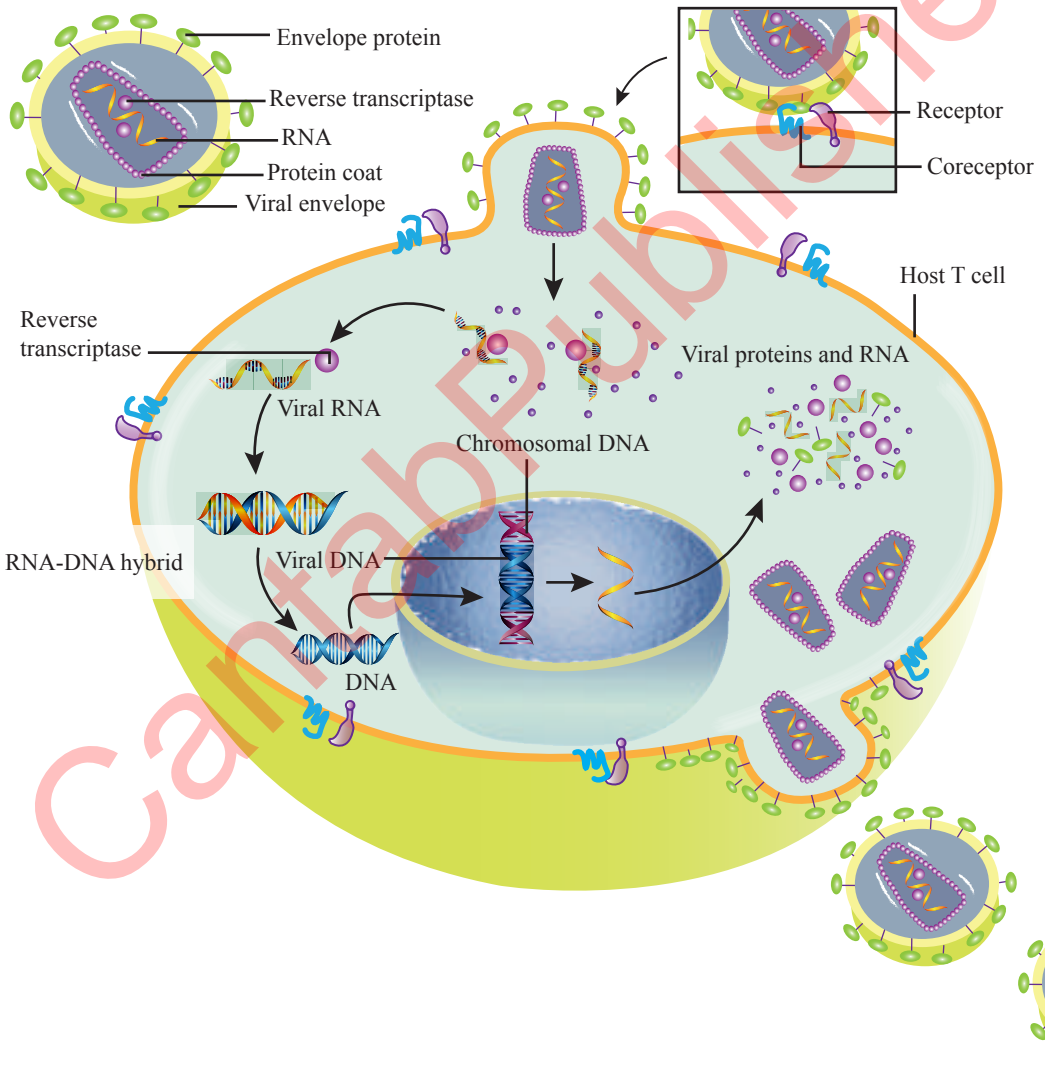
Biology

Grade 11



1. Virus binds receptors on cell membrane and enters cell. Enzymes remove viral protein coat.

2. Reverse transcriptase catalyzes formation of DNA complementary to viral RNA.

3. New DNA strand serves as a template for complementary DNA strand.

4. Double-stranded DNA is incorporated into host cell's genome.

5. Viral genes are transcribed to RNA. Some RNA will be packaged into new viruses.

6. Viral mRNA is translated into HIV proteins at ribosomes in cytoplasm

7. Protein coats surround viral RNA and enzymes. Envelope proteins migrate to cell membrane.

8. New viruses bud from host cell.

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A Textbook of A Biology
for Grade 11

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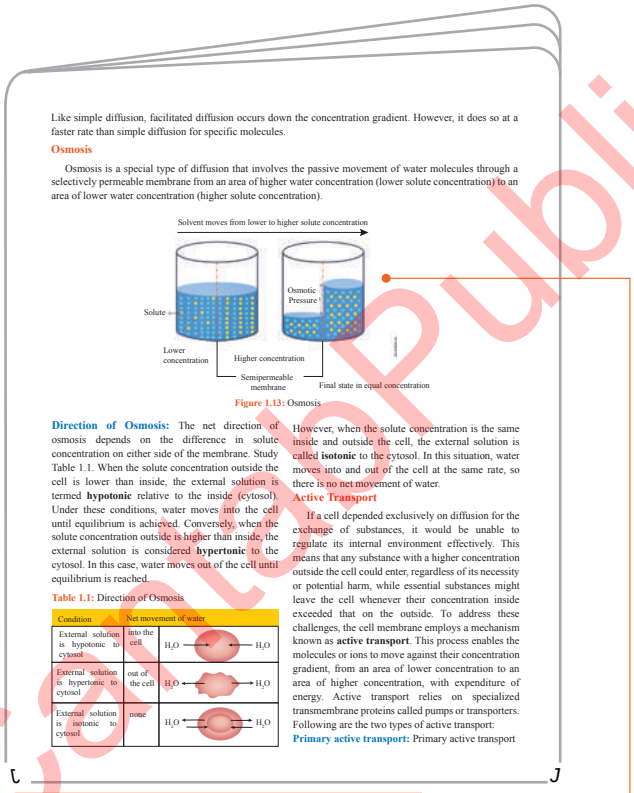
Preface

This Grade 11 Biology textbook, aligned with the 2023 curriculum, is designed to enhance students' learning experience. It features high-quality pictorial representations, real-life applications, and experimental skills. The book includes high-order thinking exercises, skill sheets for testing understanding, group activities, and recorded video lectures with animations and simulations. It is structured to aid teachers in creating assessment questions based on Bloom's Taxonomy. At the end of the book, a comprehensive glossary provides quick term references. This educational tool aims to enrich students' knowledge and appreciation of biology.

The QR codes in the biology textbook provide easy access to video lectures for gaining knowledge and skill sheets for practical application. They make learning more interactive, letting students watch lectures and practice skills right when they need them, making studying biology more engaging and effective.



Like simple diffusion, facilitated diffusion occurs down the concentration gradient. However, it does so at a faster rate than simple diffusion for specific molecules.

Osmosis

Osmosis is a special type of diffusion that involves the passive movement of water molecules through a selectively permeable membrane from an area of higher water concentration (lower solute concentration) to an area of lower water concentration (higher solute concentration).

Figure 1.13: Osmosis

Direction of Osmosis: The net direction of osmosis depends on the difference in solute concentration on either side of the membrane. Study Table 1.1. When the solute concentration outside the cell is lower than inside, the external solution is termed **hypotonic** relative to the inside (cytosol). Under these conditions, water moves into the cell until equilibrium is achieved. Conversely, when the solute concentration outside is higher than inside, the external solution is considered **hypertonic** to the cytosol. In this case, water moves out of the cell until equilibrium is reached.

Table 1.1: Direction of Osmosis

Condition	Net movement of water	
External solution is hypotonic to cytosol	into the cell	H_2O → ← H_2O
External solution is hypertonic to cytosol	out of the cell	H_2O ← → H_2O
External solution is isotonic to cytosol	none	H_2O ⇄ ⇄ H_2O

However, when the solute concentration is the same inside and outside the cell, the external solution is called **isotonic** to the cytosol. In this situation, water moves into and out of the cell at the same rate, so there is no net movement of water.

Active Transport

If a cell depended exclusively on diffusion for the exchange of substances, it would be unable to regulate its internal environment effectively. This means that any substance with a higher concentration outside the cell could enter, regardless of its necessity or potential harm, while essential substances might leave the cell whenever their concentration inside exceeded that on the outside. To address these challenges, the cell membrane employs a mechanism known as **active transport**. This process enables the molecules or ions to move against their concentration gradient, from an area of lower concentration to an area of higher concentration, with expenditure of energy. Active transport relies on specialized transmembrane proteins called pumps or transporters. Following are the two types of active transport:

Primary active transport: Primary active transport

Diagrams in a biology textbook create strong mental images that stick with students, making it easier to remember and understand complex information quickly. These visuals serve as powerful memory aids, reinforcing concepts in a way that stays in students' mind for a long time.

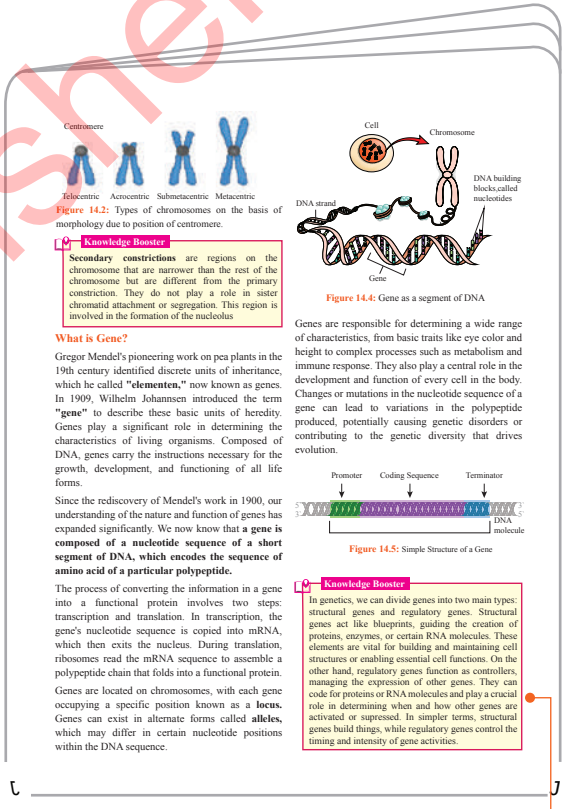


Figure 14.2: Types of chromosomes on the basis of morphology due to position of centromere.

Knowledge Booster

Secondary constrictions are regions on the chromosome that are narrower than the rest of the chromosome but are different from the primary constriction. They do not play a role in sister chromatid attachment or segregation. This region is involved in the formation of the nucleolus

What is Gene?

Gregor Mendel's pioneering work on pea plants in the 19th century identified discrete units of inheritance, which he called **"elementen,"** now known as genes. In 1909, Wilhelm Johannsen introduced the term **"gene"** to describe these basic units of heredity. Genes play a significant role in determining the characteristics of living organisms. Composed of DNA, genes carry the instructions necessary for the growth, development, and functioning of all life forms.

Since the rediscovery of Mendel's work in 1900, our understanding of the nature and function of genes has expanded significantly. We now know that **a gene is composed of a nucleotide sequence of a short segment of DNA, which encodes the sequence of amino acid of a particular polypeptide.**

The process of converting the information in a gene into a functional protein involves two steps: transcription and translation. In transcription, the gene's nucleotide sequence is copied into mRNA, which then exits the nucleus. During translation, ribosomes read the mRNA sequence to assemble a polypeptide chain that folds into a functional protein.

Genes are located on chromosomes, with each gene occupying a specific position known as a **locus.** Genes can exist in alternate forms called **alleles,** which may differ in certain nucleotide positions within the DNA sequence.

Figure 14.4: Gene as a segment of DNA

Genes are responsible for determining a wide range of characteristics, from basic traits like eye color and height to complex processes such as metabolism and immune response. They also play a central role in the development and function of every cell in the body. Changes or mutations in the nucleotide sequence of a gene can lead to variations in the polypeptide produced, potentially causing genetic disorders or contributing to the genetic diversity that drives evolution.

Figure 14.5: Simple Structure of a Gene

Knowledge Booster

In genetics, we can divide genes into two main types: structural genes and regulatory genes. Structural genes act like blueprints, guiding the creation of proteins, enzymes, or certain RNA molecules. These elements are vital for building and maintaining cell structures or enabling essential cell functions. On the other hand, regulatory genes function as controllers, managing the expression of other genes. They can code for proteins or RNA molecules and play a crucial role in determining when and how other genes are activated or supressed. In simpler terms, structural genes build things, while regulatory genes control the timing and intensity of gene activities.

Knowledge booster in a Grade 11 biology book makes the topic more interested. It expands the students' horizon beyond textbook.

SLO based Model Video lecture

Salient Features

Comprehensive Learning
Engage students with videos, simulations, and practical worksheets.

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Well-organized with clear objectives, PPTs, and a question bank.

Engaging Multimedia
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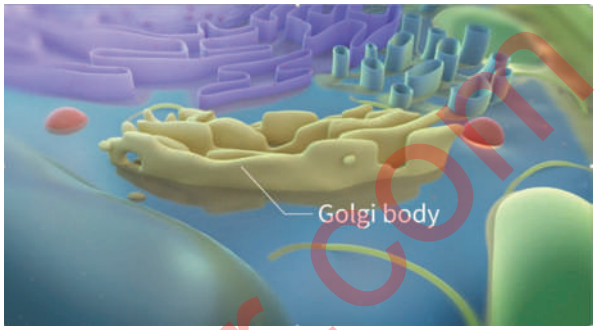
Animation



SLO No: B - 11 - O - 08
Illustrate with diagrams the great diversity of shapes and sizes found in bacteria.

KNOWLEDGE

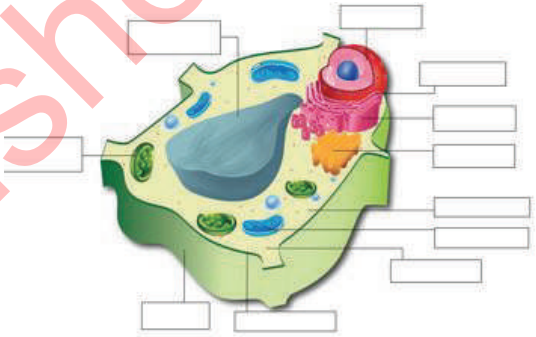


Figure 2. Plant Cell

Skills Sheet

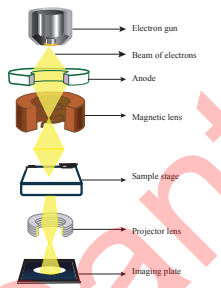


Figure 1.4: Working principle of transmission electron microscopy.

