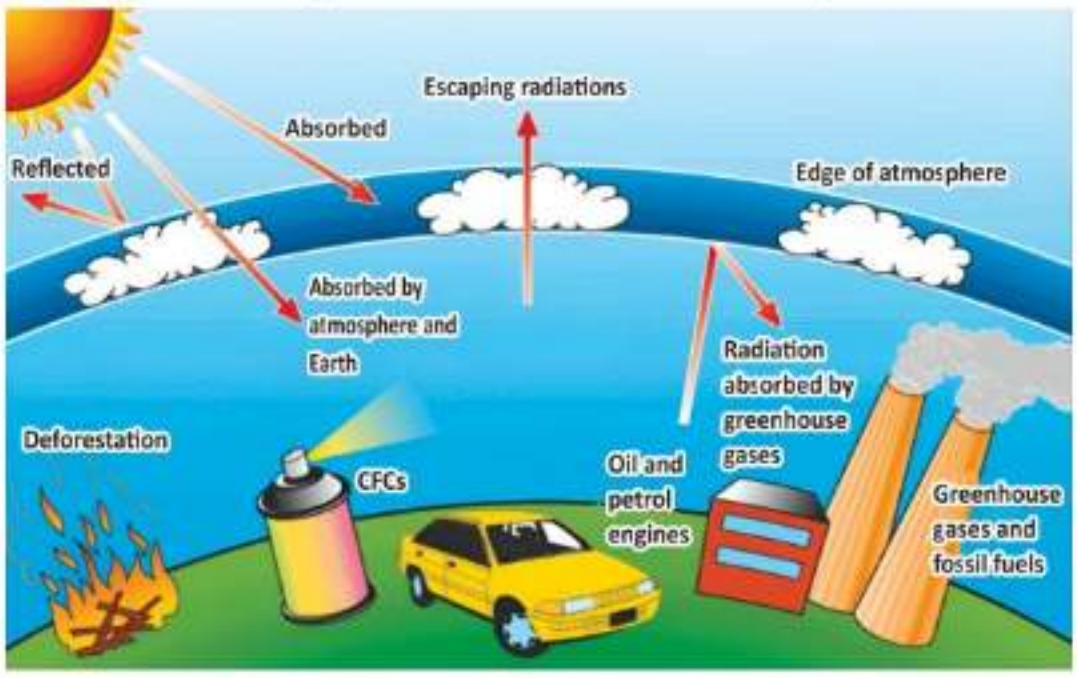


Fig. 21.5: Illustration of global warming

Hurricanes

Due to rise in the temperature, more heat is absorbed by the ocean which fuels hurricanes, making them stronger and more destructive. Intensity of hurricanes is increased by the warmer ocean waters, with higher wind speeds and heavier rainfall, causing greater damage (Fig. 21.6). Furthermore, ice begins to melt and seawater expands due to rise in the temperatures. This results in higher sea levels. Consequently, stronger storm surges and more frequent flooding in coastal areas take place, increasing the damage to homes and communities.

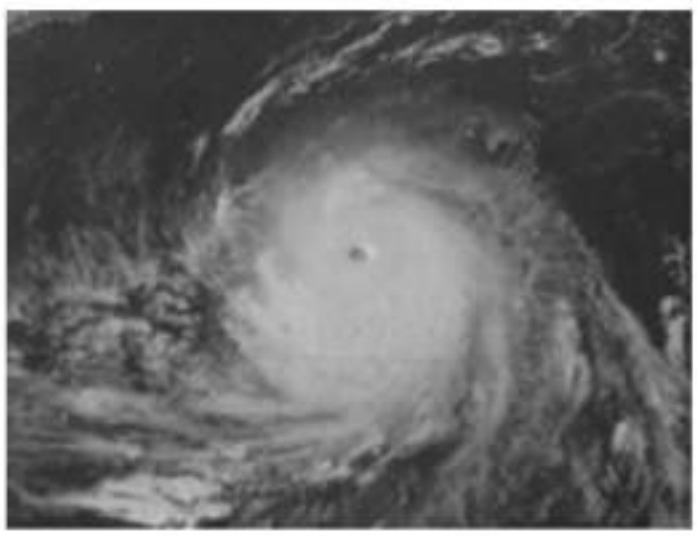


Fig. 21.6: Hurricane

Heat Waves

The rise in the global temperatures produces heat waves. The heat is trapped by the gases in the atmosphere, leading to extended periods of extreme heat. Buildings and roads absorb heat and retain it. Cities are particularly affected, as buildings and roads absorb and retain heat, causing those areas to be much hotter compared to the others (Fig. 21.7).