Skill: 1.2
Objective:
Analyze and differentiate between light and electron microscopes, focusing on their capabilities in resolution and magnification, as well as their applicability to live versus dead samples.

Test Yourself
Short answer-based questions
1. How does the resolution limit of a light microscope affect its ability to observe cellular structures compared to an electron microscope?
2. Differentiate between magnification and resolution.
3. What is the general working principle of an electron microscope?

Long answer-based questions:
1. Give a comparison of a light microscope and an electron microscope.

1.3 Knowledge

Ultrastructure of Animal and Plant Cells

We have studied the ultrastructure of animal and plant cells in grade 9 and will discuss it more in detail in this chapter. There are cellular structures that are common in both animal and plant cells namely; plasma membrane, nucleus, cytoplasm, mitochondria, endoplasmic reticulum, Golgi apparatus and ribosomes, etc. However, both cells have unique organelles that are exceptional to one cell, for example, lysosomes and centrioles to animal cells and cell wall, chloroplast, large central vacuole and chloroplast to plant cells.

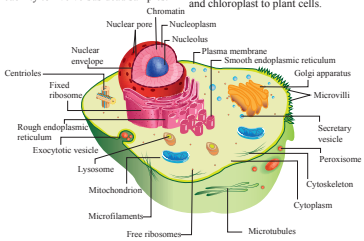


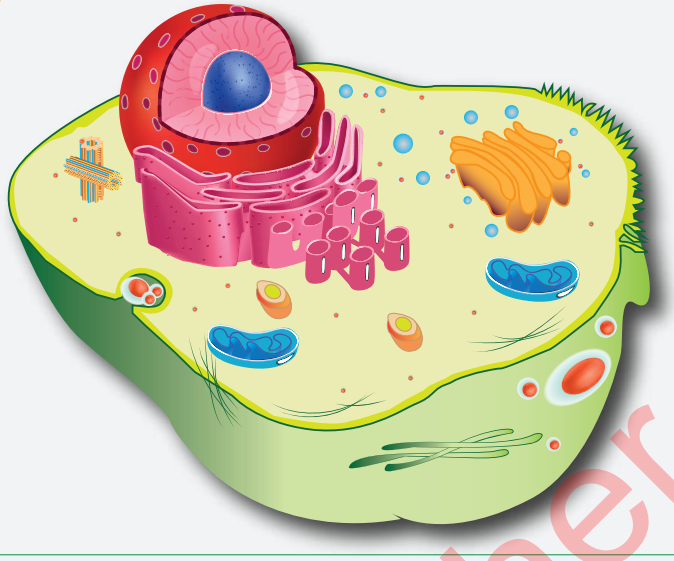
Figure 1.5: Ultrastructure of an animal cell.

CONTENTS

CHAPTER

1

The Cell



1.1 Knowledge

Cell: Basic Structural and Functional Unit of Life

Student Learning Outcomes

SLO:B-11-D-01: *Describe that cells are the basic unit of life with respect to 7 properties of Life. (Movement, Respiration, Homeostasis, Growth, Reproduction, Excretion, Nutrition)*

SLO:B-11-D-12: *State cell theory (including how to validate it and exceptions to it.)*

1.2 Knowledge

Microscopy

Student Learning Outcomes

SLO:B-11-D-13: *Compare and contrast the workings of a light microscope and electron microscope with focus on resolution and magnification and live vs dead samples.*

1.3 Knowledge

Ultrastructure of Animal and Plant Cells

Student Learning Outcomes

SLO:B-11-D-02: *Identify the ultrastructure of animal and plant cells.*

1.4 Knowledge

Structure and Functions of sub-cellular Organelles

Student Learning Outcomes

SLO:B-11-D-03: *Describe the structure and functions of sub-cellular organelles. (mitochondria, nucleus, cell , membrane chloroplast, lysosomes, cell wall, centrioles, Golgi apparatus, smooth endoplasmic reticulum, rough endoplasmic reticulum, vesicles, peroxisome, vacuoles, ribosomes,)*

SLO:B-11-D-9: *Explain the structure of the cell membrane and the techniques that can be used to study it.*

SLO:B-11-D-14: *Write the chemical structure of a single phospholipid (Glycerol as a three-carbon molecule, phosphate group, one unsaturated fatty acid tail and one saturated fatty acid tail).*

SLO:B-11-D-10: *Explain the 4 membrane transport mechanisms with diagrams: (simple diffusion, Facilitated diffusion, Osmosis, Active transport).*

SLO:B-11-D-16: *Compare and contrast simple and facilitated diffusion.*

SLO:B-11-D-15:*Descibe endocytosis and exocytosis with diagrams.*

1.5 Knowledge

Comparison of Prokaryotic and Eukaryotic cell

Student Learning Outcomes

SLO:B-11-D-11: *Differentiate between prokaryotic and eukaryotic cells with diagrams.*

1.6 Knowledge

Cell Signaling

Student Learning Outcomes

SLO:B-11-D-04: *Define cell signalling.*

SLO:B-11-D-05: *Discuss the pathway of a signal from outside the cell to the inside. (Protein signal and steroid signal).*

1.7 Knowledge

Stem Cells

Student Learning Outcomes

SLO:B-11-D-06: *Define Stem cells and advantages of using stem cells.*
SLO:B-11-D-07: *Categorize different types of stem cells.*
SLO:B-11-D-08: *Evaluate the advantages and disadvantages of using induced Pluripotent Stem Cells.*

1.8 Knowledge

Mitosis and Meiosis

Student Learning Outcomes

SLO:B-11-D-17: *Explain the steps of mitosis and meiosis with diagrams.*

"Let's embark on an exciting journey through the Student Learning Outcomes (SLOs) outlined in the curriculum. These SLOs serve as your roadmap to mastering essential knowledge and honing core skills. To make your learning experience seamless and interactive, you'll find QR codes embedded within the main text. These codes provide instant access to test skills, skill sheets, and worksheets, all thoughtfully designed to help you apply what you've learned effectively."

Introduction

Cells are the building blocks of all life, the smallest units that perform essential tasks like energy production, growth, reproduction, and maintaining balance within organisms. Understanding cells is key to grasping how life works, from simple bacteria to complex humans. In this chapter, we will explore the basic principles of cell theory, examine the different parts of cells, and learn about the processes that keep them functioning. We will also look at the microscopes used to study cells and the potential of stem cells in medicine. This chapter will help you understand why cells are essential in biology and how they support all life forms.

1.1 Knowledge

Cell: Basic Structural and Functional Unit of Life

Cells are the basic building blocks of life, representing essential life characteristics in their microscopic structure. As the smallest units capable of life, they exhibit seven key properties: movement, respiration, homeostasis, growth, reproduction, excretion, and nutrition. These traits distinguish living organisms from non-living matter, offering insights into life's diversity at the cellular level.

Properties of Life

Understanding how each of these properties is manifested at the cellular level provides insights into the complexity and functionality of life.

Movement: Cells exhibit internal movements, such as the movement of organelles and transport of substances across the cell membrane. Some specialized cells like white blood cells can also move through their environments using mechanisms like amoeboid movement.

Respiration: Cellular respiration involves converting glucose into ATP. This process is vital for maintaining the cell's activities and survival.

Homeostasis: Cells maintain stable internal conditions through mechanisms like selective permeability of membranes and regulatory pathways, despite external environmental changes.

Growth: Cellular growth includes an increase in cell size and the accumulation of mass, often as a precursor to cell division.

Reproduction: Cells reproduce by dividing, either through mitosis for somatic cells, resulting in twoidentical daughter cells, or meiosis for gametes, contributing to genetic diversity.

Excretion: Cells eliminate waste from cellular activities, including metabolic byproducts like carbon dioxide and urea, to maintain a healthy cellular environment.

Nutrition: Cells take in nutrients like oxygen, water and organic molecules from their environment for cellular functions. Autotrophic cells can produce nutrients via photosynthesis, while heterotrophic cells absorb and digest external nutrients. Each of these properties contributes to the overall functionality of cells and is essential for the sustenance and continuation of life.

Knowledge Booster

Bacteria serve as living examples of the cell theory. As single-celled organisms, they embody the core principles of the theory; "showcasing the basic unit of life", "independent functionality", and "one cell giving rise to the next cell", thus underscoring their significance in the broader study of biology.

Cell Theory

The cell theory, a fundamental concept in biology, emerged from the advancements in microscopy in the 17th century. Pioneers like **Robert Hooke**, who first used the term "cell" in 1665 after observing cork under a microscope, and Antonie van Leeuwenhoek, who described live cells in pond water, laid the groundwork for this theory. In the 19th century, **Matthias Schleiden** and **Theodor Schwann** significantly advanced the theory by proposing that all plants and animals are composed of cells, leading to the establishment of the cell theory's three main principles, given below.

Principles of the Cell Theory: The cell theory traditionally includes three basic principles:

1. **All living organisms are composed of cells.** They are the basic structural and functional units of life.
2. **The cell is the smallest unit of life.** It is the smallest structure capable of performing all the functions necessary for life.
3. **All cells arise from pre-existing cells**. This principle opposes the earlier notion of spontaneous generation and emphasizes the continuity of life.

Validation of Cell Theory

1. The validation of cell theory historically involved several key experiments and observations:
2. Experiments that isolate single cells in culture demonstrate that individual cells can survive and function independently, maintaining homeostasis and responding to their environment.
3. Louis Pasteur's experiments that disproved spontaneous generation supported the idea that all cells come from existing cells, not from non-living matter.
4. Modern techniques in imaging and molecular biology have provided detailed insights into DNA replication, mitosis and cytokinesis, conclusively showing that cells originate solely through the division of pre-existing cells.

Exceptions to the Cell Theory

- While the cell theory provides a foundation for understanding biological structure and function, there are exceptions:
- Often debated whether they are "alive", viruses are not made up of cells but are genetic material (DNA or RNA) enclosed in a protein coat. They require a host cell to replicate, challenging the definition of cells as the smallest unit of life.
- Like viruses, prions and viroids are both exceptions to cell theory, lacking cellular structure. Both challenge traditional views of life as organized in cellular structures.
- The lack of a nucleus in red blood cells (RBCs) and sieve tube elements, which inhibit their ability to reproduce, stands as a notable exception to the cell theory.
- Mitochondria and chloroplasts have their own DNA and can reproduce independently within a cell. They are often cited as exceptions because they challenge the idea that the cell is always the smallest unit of life that can replicate independently.
- The mycelium of some fungi consists of a network of hyphae that form a multicellular structure without fully divided cellular sections, creating large, multinucleated cells that can span significant distances, challenging the notion that all organisms are made up of discrete, individual cells.

Skill:1.1

Objective:

- Evaluate and describe how cells, as the basic units of life, exhibit the seven essential properties of life: movement, respiration, homeostasis, growth, reproduction, excretion, and nutrition.
- Articulate the principles of cell theory, describe experimental validations, and identify exceptions to the theory.

Test Yourself

Short answer-based questions

1. State cell theory.
2. How do viruses challenge the principles outlined in the cell theory?
3. How do modern techniques contribute to the validation of cell theory?

Long answer-based questions:

1. What are the exceptions to the cell theory?
2. Explain the properties of life.

1.2 Knowledge

Microscopy

Microscopy is the science and technology of using microscopes to observe objects that cannot be seen with the naked eye. It is crucial in various scientific fields, including biology, medicine and nanotechnology. There are many microscopes, each with a different working principle.However, magnification and resolution are fundamental concepts considered in designing and operating all types of microscopes. **Magnification** refers to the degree to which an object is enlarged when viewed through a microscope. It indicates how many times larger the object appears compared to its actual size.

Resolution is the ability of a microscope to distinguish between two closely spaced objects. It is determined by the wavelength of the light or electrons used in microscopy. Higher resolution allows for more precise and more detailed images.

In this topic, we will discuss only light microscope and electron microscope along with their working principle.

Light Microscope

A light microscope is termed a compound microscope because it utilizes a system of multiple lenses, specifically objective lenses and an ocular lens, to magnify objects (see Figure 1.1). This configuration allows for significant magnification and detailed observation. This multi-lens setup distinguishes it from simpler, single-lens microscopes.

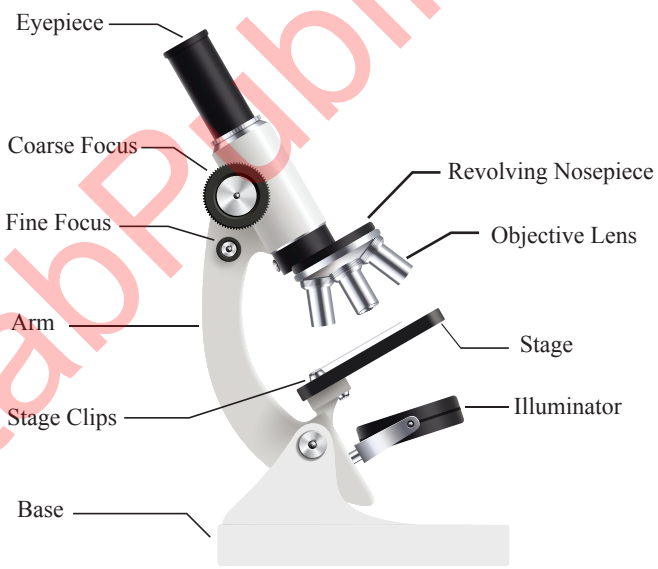


Figure 1.1: Parts of a light microscope

Working principle: A light microscope uses visible light to illuminate a specimen, which then passes through an **objective lens** present in the revolving nosepiece close to the specimen for initial magnification. This magnified image is further enlarged by an **eyepiece** or **ocular lens** present in the eyepiece (see Figure 1.2). By adjusting the objective lens's distance from the specimen, the image can be focused. The light, either transmitted or absorbed by the specimen, creates a contrasted image that allows for detailed observation of tiny structures.

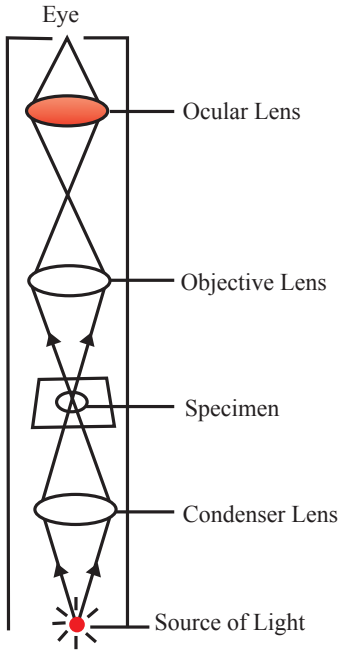


Figure 1.2: Principle of compound light microscope.

Magnification and Resolution: To calculate the total magnification, simply multiply the magnification power (4x, 10x, 40x and 100x) of the objective lens by the magnification power (usually 10x) of the ocular lens. For example, If you are using an objective lens with a magnification of 40x and an ocular lens with a magnification of 10x, the total magnification would be: 40*x* X 10x=400x
This means the image is magnified 400 times larger than the actual size of the object. Though it has magnification up to 1500x, it is less capable of distinguishing very fine details. Limited by visible light's wavelength, its resolution is about 200 nanometers. Light microscopes can be used to observe both live and dead samples. Ideal for live samples, it observes living cells and tissues in their natural state with minimal preparation, often using stains for enhanced contrast.

Knowledge Booster

The resolution of the human naked eye, in terms of distinguishing between two points or objects, is typically about 0.1 mm at a distance of about 25 cm from the eye.

Electron Microscope

Invented in the 1930s, electron microscopes use electron beams instead of light to illuminate samples. This technology provides a much deeper look into the fine details and surface features of cells, including some of the larger molecules inside them (see Figure 1.3).

Figure 1.3: Electron microscope

Working principle: An electron microscope operates by using a beam of electrons emitted from a heated filament in an **electron gun.** These electrons are accelerated and focused onto the specimen with electromagnetic lenses (see Figure 1.4). In a Transmission Electron Microscope (TEM), electrons passing through the very thin section of the specimen create an image on a photographic plate based on how they are absorbed and scattered. In a Scanning Electron Microscope (SEM), the image is formed from electrons scattered back from the specimen surface, producing a detailed 3D topographic image. The entire system is maintained under vacuum to prevent electron scattering by air, ensuring high-resolution imaging.

Magnification and Resolution: Electron microscopes have a much higher resolution, typically around 0.1 nm for transmission electron microscopes (TEM), allowing for the visualization of structures at the molecular level. It can magnify up to 50 million times, offering detailed views of a specimen's ultrastructure. Only dead, fixed samples can be observed because the preparation process and the vacuum required for operation make it impossible to view live specimens. Samples must also be thinly sliced and sometimes stained with heavy metals for enhanced contrast.

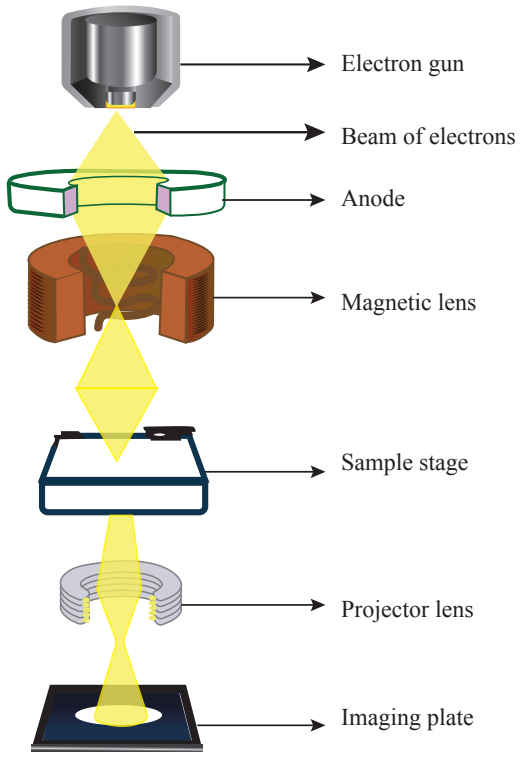


Figure 1.4: Working principle of transmission electron microscopy.

Skill:1.2

Objective:

- Analyze and differentiate between light and electron microscopes, focusing on their capabilities in resolution and magnification, as well as their applicability to live versus dead samples.

Test Yourself

Short answer-based questions

1. How does the resolution limit of a light microscope affect its ability to observe cellular structures compared to an electron microscope?
2. Differentiate between magnification and resolution.
3. What is the general working principle of an electron microscope?

Long answer-based questions:

1. Give a comparison of a light microscope and an electron microscope.

1.3 Knowledge

Ultrastructure of Animal and Plant Cells

We have studied the ultrastructure of animal and plant cells in grade 9 and will discuss it more in detail in this chapter. There are cellular structures that are common in both animal and plant cells namely; plasma membrane, nucleus, cytoplasm, mitochondria, endoplasmic reticulum, Golgi apparatus and ribosomes, etc. However, both cells have unique organelles that are exceptional to one cell, for example, lysosomes and centrioles to animal cells and cell wall, chloroplast, large central vacuole and chloroplast to plant cells (see Figure 1.5 & 1.6).

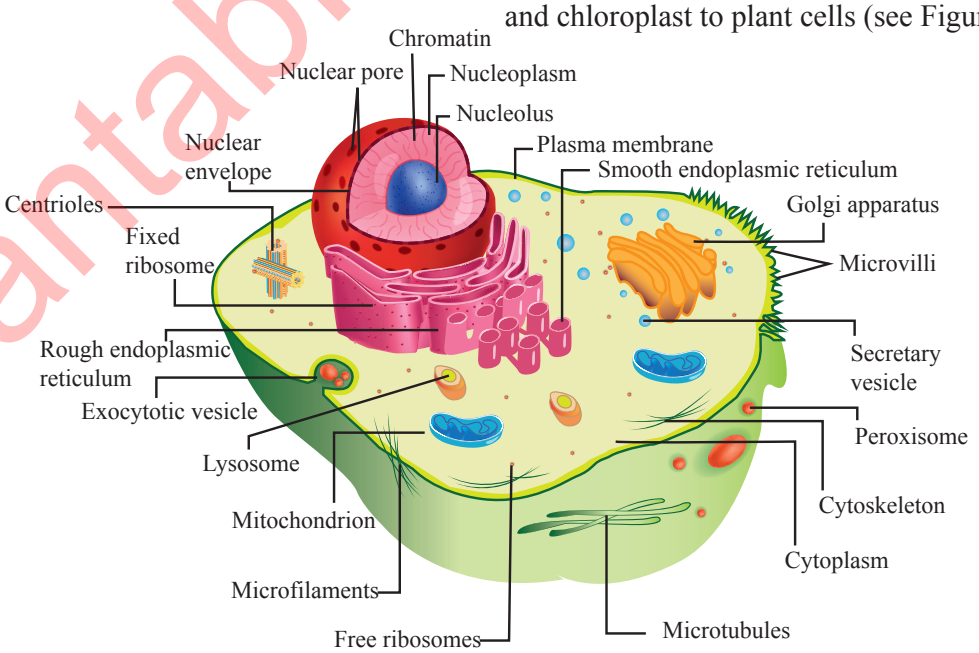


Figure 1.5: Ultrastructure of an animal cell.

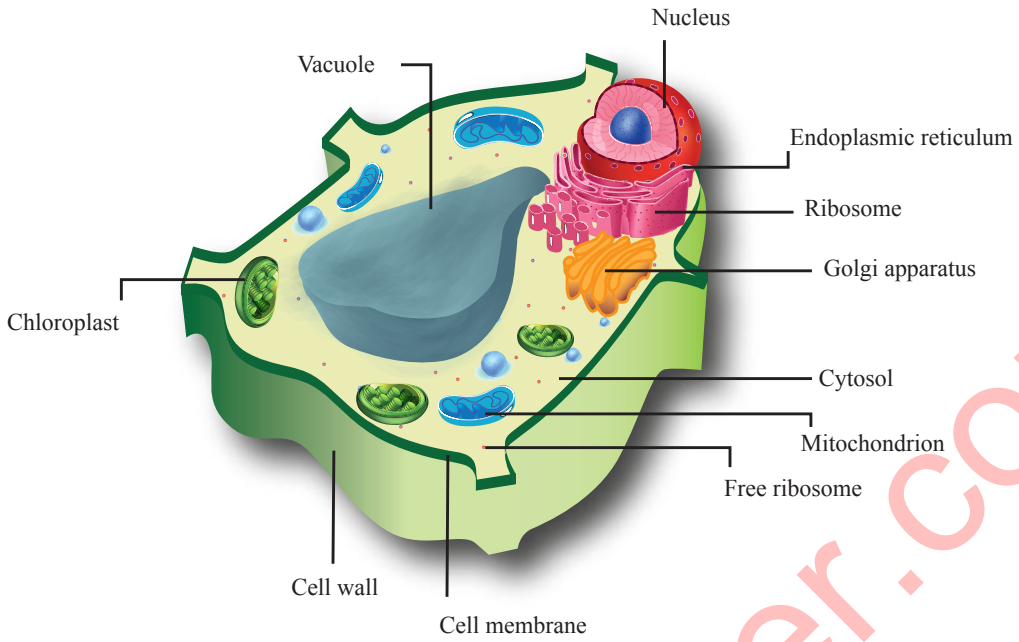


Figure 1.6: Detailed structure of a plant cell.

These structures are integral to the functions of both types of cells and illustrate the unique characteristics and adaptations of animal and plant cells to their respective environments and roles within organisms.

Skill:1.3

Objective:

- Identify the ultrastructural components of animal and plant cells, highlighting the similarities and differences in their organelles and cell structures.

Test Yourself

Short answer-based questions

1. Compare and contrast the animal and plant cell.

1.4 Knowledge

Structure and Functions of sub-cellular Organelles

A typical eukaryotic cell consists of the following components:

- Cell wall and plasma membrane
- Nucleus
- Cytoplasm with its embedded organelles.

Cell Wall

The cell wall is an extracellular structure located outside the plasma membrane in plant cells. This is one of the features that distinguishes plant cells from animal cells. The cell wall provides support, shape, and protection against invading bacteria and fungi. It also helps maintain **turgor pressure**, which is essential for keeping the plant upright and rigid. Plant cell walls are composed of cellulose fibers embedded in a network of carbohydrates. The structural arrangement of cellulose and other polysaccharides results in a porous matrix that is rigid enough to provide structural support but porous enough to allow the movement of molecules through it. The plant cell wall has three main layers as shown in Figure 1.7. The initial cell wall formed by all plant cells is the **primary cell wall**, which is relatively thin and flexible. As the cell grows, the primary cell wall increases in size. It is composed of cellulose microfibrils embedded in a matrix of hemicellulose, pectin, and proteins. The **secondary cell wall** is much thicker and more rigid than the primary wall and is deposited inside the primary wall once the cell has stopped expanding. It is rich in cellulose, hemicellulose, inorganic salts, waxes and often lignin, which provides additional strength and resistance. Not all plant cells contain a secondary cell

wall. The formation of the secondary cell wall occurs in specific cell types, such as xylem cells and sclerenchyma cells. These cells are typically involved in providing structural support and rigidity to the plant.

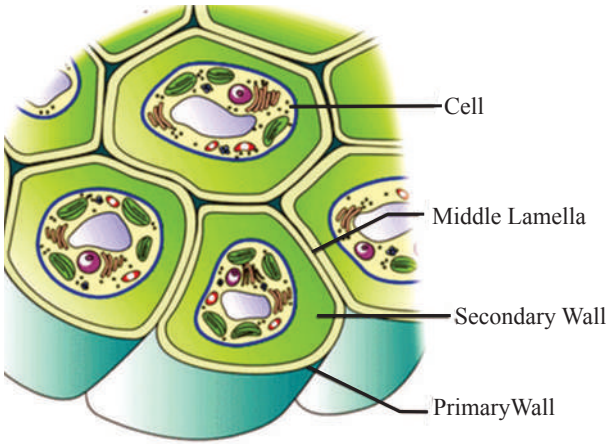


Figure 1.7: Structure of plant cell wall

A layer of gel-like polysaccharides that binds the primary cell walls of adjacent cells together is known as the **middle lamella**. It is primarily composed of pectins, which are complex polysaccharides rich in **galacturonic acid.** Pectins are highly hydrophilic and gelatinous, allowing them to fill spaces between cells effectively. Additionally, calcium and magnesium ions cross-link with the pectin molecules, increasing the rigidity and stability of the middle lamella.

Both primary and secondary cell walls have minute channels or perforations called **plasmodesmata**. These allow ions and small molecules to move directly from one cell to another through the connecting cytosol, bypassing the plasma membranes or cell walls.

Cell walls also surround the cells of fungi, some protists, and prokaryotes. Bacterial cell walls are composed of peptidoglycan, whereas those of fungi contain chitin. As mentioned earlier, animal cells do not form rigid, external cell walls. However, most animal cells secrete extracellular material and have other structures at the cell surface that play vital roles in the support and protection of cells.

Knowledge Booster

The cell wall in plants is the first line of defense against pathogens. It can physically block pathogen entry and is chemically active, capable of initiating immune responses upon detecting pathogen.

Cell Membrane

The cell surface membrane or plasma membrane is a common feature of both eukaryotic and prokaryotic cells, characterized by its extreme thinness, 5-10nm thick, yet possessing enough strength to maintain the integrity of the cell. This membrane not only holds the cell's contents together but also forms the barrier through which all substances entering or leaving the cell must pass.

Structure of cell membrane: The Fluid Mosaic Model, proposed by S.J. Singer and Garth Nicolson in 1972, revolutionized our understanding of the cell membrane's structure. This model highlights the fluid nature of the lipid bilayer and describes the mosaic-like arrangement of proteins that are embedded within it. The cell membrane contains collection of various components, including lipids, proteins, and carbohydrates.

The foundation of the cell membrane is the **phospholipid bilayer,** made up of two layers of phospholipids. Each phospholipid molecule has a hydrophilic head (water-attracting) and two hydrophobic tails (water-repelling). Proteins embedded within this lipid bilayer include **integral proteins,** often spanning its entire width, and **peripheral proteins**, which attach to its surfaces. **Cholesterol** is also interspersed within the lipid bilayer.

Carbohydrates, in the form of short-chain polysaccharides, are present on the cell surface membrane. Some are attached to proteins forming **glycoproteins** and others to lipids forming **glycolipids**, located only on the outer surface of the membrane (see Figure 1.8).