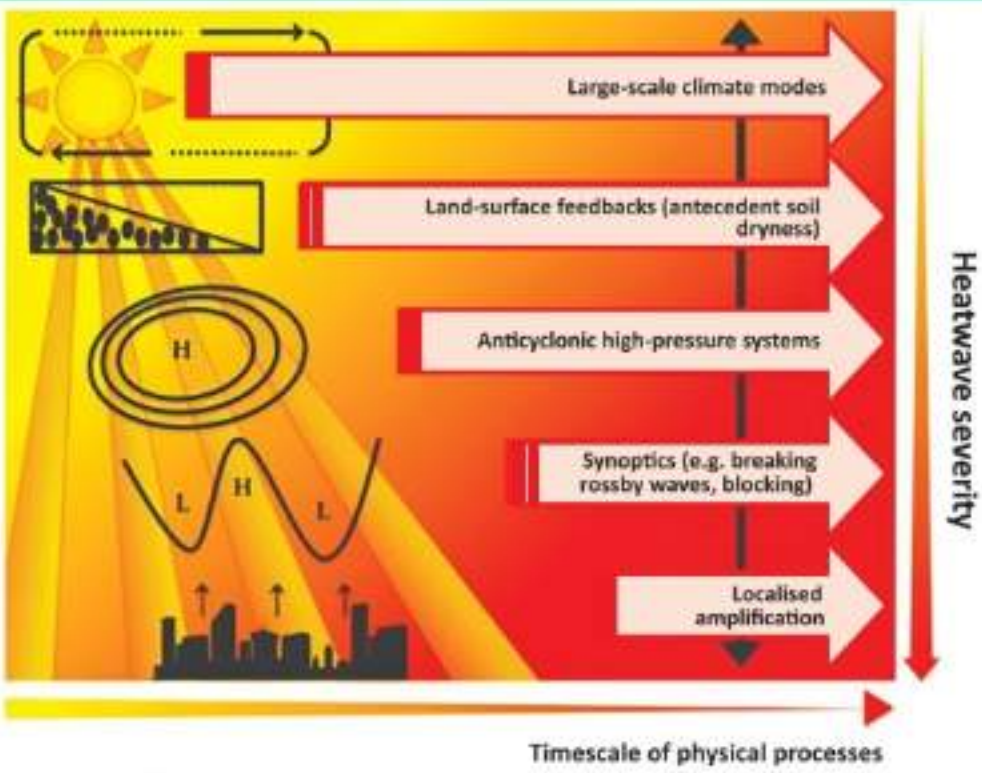


Fig. 21.7: Heatwave schematic illustrating the various physical processes

Flooding

Heavier rainfall comes to a warmer atmosphere because it can hold more moisture, resulting in intense flooding in those areas. As global warming changes weather patterns, storms become stronger, increasing the risk of both inland and coastal floods. In addition sea levels to rise due to melting glaciers and ice sheets, resulting in more flood in the coastal regions.

For Your Information

Thanks to water's high specific heat capacity, oceans absorb and release heat slowly, helping to regulate global climate and reduce the intensity of heatwaves until global warming messes with the balance.

Wildfires

Wildfires often result from high temperatures and long period of dryness. With reduced moisture in the air and soil, forests and grasslands become more susceptible to ignition. The wildfire season is also lasting longer due to earlier snowmelt and extended dry periods. As a result, wildfires are becoming more common, more severe, and more damaging, threatening ecosystems and communities alike.

California wildfire fury

Droughts

Due to increase in the temperature, more water evaporates from the land, drying out the soil. This reduces the water available for plants, animals, and people which

causes droughts to last longer and become more intense, particularly in areas already facing water shortages. Changes in rainfall patterns also lead to extended dry periods, making it harder to grow crops and provide enough drinking water for communities.