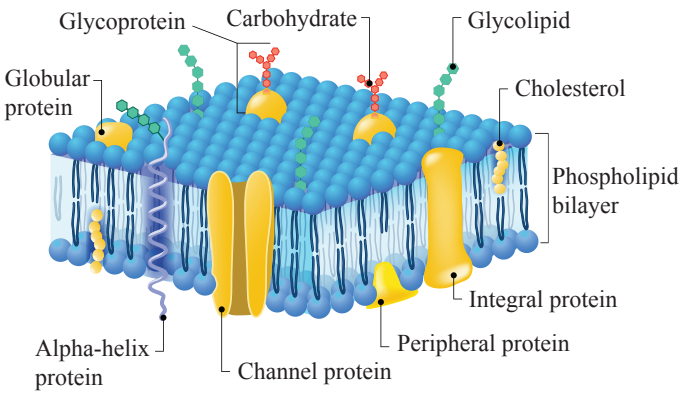


Figure 1.8: Detailed structure of the plasma membrane

Role of different components of cell membrane: The phospholipid bilayer acts as a selective barrier to most water-soluble substances. The non-polar nature of the phospholipid tails forms a hydrophobic core that prevents the passage of polar molecules such as sugars, amino acids, and proteins. This barrier function helps to maintain cellular integrity by preventing the leakage of these water-soluble molecules out of the cell and barring entry to unwanted substances.

Cholesterol plays a crucial role in maintaining the membrane's fluidity and stability. It increases fluidity at low temperatures, preventing rigidity by avoiding close packing of phospholipid tails. This adaptation allows cells to survive colder temperatures. Similarly, cholesterol helps stabilize the membrane at higher temperatures, preventing it from becoming too fluid and ensuring mechanical stability. Without it, membranes can easily break, causing cells to burst.

Proteins in the membrane serve various functions: those which are involved in the transport of substances are called **channel proteins** and those which combine with substances to move them across the membranes are called **carrier proteins**. Others act as **enzymes**, catalyzing reactions on the membrane's surface. Some proteins participate in signal transduction by acting as **receptors** that can receive and respond to various external signals, such as hormones and neurotransmitters (see Figure 1.9).

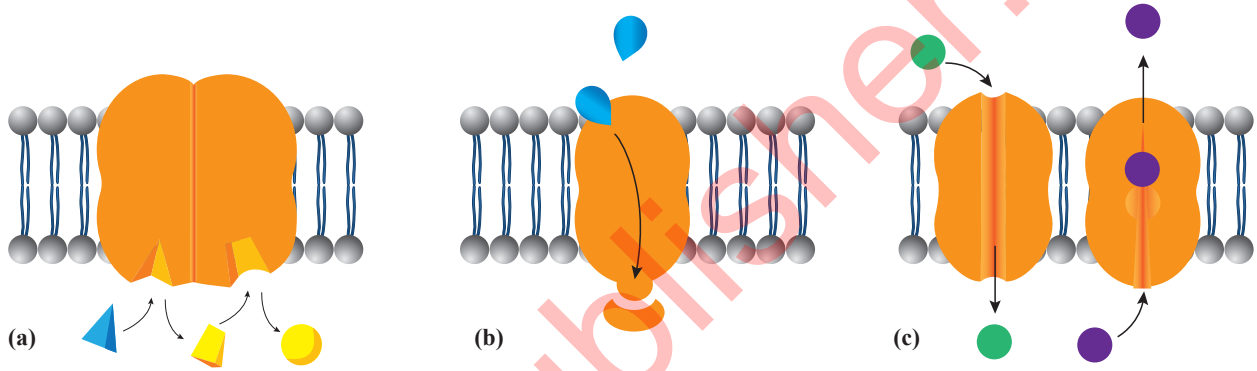


Figure 1.9: (a) Enzymatic activity (b) Protein as a receptor in signal transduction (c) Protein as a channel or carrier in transport of molecules.

Moreover, glycolipids and glycoproteins serve as **cell markers**, facilitating cell to cell recognition. Additionally, some glycoproteins are involved in cell adhesion, enabling cells to interact and bond with each other, which is fundamental for the formation of tissues and organs.

Knowledge Booster

ABO blood group antigens are glycoproteins and glycolipids with variations in their carbohydrate components, serving as cell markers for cell identification.

The cell membrane's structure and functions are integral to the survival and proper functioning of cells in organisms, serving as a dynamic interface that allows cells to interact with their surroundings while maintaining internal stability.

Phospholipids: Phospholipids in cell membrane are derivatives of **phosphatidic acid,** containing a backbone of a **glycerol** molecule (three carbon compounds with an -OH group on each carbon). Two fatty acid chains are attached to the first and second carbons of the glycerol molecule (see Figure 1.10). The chain attached to the first carbon is saturated, and the one attached to the second carbon is unsaturated. A phosphate group, along with other organic compounds (see Chapter 2), forms the polar head of the phospholipid attached to the third carbon of glycerol.

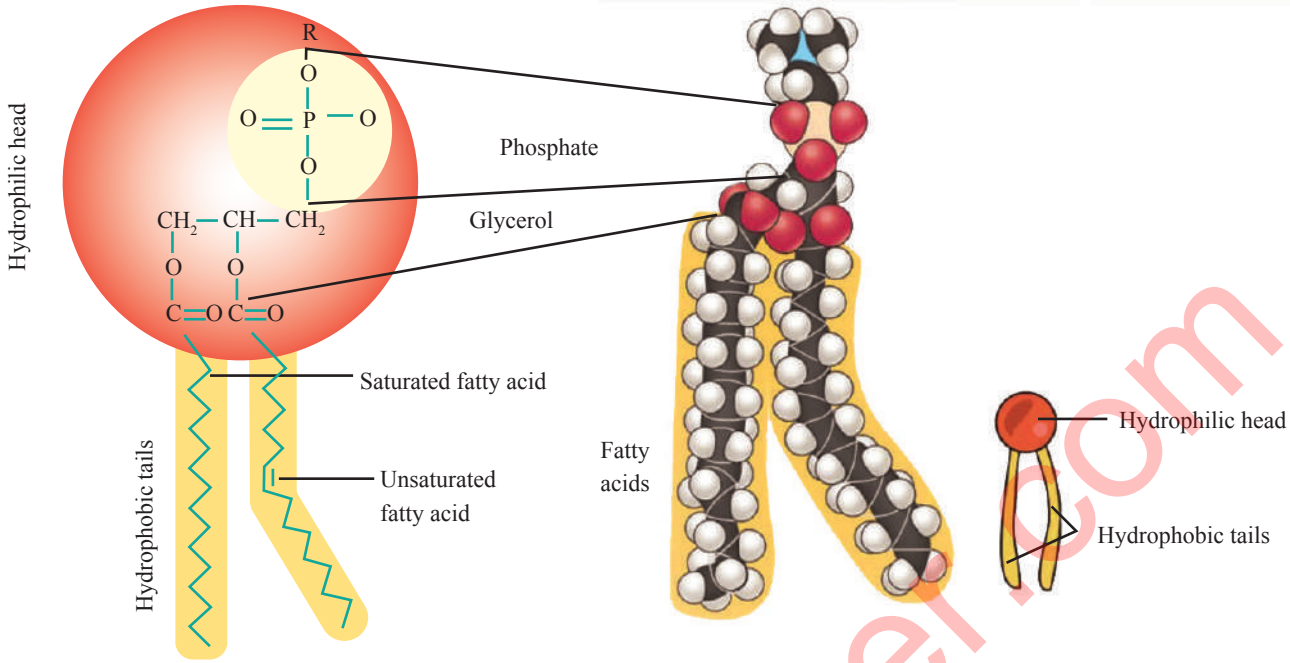


Figure 1.10: Chemical structure of a phospholipids molecule

Techniques Used to Study the Cell Membrane: Various techniques are in use to study the structure and function of the cell membrane.

- **Electron Microscopy:** Transmission and scanning electron microscopy, provides detailed images of cell membranes and their fine structure at high magnifications.
- **Fluorescence Microscopy:** Fluorescent dyes or proteins are used to label specific components of the cell membrane, to visualize and track membrane proteins or lipids in living cells.
- **X-Rays Crystallography:** This technique is used to determine the 3D structures of membrane proteins, providing detailed information about their shapes and interactions within the lipid bilayer.
- **Freeze Fracture Electron Microscopy:** Freezing and fracturing of cells to reveal the internal structures of the membrane, including the arrangement of proteins and lipids.
- **Cell Fractionation:** Fractionation techniques isolate and purify cellular components, including membranes, for biochemical analysis, allowing researchers to study the composition and functions of membrane proteins and lipids

Membrane Transport mechanisms

Cells require a constant supply of nutrients from their environment to carry out their metabolic functions. Nutrients such as glucose and amino acids must be transported into the cell to fuel these metabolic processes. Conversely, as cells metabolize these nutrients, they generate waste products like carbon dioxide and ammonia, which, if accumulated, could be toxic. However, the cell membrane does not let just anything pass through because it is selectively permeable. To manage this, cells use various transport mechanisms to intake these substances into the cell and expel the wastes, maintaining a safe internal environment. The following are the mechanisms responsible for the transport of substances through the cell membrane:

Simple Diffusion: Simple diffusion is a process by which molecules move from an area of higher concentration to an area of lower concentration across a cell membrane without the need for energy (passive transport). This process can occur only if the membrane is permeable to the substance concerned. The lipid bilayer is permeable to lipid soluble compounds such as steroids and fatty acids, as well as small molecules like oxygen and carbon dioxide, which diffuse through it rapidly.

Diffusion begins with a concentration gradient, a difference in the concentration of a substance between two areas. Molecules, driven by their kinetic

energy, spread out into available space. This movement continues until the concentration on both sides of the membrane equalizes, reaching a state of dynamic equilibrium (see Figure 1.11). At equilibrium, molecules continue to move, but there is no net movement in either direction. It is also noteworthy that different particles can diffuse in opposite directions simultaneously without interference. For example, carbon dioxide (CO_2) produced as a by-product of cellular respiration diffuses out of the cells into the surrounding tissues, while O_2 diffuses into these cells to support cellular respiration.

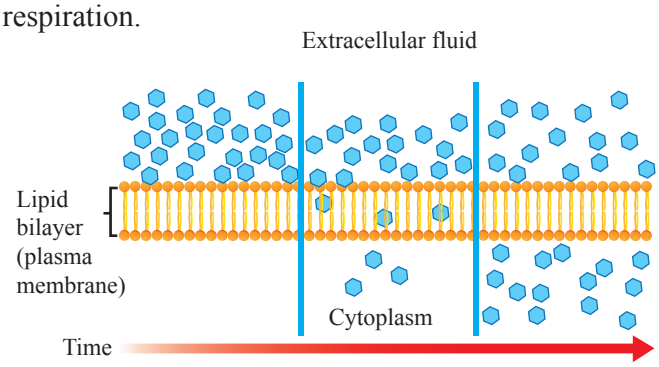


Figure 1.11: Diffusion through a permeable membrane.

The rate of simple diffusion is influenced by factors such as the concentration gradient, temperature (higher temperatures increase molecular movement), molecular size (smaller molecules diffuse more quickly), and the permeability of the membrane.

Facilitated Diffusion: Substances like polar molecules, including glucose and amino acids, and ions like sodium (Na^+), potassium (K^+) and chloride (Cl^-) cannot diffuse through the phospholipid bilayer. They need the help of specific protein molecules to cross the membrane. **Facilitated diffusion** is the process that allows these particular substances to move across cell membranes from an area of higher concentration to an area of lower concentration, using transport proteins embedded in the membrane, without the expenditure of energy.

There are two main types of transport proteins involved in this process: **channel proteins** and **transporter/carrier proteins.** Channel proteins form passageways or pores that enable specific molecules to cross the membrane. Some of these proteins are always **open**, providing a constant pathway, while others are gated and can be opened or closed as needed (see Figure 1.12 a&b). Transporter proteins, in contrast, are more selective. They bind to a specific molecule or ion on one side of the membrane and then transport these molecules to the other side without forming an open channel. For example, glucose enters a cell through a glucose transporter. Unlike channel proteins, transporter proteins only open to one side at a time (see Figure 1.12 c).

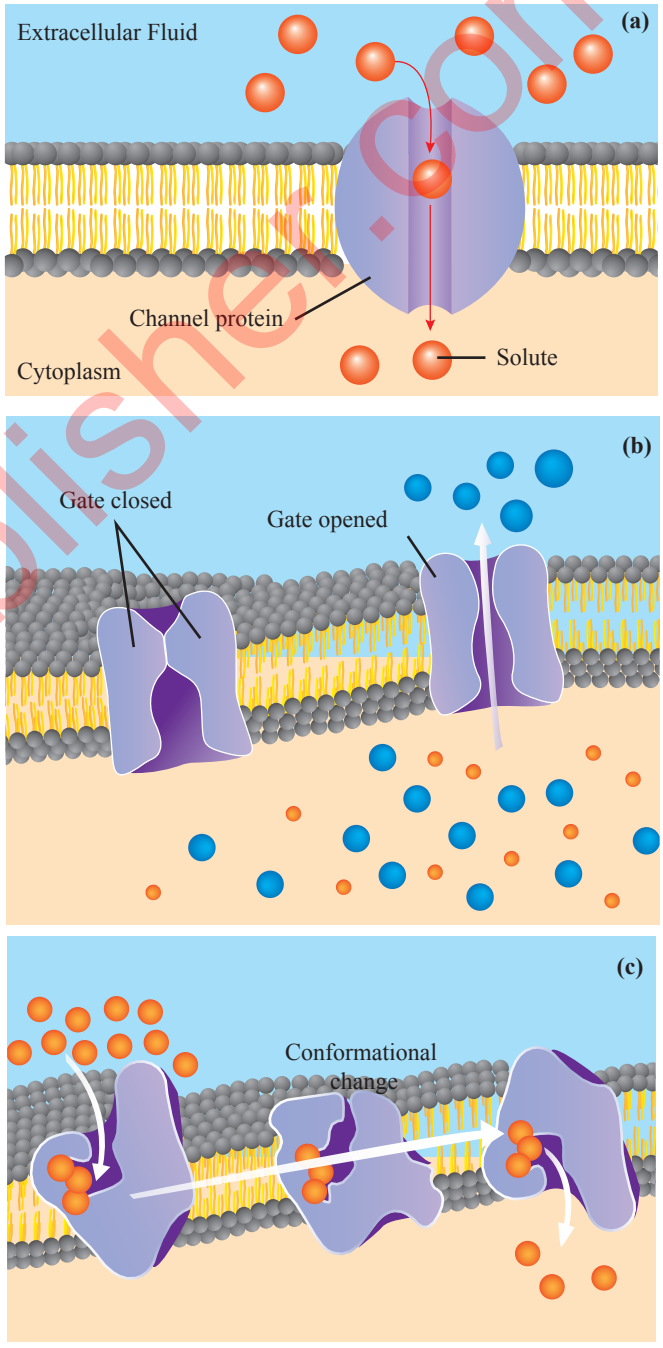


Figure 1.12: Facilitated Diffusion across the plasma membrane. (a) Open channel protein (b) Gated channel protein (c) Carrier protein

Like simple diffusion, facilitated diffusion occurs down the concentration gradient. However, it does so at a faster rate than simple diffusion for specific molecules.

Osmosis: Osmosis is a special type of diffusion that involves the passive movement of water molecules through a selectively permeable membrane from an area of higher water concentration (lower solute concentration) to an area of lower water concentration (higher solute concentration) as show in Figure 1.13.

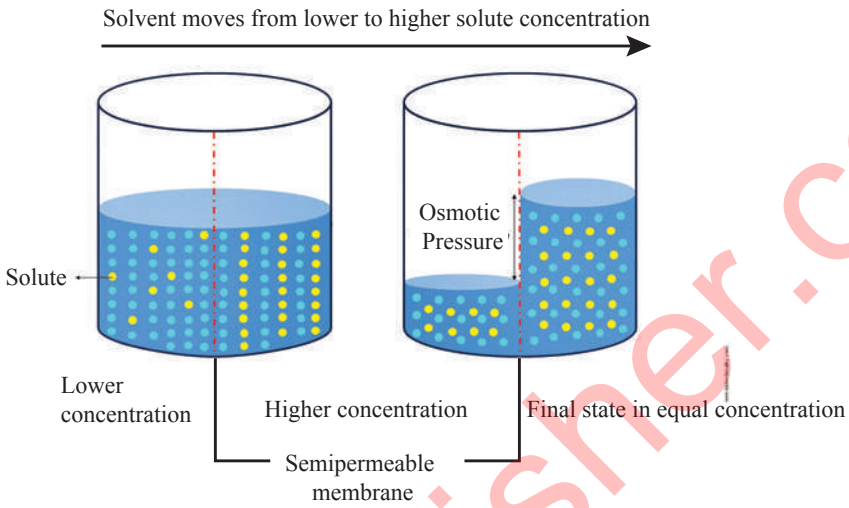


Figure 1.13: Osmosis

Direction of Osmosis: The net direction of osmosis depends on the difference in solute concentration on either side of the membrane (Study Table 1.1). When the solute concentration outside the cell is lower than inside, the external solution is termed **hypotonic** relative to the inside (cytosol). Under these conditions, water moves into the cell until equilibrium is achieved. Conversely, when the solute concentration outside is higher than inside, the external solution is considered **hypertonic** to the cytosol. In this case, water moves out of the cell until equilibrium is reached.

Table 1.1: Direction of Osmosis

Condition	Net movement of water	
External solution is hypotonic to cytosol	into the cell	H_2O → ← H_2O
External solution is hypertonic to cytosol	out of the cell	H_2O ← → H_2O
External solution is isotonic to cytosol	none	H_2O ↔ H_2O

However, when the solute concentration is the same inside and outside the cell, the external solution is called **isotonic** to the cytosol. In this situation, water moves into and out of the cell at the same rate, so there is no net movement of water.

Active Transport: If a cell depended exclusively on diffusion for the exchange of substances, it would be unable to regulate its internal environment effectively. This means that any substance with a higher concentration outside the cell could enter, regardless of its necessity or potential harm, while essential substances might leave the cell whenever their concentration inside exceeded that on the outside. To address these challenges, the cell membrane employs a mechanism known as **active transport**. This process enables the molecules or ions to move against their concentration gradient, from an area of lower concentration to an area of higher concentration, with expenditure of energy. Active transport relies on specialized transmembrane proteins called pumps or transporters. Following are the two types of active transport:

Primary active transport: Primary active transport

directly uses ATP to fuel the transport of molecules. One common example of primary active transport is the ion pump, such as the **sodium-potassium pump** which actively transports three sodium ions (Na^+) out of the cell and two potassium ions (K^+) into the cell, using ATP to power the process (see Figure 1.14).

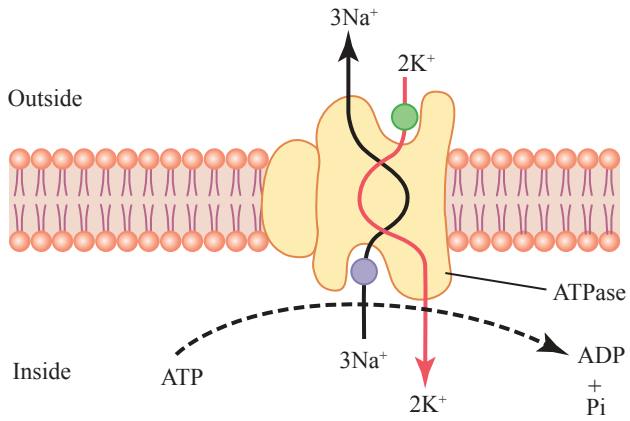


Figure 1.14: Primary active transport through sodium-potassium pump.

Secondary Active Transport (Co-transport): Secondary active transport utilizes the energy released from the movement of one molecule down its concentration gradient to drive the movement of another molecule against its gradient. This process does not directly use ATP; instead, it relies on the energy gradient created by primary active transport. For example, the sodium-glucose transport protein (SGLT) uses the sodium gradient established by the Na^+/K^+ pump to transport glucose into cells (see Figure 1.15).

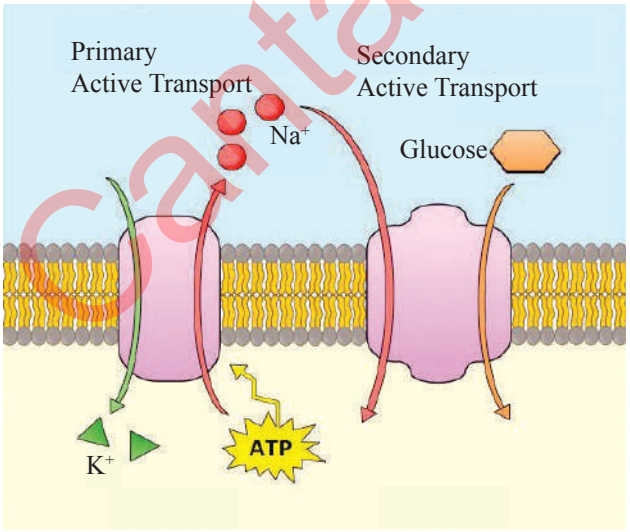


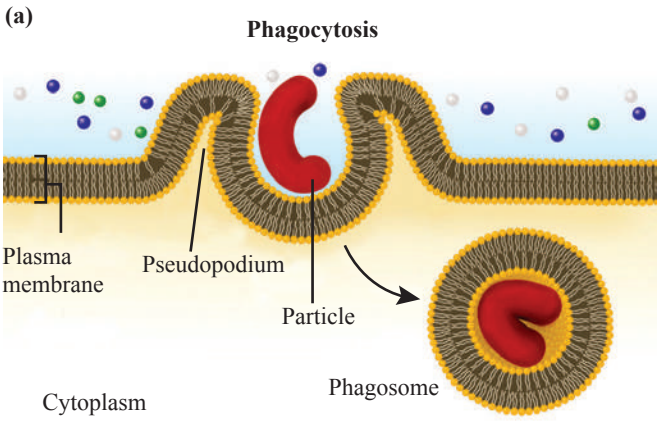
Figure 1.15: Primary and Secondary active transport

Endocytosis and Exocytosis: Macromolecules such as proteins and polysaccharides are often too large to be moved through the cell membrane by transport proteins. Endocytosis and exocytosis are essential cellular processes that transport these large molecules and particles across the cell membrane by using energy.

Endocytosis: Endocytosis is the process by which cells take in substances from the external environment by engulfing them into a vesicle formed from the cell membrane. Phagocytosis and pinocytosis are the two main forms of endocytosis.

Phagocytosis: In phagocytosis, solid particles are engulfed by the cell. This process begins when the phagocyte identifies a target particle and extends **pseudopodia** (false feet) to surround and enclose it within a vesicles or **phagosome** [see Fig 1.16 (a)]. This mechanism is common among unicellular organisms like amoeba and also occurs in humans. Certain white blood cells in humans are capable of engulfing debris like worn-out red blood cells or bacteria.

Pinocytosis: In pinocytosis, small droplets of fluid or dissolved substances are engulfed by the cell. The cell membrane invaginates, creating small vesicles called **pinosomes** that contain the ingested molecules [see Figure 1.16 (b)]. Microvilli, bristle-like protrusions in the small intestine, use pinocytosis to absorb nutrients (amino acids, vitamins, etc.) from food.



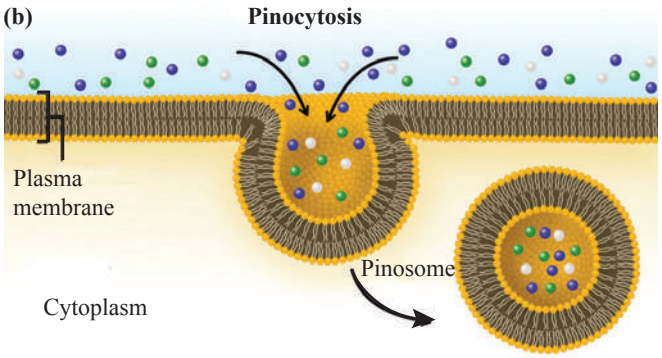


Figure 1.16: Types of endocytosis (a) Phagocytosis (b) Pinocytosis

Exocytosis: Exocytosis is the process by which cells expel substances from the cell interior to the extracellular space. This involves the fusion of vesicles containing cellular products with the cell membrane, thereby releasing the contents outside the cell (see Figure 1.17). An example of this is the secretion of digestive enzymes from pancreatic cells, where secretory vesicles from the Golgi apparatus carry enzymes to the cell surface for release.

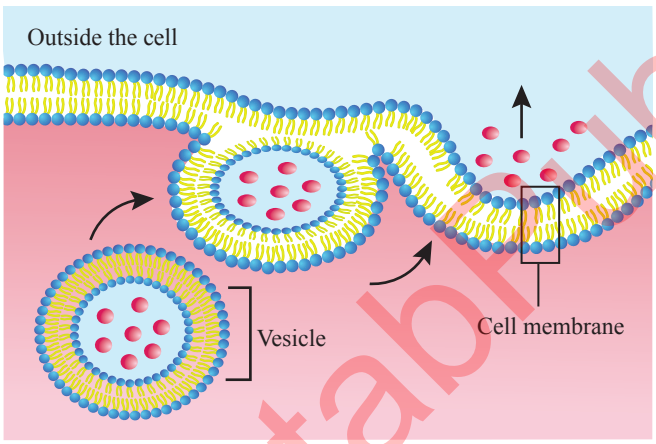


Figure 1.17: Exocytosis

Nucleus

The nucleus is a prominent organelle in eukaryotic cells, responsible for storing the cell's genetic material and acting as its control center. It is typically spherical or oval and has an average diameter of 5 µm. The nucleus is composed of the following key components, each with its important role to play:

The **nuclear envelope**, also known as the nuclear membrane, is a double-layered barrier that surrounds the nucleus, effectively separating it from the cytoplasm. The outer layer of the nuclear envelope is continuous with the endoplasmic reticulum (ER) membrane, while the inner layer faces the nucleoplasm. The space between the inner and outer membranes is called the **perinuclear space.** The nuclear envelope is perforated with **nuclear pores**, which are protein channels spanning both membranes (see Figure 1.18). These pores allow for the passage of materials between the cytosol and the nucleus. Each nuclear pore is made up of specialized proteins called **nucleoporins.**

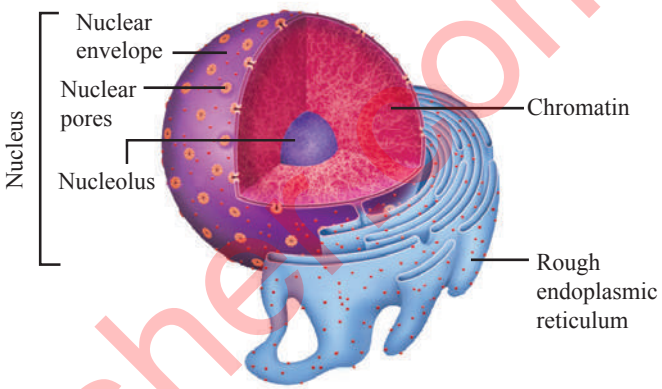


Figure 1.18: Structure of a Nucleus

Within the nucleus lies the **nucleoplasm**, a gel-like substance, which is primarily made up of water, dissolved ions such as K□, Ca²□ and Mg²□, nucleotides, enzymes, RNA and proteins (histone and non-histone proteins). It also contains **chromatin**, which is formed by wrapping DNA around histone proteins, as well as the **nucleolus** and other nuclear components. Chromatin stores genetic information in a loosely coiled state during the non-dividing stage of the cell. During cell division, chromatin condenses into visible **chromosomes** (see detail of chromosomes in Chapter 14).

The nucleolus is a prominent structure within the non-dividing nucleus. It is a dense, non-membrane-bound region and plays a key role in ribosome biogenesis. The nucleolus comprises a central fibrillar area surrounded by a peripheral granular area. The **central fibrillar area** is primarily involved in the transcription of rRNA (ribosomal RNA) from rDNA, while the **peripheral granular area** is associated with the formation of both the small and large subunits of ribosomes.

These subunits are then transported to the cytoplasm through nuclear pores, where they join to form functional ribosomes.

Cytoplasm

Cytoplasm is the living component and lies between the nuclear membrane and cell membrane. It is gel-like in nature and is composed of water (about 90%) and embedded substances. The embedded substances include the organelles and chemicals consisting of ions, molecules like salts, vitamins and dissolved gases. The water and suspended or dissolved substances form the cytoplasmic matrix. The dissolved micromolecules make it a **true solution**, while the macromolecules, such as proteins, make it a **colloidal solution**. Cytoplasm can be differentiated into two parts;

Ectoplasm: The outer or the peripheral portion of the cytoplasm is comparatively non granular, viscous and gel-like (Cytogel).