Tidbit

As temperatures rise, more water evaporates from land and water bodies. This leads to longer droughts, drying out the soil and stressing water supplies for agriculture, wildlife, and cities.

Winter Storms

Global warming can also make winter storms stronger. Warmer air holds more moisture, which means heavier snowfall when temperatures are cold enough. This leads to extreme winter storms, including heavy snow, ice storms, and longer periods of freezing weather in unexpected places.

Florida winter storm chaos

Tidbit

Global warming heats up the oceans, and warm ocean water acts like fuel for hurricanes. The hotter the water, the more energy the storm gets leading to stronger winds, heavier rainfall, and longer-lasting storms.

21.3 Radiation Exposure

Radiation exposure happens when someone comes into contact with radiation, which is a type of energy (Fig. 21.8). This energy can come from natural sources like the Sun and the ground or from man-made sources like X-ray machines and nuclear power plants. A small amount of radiation is usually safe, but too much exposure can harm our bodies by damaging cells. That is why we use safety measures, like protective wear and limited exposure, to stay safe while using radiation for useful purposes.

Fig. 21.8: Radiation exposure warning

Background Radiation

The radiation that exists around us all the time is known as background radiation.

It is the constant, low-level ionizing radiation present in the environment from both

natural and human-made sources. It includes cosmic rays from space, radioactive materials in the Earth's crust (like uranium and radon), and even tiny amounts of radiation in our food and bodies. Human activities, such as medical procedures (X-rays, CT scans), nuclear power plants, and past nuclear testing, also contribute to it. Background radiation is usually harmless at normal levels, but it is an ever-present part of our world, reminding us of the natural and human influences that shape our environment (Fig. 21.9).

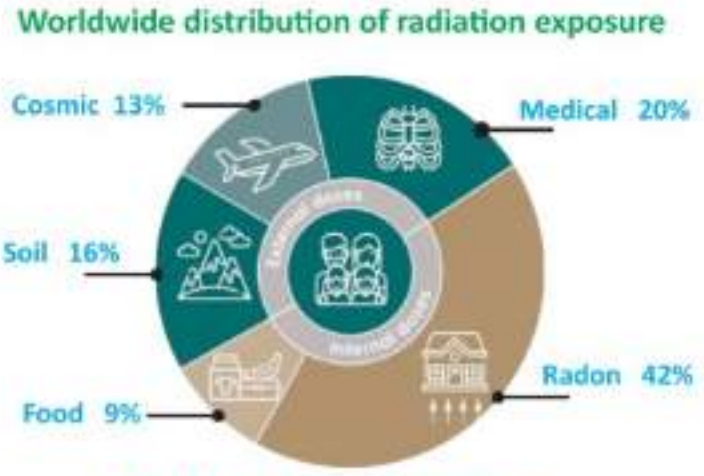


Fig. 21.9: Sources of radiation

Sources of Radiation

(a) Radon gas (in the air)

1. Radon gas is an alpha emitter.
2. Radon gas is particularly dangerous if it is inhaled into the lungs in large quantities.
3. The gas is tasteless, colourless and odourless, but it is not generally a health issue unless levels are significantly high.

Tidbit

Radon gas from the ground can seep into homes especially basements and contribute to natural background radiation. It is invisible, odourless, and radioactive.

(b) Rocks and buildings

1. Natural radioactivity can be found in building materials, including decorative rocks, stones and bricks.
2. Heavy radioactive elements, such as uranium and thorium, occur naturally in rocks in the ground.
3. Uranium decays into radon gas.

(c) Food and Drink

1. Food and water contain small amounts of naturally occurring radioactive isotopes, such as potassium-40 and carbon-14.
2. These isotopes are absorbed by plants and animals and enter the human body through consumption.
3. The contribution from food and drink is generally small but consistent.

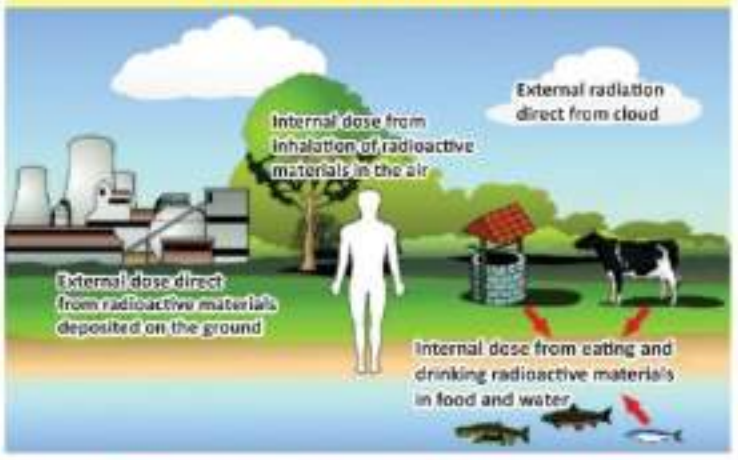
Do You Know?

Some cosmic rays that hit the Earth have travelled for millions of years from distant galaxies before colliding with atoms in our atmosphere to produce background radiation.

(d) Cosmic rays from space

1. The Sun and other stars emit an enormous number of cosmic rays including protons every second.
2. Some of these enter the Earth's atmosphere at high speeds.
3. When they collide with molecules in the air, they lead to the production of gamma radiation.

For Your Information



Exposure pathways to humans from environmental release of radioactive materials

4. High exposure to radiation in a short time can cause radiation sickness, with symptoms like nausea, vomiting, fatigue, and organ damage.
5. Long-term exposure to low levels of radiation increases the risk of cancer, especially in organs like the lungs, thyroid, and bones.
6. Radiation can damage DNA, leading to genetic mutations that may affect future generations.
7. Radioactive materials can contaminate air, water, soil, and food, spreading radiation to the environment.
8. Inhaling radioactive dust or drinking contaminated water can cause internal exposure, where radioactive particles stay in the body and keep emitting radiation.
9. Accidents, such as leaks, spills, or explosions, can occur if radioactive materials are not stored or handled safely.
10. Nuclear power plant accidents or improper waste management can lead to large-scale disasters, harming communities and ecosystems.
11. Radioactive materials can be misused in nuclear bombs, which spread radiation using conventional explosives, causing panic and long-term contamination.

Brain Teaser

Which type of radiation comes from space and can affect airline pilots, but never passes through walls?

EXERCISE

A. Multiple Choice Questions

Tick (✓) the correct answer.

21.1 What process generates energy in the Sun?
(a) Nuclear fission
(b) Nuclear fusion
(c) Radioactive decay
(d) Chemical reactions

21.2 The factor which primarily determines a planet's surface temperature:
(a) its density
(b) its orbital distance from the Sun
(c) its gravitational field strength
(d) the number of moons it has

21.3 What is the primary reason cyclones form over warm ocean waters?
(a) The presence of strong winds
(b) The high atmospheric pressure
(c) The rising of warm, moist air creating low pressure
(d) The gravitational pull of the moon

21.4 Which of the following gas contributes the most to global warming?
(a) Oxygen
(b) Carbon dioxide
(c) Nitrogen
(d) Argon

21.5 How does the Coriolis effect influence cyclones?
(a) It causes cyclones to spin in opposite directions in different hemispheres
(b) It strengthens cyclones over land
(c) It prevents warm air from rising
(d) It stops the formation of low-pressure areas

21.6 A major cause of rising sea levels is:
(a) increased volcanic activity
(b) the Earth moving closer to the Sun
(c) melting glaciers and ice sheets
(d) decreased solar radiation

21.7 A significant source of background radiation is:
(a) oxygen in the air
(b) cosmic rays from space
(c) sound waves in the atmosphere
(d) light from the Sun

B. Short Answer Questions

21.1 What are the two main elements that make up the Sun?
21.2 What factors are used to compare planets in terms of their characteristics?
21.3 Explain how global warming increases the intensity of hurricanes.
21.4 What is background radiation, and what are its natural sources?
21.5 Name three safety measures used to handle radioactive materials safely.
21.6 Why do cyclones weaken when they move over land?
21.7 How does the Coriolis Effect influence the movement of cyclones?
21.8 What is the primary cause of rising sea levels due to global warming?