Endoplasm: The inner or central portion of the cytoplasm is granular, contains organelles and is less viscous (Cytosol).

The cytoplasm acts as a site for certain metabolic reactions, e.g. glycolysis, protein synthesis and mitosis. It is a reservoir of important chemicals such as hormones and enzymes. Cellular wastes are also dissolved here. Cytoplasm houses a number of cell organelles that perform specific functions in the cell. The cell organelles found in eukaryotic cells are Ribosomes, Endoplasmic Reticulum, Golgi bodies, Lysosomes, Peroxisomes & Glyoxysomes, Centriole, Mitochondria and Plastids.

Ribosomes

Ribosomes are cellular structures which are involved in protein synthesis in living cells. Ribosomes are **ribonucleoprotein** complexes that are composed of ribosomal RNA (rRNA) and proteins. They consist of two subunits, the large and the small subunits, and are found in both prokaryotic and eukaryotic cells (see Figure 1.19). Prokaryotic ribosomes are typically smaller and measure about 70S, while eukaryotic ribosomes are slightly larger and measure about 80S.

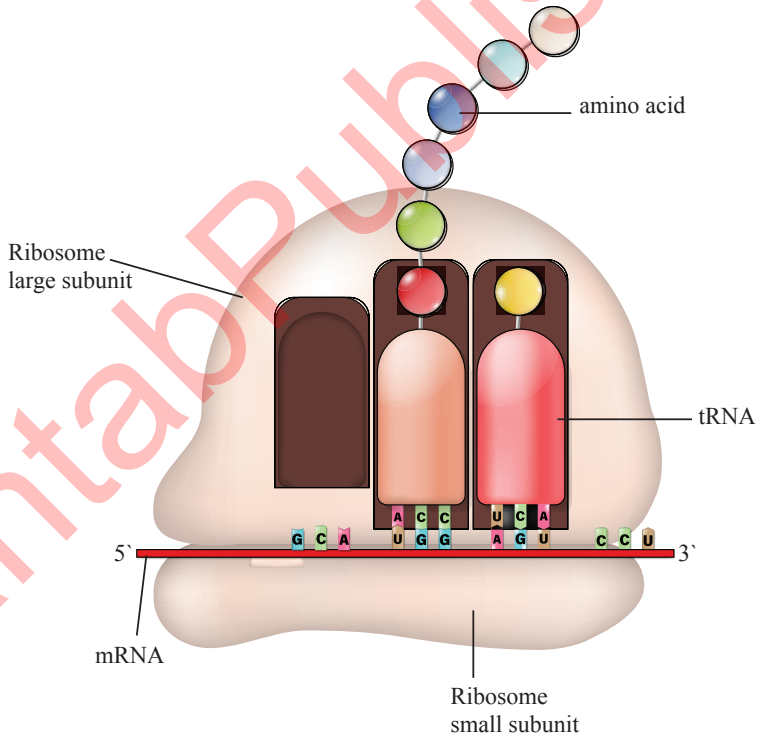


Figure 1.19: Larger and smaller subunit of ribosome

Knowledge Booster

"S" stands for Svedberg unit, a measure of sedimentation rate during centrifugation, which reflects how quickly particles settle.

In both prokaryotes and eukaryotes, these small and large subunits join to form a functional ribosome only when attached to an mRNA molecule. Ribosome catalyzes the formation of peptide bonds between amino acids during protein synthesis. The small subunit reads the mRNA sequence, while the large subunit helps to link the amino acids together to form the growing polypeptide chain. However, when a cell has a high demand for protein synthesis, such as during cell growth, replication, and division, multiple ribosomes translate a mRNA simultaneously, forming a complex called **polysomes** or **polyribosomes** (see Figure 1.20). This structure significantly increases the efficiency of protein synthesis.

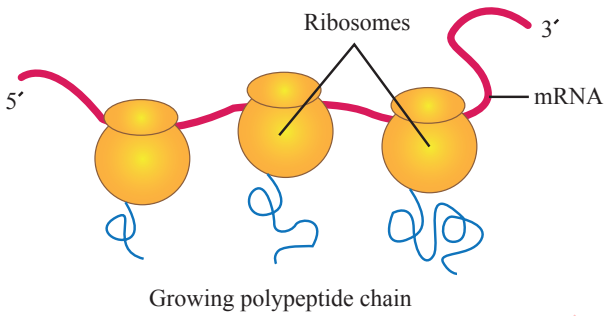


Figure 1.20: Polysome formation

Eukaryotic ribosomes may be either free, or bound to the rough endoplasmic reticulum. However, both bound and free ribosomes are structurally identical. The number of ribosomes can vary depending on the cell type and its specific needs. Cells that have high rates of protein synthesis have a large number of ribosomes, as well as prominent nucleoli, given the role of nucleoli in ribosome assembly.

Endoplasmic Reticulum

The endoplasmic reticulum is a vast network of channels and interconnections that spreads throughout the cell. It is comprised of membranous tubules and sacs, known as **cisternae**, and is continuous with the outer membrane of the nuclear envelope. The space within these tubular and sac-like structures of the ER is called the **ER lumen** or the endoplasmic reticulum cisternal space, and it is entirely enclosed by the ER membrane, separating it from the cytosol of the cell. There are two distinct regions of the ER that differ in structure and function. These are rough endoplasmic reticulum (RER) and smooth endoplasmic reticulum (SER).

Rough endoplasmic reticulum: The rough endoplasmic reticulum (RER) appears rough under a microscope due to the presence of ribosomes on its outer surface (see Figure 1.21). The rough ER is characterized by flattened sacs or cisternae, often extending from the nuclear envelope and is abundant in cells actively producing proteins for export, such as plasma cells and pancreatic cells. The rough endoplasmic reticulum (ER) plays an essential role in the synthesis and assembly of proteins, including those that are exported from the cell, destined for other organelles, or become a part of a membrane. Polypeptides, which are intended for export to other organelles, enter the ER lumen directly. Enzymes within the ER lumen modify and assemble proteins, including protein folding and adding carbohydrates to them. Once modified and assembled, the proteins are packaged into transport vesicles. These **transport vesicles** bud off at a specialized area of rough ER that lacks bound ribosomes called the **transitional ER** and transport the proteins to their respective destinations within the cell, such as other organelles or the cell surface, for secretion.

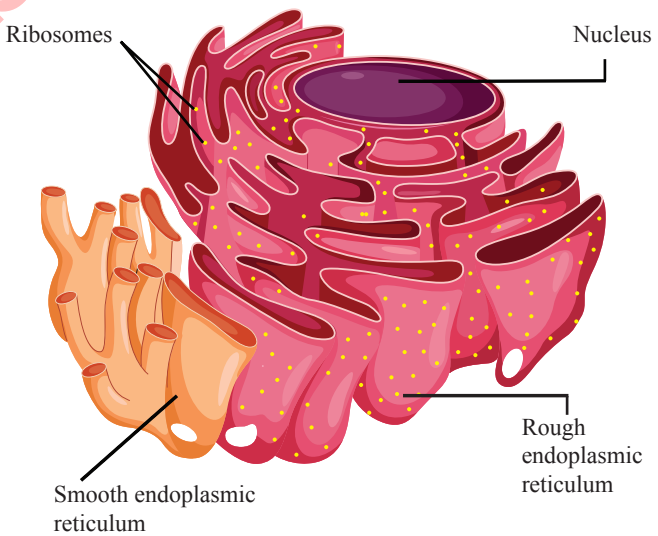


Figure 1.21: Endoplasmic Reticulum

Smooth endoplasmic reticulum: The smooth ER, which lacks ribosomes on its surface, giving it a "smooth" appearance, has a tubular network structure. SER is involved in various functions, such as lipid metabolism, including the synthesis of lipids such as phospholipids and steroids. It also plays a role in

the metabolism of carbohydrates and the detoxification of drugs and toxins by modifying them to be more water-soluble for easier removal from the cell. One of the most important functions of the smooth ER in animal cells is the production of sex hormones such as estrogen and testosterone. Additionally, in muscle cells, a specialized type of smooth ER called the **sarcoplasmic reticulum** stores and delivers the calcium ions required for muscle contraction.

Both rough and smooth ER contribute to the biosynthesis of new cellular membranes, providing components like phospholipids and proteins necessary for membrane formation and growth.

Golgi apparatus

The Golgi apparatus, also known as the Golgi complex or Golgi body, was named after its discoverer, Camillo Golgi. It is made up of a stack of slightly curved, flat, membrane-enclosed sacs called **cisternae** (sing. cisterna). Each cisterna has an internal space or lumen. The Golgi apparatus is divided into three distinct regions: the cis face, the trans face, and a medial region in between.

The **cis face**, which is the entry surface or forming face, is convex and located adjacent to the nucleus or transitional ER. It receives transport vesicles bringing molecules from the ER. The trans face, which is the exit surface or maturation face, is concave and closest to the plasma membrane. It packages molecules in vesicles and transports them out of the Golgi.

The Golgi apparatus plays a key role in the modification and processing of proteins and in directing them to their proper destinations. Secretory proteins that are assembled in the rough ER lumen are first transported to the cis face of the Golgi complex via transport vesicles formed from the ER membrane. These proteins then progress through the Golgi stack, undergoing successive modifications until they reach the trans face of the Golgi, where they are packaged into **secretory vesicles** and shipped to their destination. Outgoing secretory vesicles may be used within the cell or proceed to the plasma membrane, where they discharge their contents during secretion. In animal cells, some of the vesicles that leave the Golgi contribute to the formation of **lysosomes.** The Golgi body contains enzymes that are particularly involved in the modification and formation of conjugated molecules such as glycoprotein and lipoprotein (see Figure 1.22).

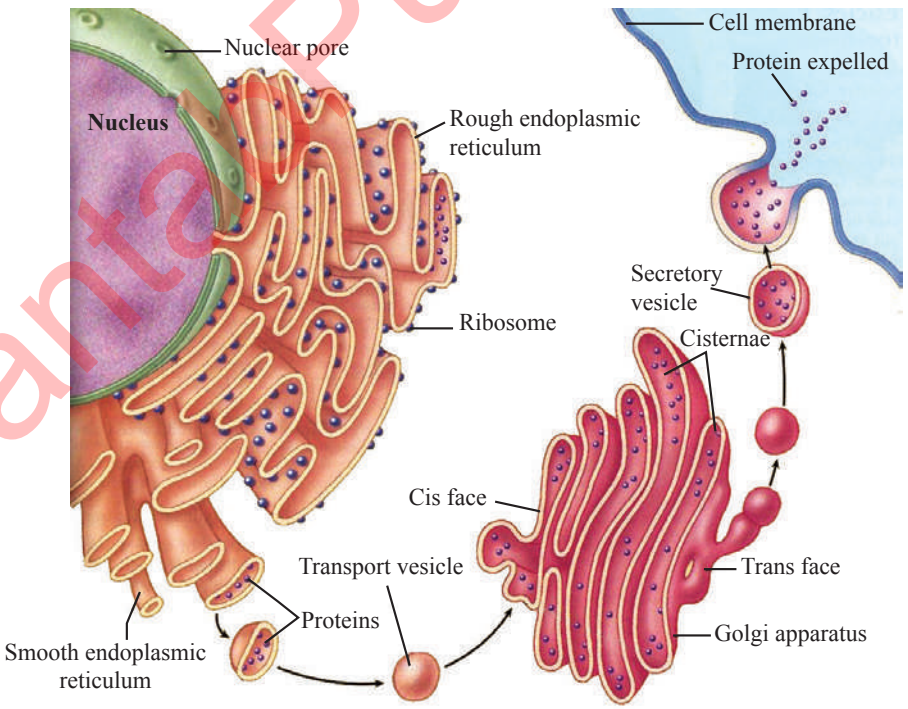


Figure 1.22: Proteins synthesized at the RER are modified in the Golgi apparatus and released as secretory vesicles.

polypeptides synthesized on ribosomes → protein assembled and carbohydrate component added in lumen of ER → transport vesicles move glycoprotein to Golgi (cis face) → glycoprotein further modified in Golgi → in trans face, glycoproteins packaged in secretory vesicles → glycoproteins transported to plasma membrane → contents released from cell.

In plants, the Golgi body is mainly involved in the secretion of materials of primary and secondary cell walls. During cytokinesis of mitosis or meiosis, the vesicles originated from the Golgi apparatus coalesce in the **phragmoplast** to form a cell plate.

Lysosomes

Lysosomes, derived from Greek ("lyso" meaning digestive and "soma" meaning body), are small vesicles filled with about 40 different types of digestive enzymes, such as lipases, nucleases and proteases, that are active under acidic conditions (pH around 5) as shown in Figure [1.23(a)]. An ATP-driven proton (H^+) pump within the membrane of the lysosome maintains this acidic environment. If lysosomes break, open or leak, their enzymes become inactive due to the near-neutral pH (about 7.2) of the cytosol. However, extensive leakage from many lysosomes can lead to cell destruction through self-digestion.

The hydrolytic enzymes of lysosomes are synthesized in the rough ER and then transported to the Golgi apparatus. There, these enzymes are modified, and packaged into Golgi vesicles, which eventually bud off as **primary lysosomes.** Lysosomes facilitate both intracellular and extracellular digestion. In the case of intracellular digestion, the primary lysosome fuses with an incoming vesicle, such as a pinosome or phagosome, carrying food content from outside the cell via endocytosis to form a large vesicle called a **secondary lysosome**. Powerful enzymes in the secondary lysosome come in contact with the ingested molecules and begin the digestion process. Digestion products such as simple sugars, amino acids, and other monomers pass into the cytosol and become nutrients for the cell. In addition, certain human cells, like macrophages, help defend the body by engulfing and destroying bacteria and other invaders with the help of lysosomes.

Lysosomes also use their hydrolytic enzymes to recycle the cell's own material, which is called **autophagy**. During autophagy, the lysosome appears to flow around the damaged organelle and fuse to form **autophagosome** [see Figure 1.23(b)].