C. Constructed Response Questions

21.1 Why do gas giants like Jupiter, despite their larger size, have lower densities than rocky planets such as Earth and Mars? What does this tell us about their internal structure?
21.2 If two planets receive the same amount of sunlight but have different atmospheric compositions, why might their surface temperatures still differ significantly?
21.3 How does the coriolis effect play a role in creating the spiraling motion of cyclones, and what might happen to cyclone formation if the Earth stopped rotating?
21.4 Compare the ways radiation, conduction, and convection each contribute to geothermal activity. Why is convection considered the primary driver of tectonic plate motion?
21.5 Explain why background radiation is always present in our environment and how cosmic and terrestrial sources balance each other despite fluctuations in human activity.

D. Comprehensive Questions

21.1 Describe the process of nuclear fusion in the Sun and explain how it generates energy.
21.2 How does a planet's orbital distance affect its surface temperature and the amount of solar energy it receives?
21.3 Explain the role of convection in the formation and strengthening of cyclones.
21.4 What are the major sources of background radiation, and how does human activities contribute to it?
21.5 Explain how radiation exposure can be harmful and describe three key safety measures used to minimize its risks.

Pairing Scheme / Instructions for Preparation of Examination Paper

The paper of Physics for class-10 will consist of 60 marks. Timing of the paper will be two (02) hours (Objective 15 minutes and Subjective 1: 45 hours). The paper will be made as per following details:

Objective	**Q-1:** 12 Multiple Choice Questions (MCQs) will be developed from the entire content of the textbook. One MCQ will be asked from each chapter.	(1×12) = 12
Subjective Part-I	This section will contain three short answer questions. Each short answer question will be asked from the content of the textbook. The detail is as follows: **Q-2:** 5 short answer questions have to be answered out of 8. The detail is as follows: • Two short answer questions should be asked from each chapter; 10, 11, 12 and 13.	(2 × 5) = 10
	Q-3: 5 short answer questions have to be answered out of 8. The detail is as follows: • Two short answer questions should be asked from each chapter; 14, 15, 16 and 17.	(2 × 5) = 10
	Q-4: 5 short answer questions have to be answered out of 8. The detail is as follows: Two short answer questions should be asked from each chapter; 18, 19, 20 and 21.	(2 × 5) = 10
Part-II	This section will contain three detailed questions and students have to attempt any two (02) questions carrying 9 marks each. Each detailed question will be asked form the content of the textbook. The detail is as follows: **Q-5:** One detailed question will be asked from chapters; 10, 11, 12 and 13. **Q-6:** One detailed question will be asked from chapters; 14, 15, 16 and 17. **Q-7:** One detailed question will be asked from chapters; 18, 19, 20 and 21.	(2 × 9) = 18

Note:	In this section, each question will consist of two parts. Part (a) may be asked form any chapter. Part (b) will be asked from any different chapter (not from the same chapter as Part (a). Part (a) will carry 4 marks, while Part (b) will carry 5 marks.

MODEL PAPER

Objective Type

Max. Marks: 12 — **کل نمبر:12**

Time allowed: 15 Min. — **وقت:15منٹ**

نوٹ: ہر سوال کے چار ممکنہ جوابات A، B، C اور D دیے گئے ہیں۔ جو انتخاب آپ کے خیال میں درست ہے، اس سوال کے سامنے والے دائرے کو مار کر یا پین کی سیاہی سے بھریں۔ دو یا دو سے زیادہ دائروں کو کاٹنے یا بھرنے کی صورت میں جواب غلط تصور ہو گا۔

Note: Four possible answers A, B, C and D to each question are given. The choice which you think is correct, fill that circle in front of that question with marker or pen ink in the answer-book. Cutting or filling two or more circles will result in zero mark in that question

1. Select the correct answer. (1x12=12) — 1- درست جواب کا انتخاب کریں۔

(i) The latent heat of vaporization of water is: — (i) پانی کی ویپورائزیشن کی مخفی حرارت ہے:

(a) 2.26×10^6 J (b) 2.26×10^6 J kg^{-1} (c) 2.26×10^5 J (d) 2.26×10^5 J kg^{-1}

(ii) The natural phenomenon caused by convection currents is: — (ii) کنویکشن کرنٹس سے وجود میں آنے والا قدرتی مظہر ہے:

(a) Earthquakes زلزلے (b) Land and sea breezes زمینی اور سمندری ہوائیں

(c) Magnetic fields میگنیٹک فیلڈز (d) Solar eclipses سورج گرہن

(iii) Which of the following wave type requires a medium to travel? — (iii) ویو کی کون سی قسم کو اشاعت کے لیے کسی میڈیم کی ضرورت ہوتی ہے؟

(a) X-rays ایکس۔ریز (b) Light waves روشنی کی ویوز

(c) Radiowaves ریڈیوویوز (d) Sound waves ساؤنڈ ویوز

(iv) What is the approximate speed of sound in air? — (iv) ہوا میں ساؤنڈ کی سپیڈ قریباً کیا ہے؟

(a) 150 m s^{-1} (b) 330-350 m s^{-1} (c) 500 m s^{-1} (d) 1,000 m s^{-1}

(v) A ray of light travelling from water to air bends: — (v) روشنی کی رے پانی سے ہوا میں داخل ہوتے وقت پر مڑ جاتی ہے:

(a) Towards the normal نارمل کی طرف (b) Away from the normal نارمل سے پرے

(c) At 90° to the normal نارمل پر 90° پر (d) Parallel to the normal نارمل کے متوازی

(vi) What happens when two unlike charges are brought close to each other? — (vi) دو مختلف قسم کے چارجز ایک دوسرے کے قریب لانے پر کیا ہوتا ہے؟

(a) They attract وہ کشش کرتے ہیں (b) They repel وہ دفع کرتے ہیں

(c) They neutralize each other وہ ایک دوسرے کے اثر کو زائل کرتے ہیں (d) Nothing happens کچھ بھی نہیں ہوتا

(vii) The device used to measure electric current is: — (vii) الیکٹرک کرنٹ کی پیمائش کے لیے استعمال ہونے والا آلہ ہے:

(a) Voltmeter وولٹ میٹر (b) Ammeter ایمیٹر (c) Ohmmeter اوہم میٹر (d) Wattmeter واٹ میٹر

(viii) One tesla is equal to: — (viii) ایک ٹیسلا برابر ہے:

(a) 1T = 1 N A^{-1} m^{-1} (b) 1T = 1 N A m^{-1} (c) 1T = 1 A^{-1} m^{-1} (d) 1T = 1 N A^{-1} m

(ix) The sky appears blue during the day due to: — (ix) دن کے وقت آسمان نیلا نظر آتا ہے۔ اس کی وجہ ہے:

(a) Reflection of light روشنی کی رفلیکشن (b) Scattering of shorter wavelengths چھوٹی ویو لینگتھ کا بکھر جانا

(c) Absorption of blue light نیلی روشنی کا انجذاب (d) Refraction of light روشنی کی رفریکشن

(x) The output of NOR gate is: (x) نار گیٹ کی آؤٹ پٹ ہے:

(a) $X=\overline{A-B}$ (b) $X=A+B$ (c) $X=\overline{A}$ (d) $X=\overline{A+B}$

(xi) درج ذیل میں سے کون سا آئسوٹوپ طبی علاج اور بطور ریڈیو ایکٹیو ٹریسر کے استعمال ہوتا ہے؟

(xi) Which one of the following isotope is used in medical treatment and as a radioactive tracer?

(a) Strontium -90 90- اسٹرونشیئم (b) polonium -210 210- پولونیم

(c) Cobalt -60 60- کوبالٹ (d) Radon -222 222- ریڈون

(xii) درج ذیل میں سے کون سی گیس گلوبل وارمنگ میں سب سے زیادہ کردار ادا کرتی ہے؟

(xii) Which of the following gas contributes most to global warming?