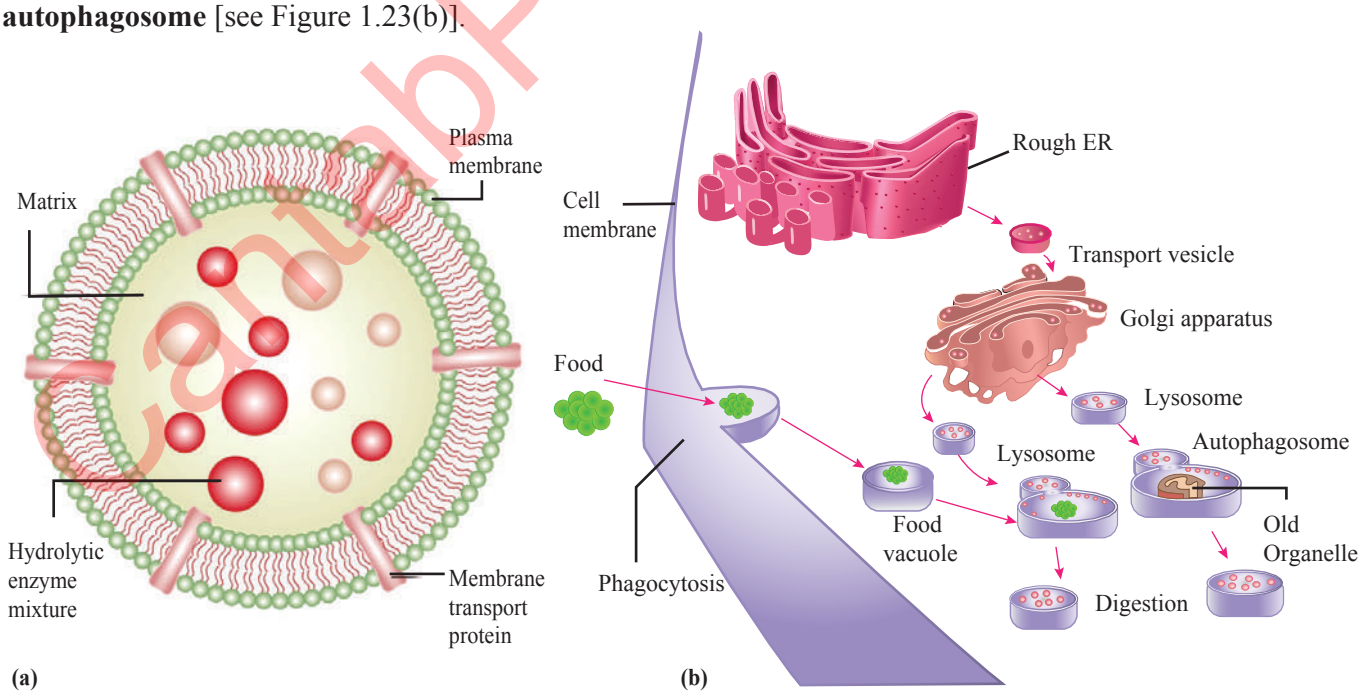


Figure 1.23: (a) Structure of Lysosomes (b) Formation and function of Lysosomes

The lysosomal enzymes dismantle the enclosed material, and the resulting small organic compounds are released into the cytosol for reuse. In this way, a cell continually renews itself.

In certain pathological conditions, when a cell dies, the lysosomal enzymes are released into the cell cytoplasm and begin to break down cellular components. This process is called **autolysis**. This can help in clearing dead cells and tissues.

Extracellular digestion by lysosomes is less common than intracellular digestion. It is a process where lysosomes release their hydrolytic enzymes outside the cell to break down substances in the extracellular matrix. For example, the heads of sperm contain a special lysosome called the **acrosome,** which digests a path to the ovum (egg) during fertilization. Similarly, during development, lysosomes facilitate cartilage replacement by breaking down the cartilage matrix, allowing for the formation of bone.

In certain genetic diseases of humans, known as **lysosomal storage diseases**, one of the digestive enzymes usually present in lysosomes is absent. For instance, In **Tay-Sachs disease**, a lipid-digesting enzyme is missing or inactive, and the brain becomes impaired by an accumulation of lipids in the cells. The accumulation of this lipid in brain cells causes severe intellectual disability, blindness, and death before age 4.

Peroxisomes and glyoxisome

Microbodies are small, membrane-bound organelles present in nearly all eukaryotic cells, including those of plants, animals, fungi, and protists. Enclosed by a single lipid bilayer, they contain a collection of enzymes. A notable type of microbody is the peroxisome present in animal cells and higher plants, which houses oxidative enzymes such as oxidase, peroxidase, and catalase (see Figure 1.24). Peroxisomes originate from the endoplasmic reticulum (ER), where specific proteins are integrated into ER-derived vesicles. These vesicles mature to form fully functional microbodies.

Peroxisomes are especially abundant in cells involved in the synthesis, storage, or degradation of lipids. They play a crucial role in the **oxidation of fatty acids**, converting long-chain fatty acids into smaller molecules that the cell can use for energy production. This process generates hydrogen peroxide (H□O□), a potentially harmful by product. However, peroxisomes are equipped with catalase, an enzyme that efficiently converts hydrogen peroxide into water and oxygen, thus neutralizing its toxicity. In liver and kidney cells, peroxisomes also **detoxify** various toxic compounds, including ethanol, converting them into less harmful products for elimination.

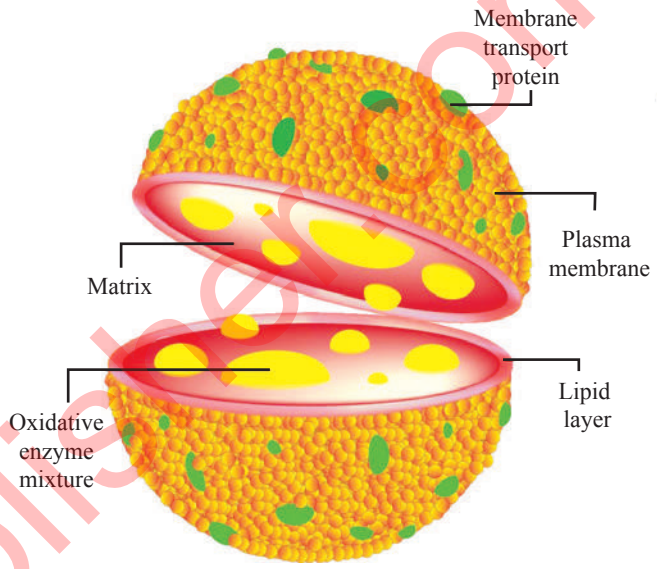


Figure 1.24: Structure of peroxisome

Certain plant seeds, rich in fats and oils, such as corn, soybean, sunflower, and peanut, contain specialized peroxisomes called **glyoxysomes**. It contains enzymes that are involved in the **glyoxylate cycle**, which allows the conversion of stored **lipids** (fats) into **sugars.** The sugars are used by the young plant as an energy source and as a component for synthesizing other compounds.

Vacuoles

A vacuole, like a vesicle, is a membrane-bound organelle found in the cells of plants, fungi, protists, and some animals. However, vacuoles are typically larger than vesicles. It is essentially a compartment filled with water that contains inorganic and organic molecules, including enzymes in solution. The membrane surrounding the vacuole is called the **tonoplast.**

Vacuoles are derived from the endoplasmic reticulum and Golgi apparatus. Immature plant cells contain

numerous small vacuoles, which fuse together to form a large central vacuole as the cell matures (see Figure 1.25). The vacuole contains a high concentration of solutes and takes in water, creating hydrostatic pressure called **turgor pressure**, which helps plants stay rigid and upright. Plant cells grow by adding water to the central vacuole, which can occupy as much as 80% of the cell's volume. The vacuole also serves as a storage compartment for many compounds, including salts, sugars, and weak acids. Plant vacuoles contain hydrolytic enzymes and behave like **lysosomes**, breaking down wastes, damaged organelles, and other cell components. In some plant vacuoles, compounds that are poisonous to herbivores are stored as a means of defense.

In unicellular protists such as protozoa, **food vacuoles** (originate from the cell membrane by endocytosis) are present, which fuse with lysosomes that digest the food. Some protozoa also have **contractile vacuoles**, which remove excess water from the cell.

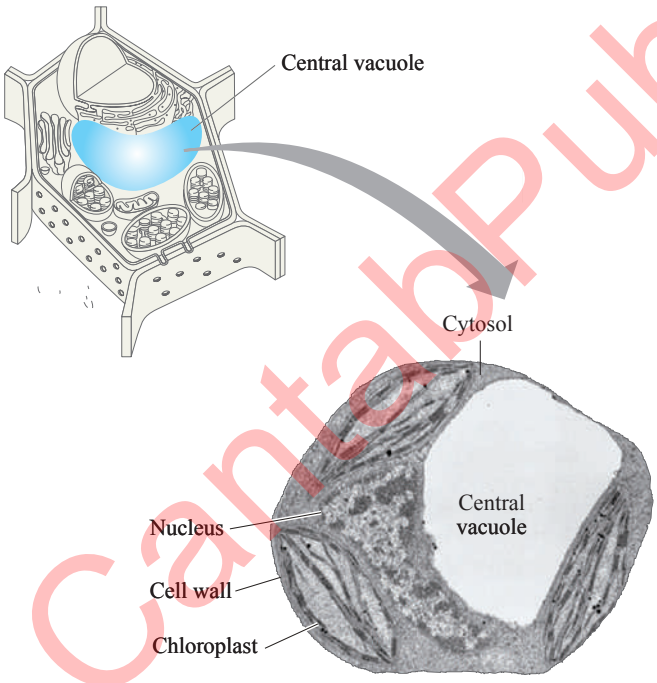


Figure 1.25: A large central vacuole in plant cell

Vesicles

Vesicles (from the Latin word "*vesicula*," meaning "small bladder") are small sacs enclosed by lipid bilayers. These structures are essential for various cellular processes such as transport, storage, and communication. Because of the phospholipids in their membranes, vesicles can bud off and fuse with other membrane structures within the cell (see Figure 1.26). Vesicles come in different sizes and serve specialized functions. They are involved in transporting molecules within the cell. For example, proteins from the endoplasmic reticulum are transported to the Golgi apparatus through **transport vesicles.** Additionally, **secretory vesicles** originating from the Golgi apparatus can release their contents outside the cell by fusing with the cell membrane, a process vital for the secretion of various substances.

Some vesicles, called **endocytic vesicles**, are formed during endocytosis, where they engulf external materials and bring them into the cell for processing. Another example of a vesicle, **lysosomes**, contains digestive enzymes that break down waste materials and maintain cellular balance. Some vesicles are specialized for storage; for instance, **synaptic vesicles** in nerve cells store neurotransmitters that are released during synaptic transmission.

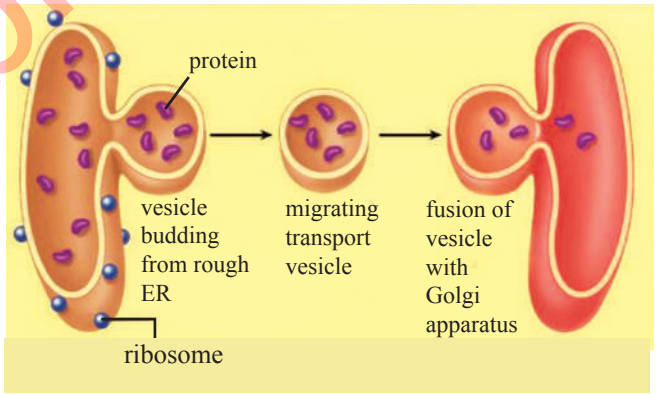


Figure 1.26: Transport vesicles transferring proteins from ER to Golgi apparatus.

Centrioles

Centrioles are cylindrical structures that usually occur in pairs and are located near the nucleus in a region called the **centrosome**. Within the centrosome, a pair of centrioles lies at right angles to each other. Centrioles are known as **"9 × 3 structures"** because each centriole is composed of nine sets of microtubule triplets arranged to form a hollow cylinder (see Figure 1.27). These microtubule triplets are surrounded by a protein matrix, which supports

and stabilizes their structure. Centrioles are mainly found in animal cells and are absent in fungi and plant cells. During the S phase of cell division (mitosis and meiosis), a pair of centrioles duplicate and later migrate to opposite poles of the cell during Prophase. These centrioles serve as the primary organizing centers for the formation of **spindle fibers** (for details, see Knowledge 1.8), which are necessary for the separation of chromosomes into daughter cells. The complete set of spindle fibers and centrioles is collectively called mitotic apparatus. Centrioles are also involved in the formation of basal bodies of **cilia** and **flagella**, which are hair-like structures that project from the cell surface.

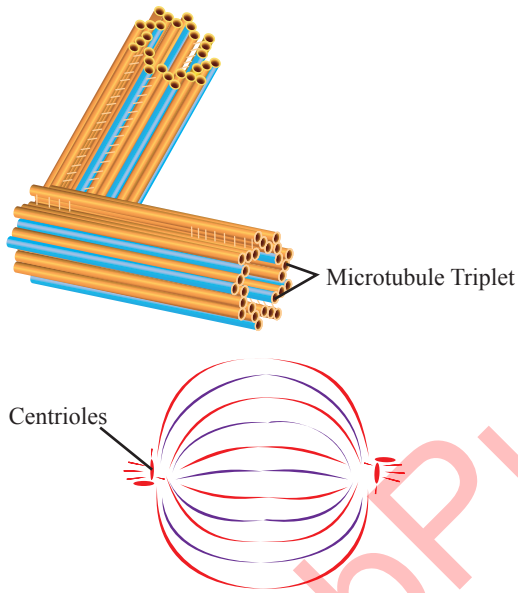


Figure 1.27: A Pair of Centrioles forming spindle fibers during cell division.

Mitochondria

The term 'mitochondrion' is derived from the Greek words "mitos" and "chondrion" which means "thread" and "granules-like", respectively. They are often known as the "powerhouse of the cell" due to their crucial role in energy production. Mitochondria are the double membranous organelles that are found in most eukaryotic cells. The outer layer of mitochondria is smooth and encloses the entire organelle. It contains special proteins called **porins** that form channels that allow molecules such as ions, ATP, and other metabolites to pass through. The inner membrane is folded into projections called **cristae**, which increase the surface area for chemical reactions. The inner membrane contains **ATP synthase enzymes** that are required for ATP production. ATP synthase enzymes consist of two components: F_0 and F_1 particle (see detail of ATP synthase in Chapter 10). The space between the outer and inner membranes is called **inter-membranous space**. The inner membrane encloses the innermost compartment called the **mitochondrial matrix** (see Figure 1.28). It contains enzymes responsible for the Krebs cycle (citric acid cycle) and other metabolic reactions that occur in the matrix. It also contains mitochondrial DNA (mtDNA) and ribosomes for synthesizing some mitochondrial proteins.