(a) Oxygen آکسیجن (b) Carbon dioxide کاربن ڈائی آکسائڈ

(c) Nitrogen نائٹروجن (d) Argon آرگون

Subjective Type
(Part-I)

Max. Marks: 48 **کل نمبر:48**

Time allowed: 1.45 Hours **وقت:1:45 گھنٹے**

2. Write short answers to any five (05) questions: **2. کوئی سے پانچ(05)سوالات کے مختصر جوابات لکھیے۔** **(2x5=10)**

(i) What is latent heat of fusion? (i) پگھلاؤ کی مخفی حرارت سے کیا مراد ہے؟

(ii) اویپوریشن ہماری روزمرہ زندگی میں ٹھنڈک پیدا کرنے کے عمل میں کیسے کردار ادا کرتی ہے؟

(ii) How does evaporation contribute to cooling processes in everyday life?

(iii) How is heat transferred through radiation? (iii) ریڈی ایشن کے ذریعے حرارت کیسے منتقل ہوتی ہے؟

(iv) گرین ہاؤس ایفیکٹ زمین کے ٹمپریچر کو متوازن رکھنے میں کس طرح مدد کرتا ہے؟

(iv) How does the greenhouse effect help regulate Earth's temperature?

(v) What is meant by wavelength and frequency? (v) ویولینگتھ اور فریکوینسی سے کیا مراد ہے؟

(vi) What are electromagnetic waves? Give examples. (vi) الیکٹرومیگنیٹک ویوز سے کیا مُراد ہے؟اس کی مثالیں دیں۔

(vii) ایک شخص جب ایک بلند عمارت کے پاس اونچی آواز میں بولتا ہے تو اپنی ایکو کو سنتا ہے۔ ایکو واضح طور پر سننے کے لیے عمارت سے فاصلہ کم از کم 17 میٹر ہونا کیوں ضروری ہے؟

(vii) A person hears his echo when shouting near a tall building. Why must the building be at least 17 metres away for the echo to be heard clearly?

(viii) Define reflection and diffraction of sound waves. (viii) ساؤنڈ ویوز کی رفلیکشن اور ڈفریکشن کی تعریف کریں۔

(10)

3. Write short answers to any five (05) questions: **3. کوئی سے پانچ(05)سوالات کے مختصر جوابات لکھیے:** **(2x5=10)**

(i) How does the power of a lens relate to its focal length? (i) لینز کی پاور اور اس کی فوکل لینگتھ کا آپس میں کیا تعلق ہے؟

(ii) Define linear magnification and write its formula. (ii) لینیئر میگنی فیکشن کی تعریف کریں اور اس کا فارمولا لکھیں۔

(iii) ایک کنڈکٹر اور ایک انسولیٹر دونوں کو الیکٹرک فیلڈ میں رکھا گیا ہے۔ دونوں کا طرزِ عمل کیسے اور کیوں ایک دوسرے سے مختلف ہو گا؟

(iii) A conductor and an insulator are both placed in an electric field. How will their behaviour differ, and why?

(iv) Define electrostatic induction. (iv) الیکٹروسٹیٹک انڈکشن کی تعریف کریں۔

(v) State Ohm's law and define resistivity. (v) اوہم کا قانون بیان کریں اور رزسٹیویٹی کی تعریف کریں۔

(iv) ٹمپریچر کسی کنڈکٹر کی رزسٹنس پر کس طرح سے اثرانداز ہوتا ہے؟

(vi) How does temperature affect the resistance of a conductor?

(vii) What role does commutator play in a D.C motor? (vii) ڈی۔سی موٹر میں کموٹیٹر کیا کردار ادا کرتا ہے؟

(viii) State right–hand grip rule. (viii) دائیں ہاتھ گرپ کا اصول بیان کریں۔

(10)

4. کوئی سے پانچ (05) سوالات کے مختصر جوابات لکھیے:

4. Write short answers to any five (05) questions: (2x5=10)

(i) ٹرانسفارمرز میں لکڑی اور پلاسٹک کی بجائے آئرن کور کیوں استعمال کی جاتی ہے؟ مختصراً بیان کریں۔

(i) Why is an iron core used in transformers instead of wood or plastic? Explain briefly.

(ii) اگر ہم میگنیٹ کو کوائل کے نزدیک حرکت دینا بند کر دیں تو انڈیوسڈ کرنٹ پر کیا اثر پڑے گا؟

(ii) If we stop moving a magnet near a coil, what happens to the induced current?

(iii) What is the role of an AND gate in digital circuits? (iii) ڈیجیٹل سرکٹس میں اینڈ گیٹ کیا کردار ادا کرتا ہے؟

(iv) What is NAND gate? Write its truth table. (iv) نینڈ گیٹ کیا ہے؟ اس کا ٹرتھ ٹیبل لکھیں۔

(v) Define nuclear fission with an example. (v) نیوکلیئر فشن کی تعریف کریں اور اس کی ایک مثال دیں۔

(vi) فرض کریں کہ ایک ریڈیو ایکٹیو ایلیمنٹ دریافت ہوا ہے۔ سائنسدان ہزاروں سال ضائع کیے بغیر اس کی ہاف–لائف کیسے معلوم کر سکتے ہیں؟

(vi) Imagine a new radioactive element is discovered. How could scientists estimate its half-life without waiting thousands of years?

(vii) گلوبل وارمنگ کی کے باعث سمندر کی سطح میں اضافے کی بنیادی وجہ کیا ہے؟

(vii) What is the primary cause of rising sea levels due to global warming?

(viii) How are cyclones formed? Describe briefly. (viii) سائیکلون کیسے بنتے ہیں؟ مختصر بیان کریں۔

(Part-II)

Write detailed answers of any two (02) questions. کوئی سے دو (02) سوالات کے تفصیلاً جوابات لکھیے۔

(2x9=18)

(4)

5. (الف) انفراساؤنڈ اور الٹراساؤنڈ کیا ہیں، یہ مختلف مقاصد کے لیے کس طرح استعمال ہوتے ہیں؟

5. (a) What are infrasound and ultrasound, and how are they used in different applications? **(4)**

(5) (ب) ایک ویو 10 چکر مکمل کرنے میں 5 سیکنڈ لیتی ہے۔ اگر ویو کی ویولینگتھ 1.2 میٹر ہو، تو معلوم کریں: (الف) ویو کی فریکوینسی (ب) ویو کی سپیڈ

(b) A wave takes 5 seconds to complete 10 cycles. If the wavelength of the wave is 1.2 metres, calculate: (a) frequency of the wave (b) speed of the wave **(5)**

(4)

6. (الف) کسی میٹریل کی رزسٹیویٹی سے کیا مراد ہے؟ یہ میٹریل کی نوعیت پر کیسے منحصر ہوتی ہے، اور ٹمپریچر کا کسی میٹریل کی رزسٹیویٹی میں تبدیلی پر کیا اثر ہوتا ہے، خاص طور پر کنڈکٹرز اور سیمی کنڈکٹرز میں؟

6. (a) What is meant by resistivity of a material? How does it depend on the material, and what role does temperature play in changing the resistivity of conductors and semiconductors? **(4)**

(5)

(ب) روشنی کی ایک رے ہوا سے ایک نامعلوم مائع میں داخل ہوتی ہے۔ ہوا میں اینگل آف انسیڈینس 45° ہے، اور اس مائع میں اینگل آف رفریکشن 30° ہے۔ مائع کا رفریکٹیو انڈیکس معلوم کریں۔

(b) A ray of light travels from air into an unknown liquid. The angle of incidence in air is 45°, and the angle of refraction in the liquid is 30°. Calculate the refractive index of the liquid. **(5)**

(4)

7. (الف) لاجیک گیٹس کیا ہیں؟ "نینڈ گیٹ" اور "آر گیٹ" کے کام کرنے کے طریقہ کار کو ٹرتھ ٹیبل اور سرکٹ ڈایاگرام کی مدد سے بیان کریں۔

7. (a) What are logic gates? Describe the working of NAND and OR gates with the help of truth tables and circuit symbols. **(4)**

(5)

(ب) 420 دنوں کے بعد پولونیم کا آٹھواں حصہ ڈی کے ہوئے بغیر رہ جاتا ہے۔ پولونیم کی ہاف لائف معلوم کریں۔

(b) In 420 days, one-eighth of polonium (Po) remains un-decayed. Calculate the half-life of polonium. **(5)**