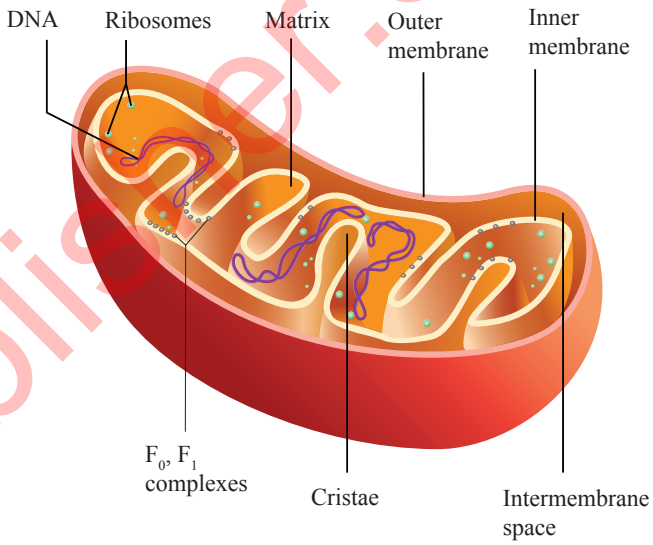


Figure 1.28: Structure of a Mitochondrion

Mitochondria play a multifaceted role in cellular metabolism beyond ATP production. It has metabolic pathways for carbohydrates, fats, and proteins, converting these compounds into usable energy and other crucial molecules necessary for cellular processes. It is also involved in **calcium regulation.** In specialized brown fat cells, mitochondria contribute to **heat generation**, a process known as non-shivering thermogenesis.

Plastids

Plastids are organelles found in the cells of plants and algae. There are three main types of plastids: **Chromoplasts** are involved in pigment synthesis and storage other than chlorophyll, giving fruits, flowers, roots, and aging leaves their distinctive colours.

Leucoplasts are colourless plastids found in roots and seeds, where they store food. **Chloroplasts** contain green pigment chlorophyll and are involved in photosynthesis, the process by which light energy is converted into chemical energy (carbohydrate) using of carbon dioxide and water.

In plants, chloroplasts are primarily located within the mesophyll cells of the leaf, with each mesophyll cell containing 20 to 100 chloroplasts. Like mitochondria, chloroplasts are enclosed by outer and inner membranes, forming the chloroplast **envelope**. These membranes are separated by a very narrow **intermembrane space**. The inner membrane encloses a fluid-filled region called the **stroma**, which contains most of the enzymes required for carbohydrate synthesis. Similar to mitochondria, chloroplasts also contain their own DNA and ribosomes.

Suspended in the stroma is a third membrane system forming interconnected, flat, disc-like sacs known as **thylakoids.** The thylakoid membrane encloses an interior space called the thylakoid lumen. In some regions of the chloroplast, thylakoid sacs are stacked to form structures called **grana** (singular, granum), with some thylakoid membranes extending between grana, often called lamella (see Figure 1.29). Like the inner mitochondrial membrane, the thylakoid membrane is involved in ATP synthesis.

Thylakoid membranes house several types of pigments that absorb visible light, with different pigments absorbing various wavelengths.

Chlorophyll, the primary photosynthetic pigment, mainly absorbs light in the blue and red regions of the visible spectrum. Energy absorbed from sunlight excites electrons within the chlorophyll molecules; these electrons are used in **light-dependent reactions** to produce ATP and NADPH. The ATP and NADPH generated are then utilized in the **light-independent reactions** (Calvin Cycle) in the stroma to convert carbon dioxide into glucose.

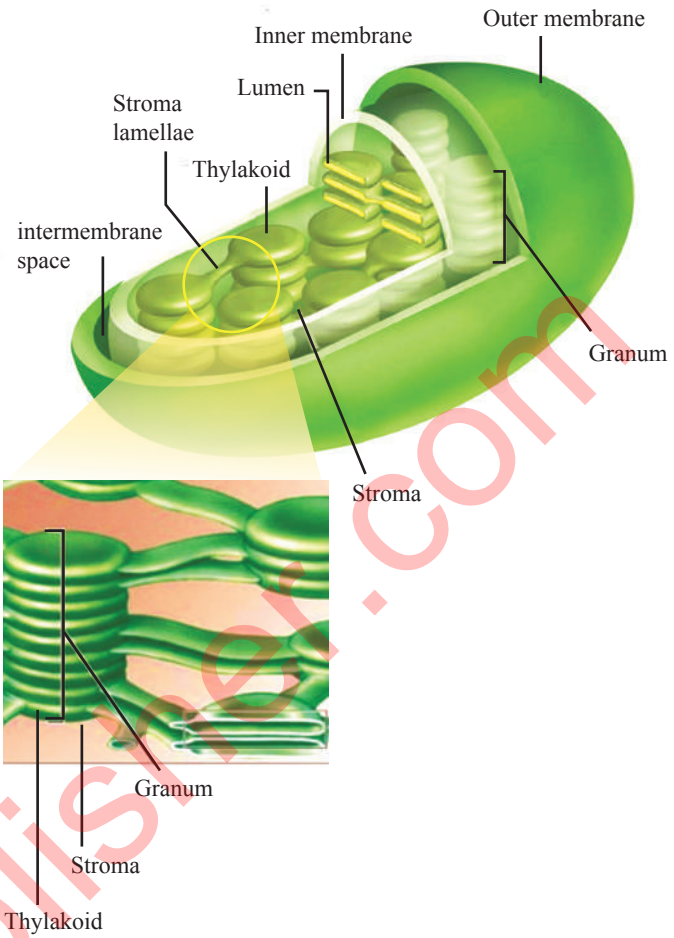


Figure 1.29: Structure of a Chloroplast

Skill:1.4

Objective:

- Identify and describe the structural components and functions of various sub-cellular organelles.
- Critically evaluate different scientific techniques used for studying the structure and function of cell membranes.
- Illustrate the chemical structure of a phospholipid, detailing its components and their arrangement.
- Analyze and distinguish between simple diffusion and facilitated diffusion.
- Demonstrate and visually represent the four key membrane transport mechanisms: simple diffusion, facilitated diffusion, osmosis, and active transport, highlighting their distinct processes and roles in cellular function.
- Analyze and distinguish between endocytosis and exocytosis with the help of diagrams.

Test Yourself

Short answer-based questions

1. What are the main functions of mitochondria in cellular processes?
2. How does the Golgi apparatus contribute to protein modification and transport within a cell?
3. In what ways do lysosomes maintain cellular homeostasis?
4. Describe the role of ribosomes in protein synthesis.
5. What is the significance of chloroplasts in plant cells?
6. What are the different roles of cell membrane's protein?
7. How does facilitated diffusion differ from simple diffusion?
8. What is the purpose of vacuole in a plant cell?

Long Questions

1. Analyze the different components of the nucleus in a eukaryotic cell.
2. Discuss the structure of the cell membrane, focusing on its composition and the role of its components.
3. What techniques are commonly used in scientific research to study the cell membrane?
4. Which organelles are involved in the formation of lysosomes and what functions do lysosomes perform in a cell?

1.5 Knowledge

Comparison of Prokaryotic and Eukaryotic cell

Cells are classified into two types based on their structure, namely prokaryotic and eukaryotic cells. Table 1.2 differentiate between these two cell types with diagrams.

Table 1.2: Key Differences between Prokaryotic and Eukaryotic cells

FEATURES	PROKARYOTE CELLS	EUKARYOTE CELLS
NUCLEUS	The type of cell that lacks a nucleus is called a prokaryotic cell and the organism is called a prokaryote.	The type of cell that contains a well defined nucleus is called eukaryotic cell and the organism is called a eukaryote.
DNA	DNA is without any nuclear membrane covering and is directly submerged in cytoplasm.	DNA is enclosed inside the nucleus covered by nuclear membrane.
MEMBRANE-BOUNDED STRUCTURES	Membrane-bounded structures are absent.	Membrane-bounded structures are present.
RIBOSOMES	They have small sized 70S ribosomes.	They have large sized 80S ribosomes.
CELL WALL	Their cell wall is composed of polysaccharide chains covalently bonded with shorter chains of amino acids forming peptidoglycan or murein.	Cell wall of plants is generally composed of cellulose while cell wall of fungi contains chitin.
CELL DIVISION	They reproduce by binary fission.	They reproduce by mitosis and meiosis.

NUCLEOLUS	Nucleolus is absent.	Nucleolus is present.
CHOLESTEROL	Cholesterol is not found in the membrane of prokaryotic cell.	Cholesterol is present in the membrane of eukaryotic cell.
EXAMPLE	Bacteria, blue green algae and archaebacteria.	Algae, protozoa, fungi, plants and animals.

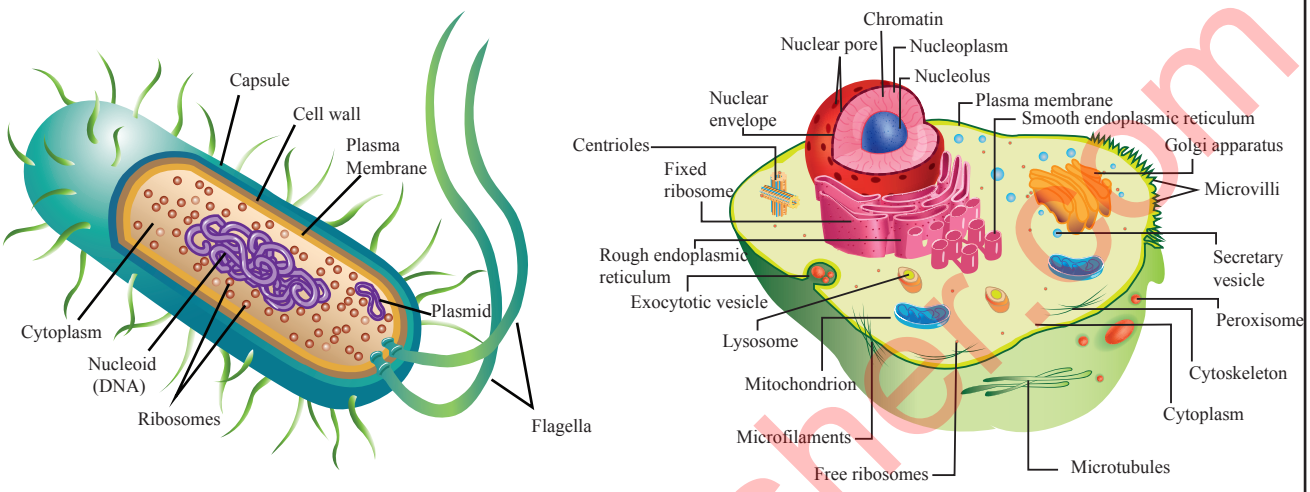


Figure 1.30: (a) A prokaryotic cell (b) A eukaryotic cell

Skill:1.5

Objective:

- Differentiate between prokaryotic and eukaryotic cells and use diagrams to highlight their structural differences and unique characteristics.

Test Yourself

Short answer-based questions

1. Mention any four differences between prokaryotic and eukaryotic cell.

1.6 Knowledge

Cell Signaling

Cell signalling is the process by which cells communicate with each other and respond to their environment to coordinate and regulate various cellular activities. It involves the transmission of molecular signals from one cell to another, or from a cell to itself, to elicit a specific response or change in behaviour. The basic idea of a signalling pathway can be summarized in a simple diagram (Figure 1.31).

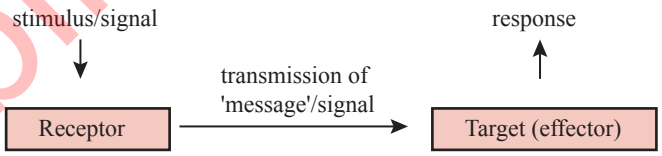


Figure 1.31: Summary of a signalling pathway.

Cell signalling can occur over short distances or long distances. It involves ligand-receptor interaction at the target site.

Ligand: A signalling molecule that binds to a specific site on a receptor is called a ligand. After binding, it forms a ligand-receptor complex, initiating a biological response within a cell. By nature, ligand can be proteins, lipids and gases among others.

Receptor: A receptor is a protein molecule usually found on the surface of a cell or within its interior that binds to specific ligands. When a ligand binds to its receptor, it causes the receptor to change its shape, which can activate or inhibit the receptor's associated signalling pathways. Receptors are typically highly selective, binding only to specific ligands or types of ligands. This selectivity is crucial because it ensures that cells respond only to the appropriate signals.

The Three Stages of Cell Signalling

The process of cell signalling occurs in three main stages: reception, transduction, and response.

Reception begins when a ligand binds to a specific receptor, either on the cell surface or within the cell, activating the receptor to initiate the signalling process.

Transduction occurs after the receptor is activated. The signal is relayed and amplified through a series of biochemical reactions inside the cell, ensuring the signal reaches its appropriate targets efficiently. This stage is crucial for accurately transmitting the signal to produce the appropriate cellular response.

Finally, in the **response** stage, the signal triggers a specific cellular action, such as changes in gene expression, enzyme activity, or cytoskeletal arrangement. This process ensures that vital cellular activities are precisely coordinated and occur within the organism at the right time and place.

Pathway of a Signal

The process by which a cell converts an external signal into a specific cellular response through a series of biochemical interactions is called the **signal transduction pathway**. Each step in a signal transduction pathway is highly regulated and can involve amplification of the signal, ensuring that even small amounts of a ligand can have significant effects on a cell.

Protein Signal Pathway

Protein signals cannot go through the cell membrane because they are hydrophilic (water-attracting), so they attach to special receptors on the cell's surface. These receptors are typically transmembrane proteins that span across the cell membrane.When a protein signal binds to its matching receptor, the receptor changes shape, getting activated. This activated receptor then starts a chain of reactions inside the cell. This chain passes the signal through different molecules within the cell, like cyclic AMP (cAMP), calcium ions (Ca^{2+}) or protein kinases. These molecules help relay the signal to where it needs to go inside the cell. Signal transduction amplifies the initial signal, leading to a larger response within the cell. The signalling pathway results in a specific cellular response like changes in gene expression, modifications in enzyme activity, cell movement, secretion of substances, or other cellular activities (see Figure 1.32).

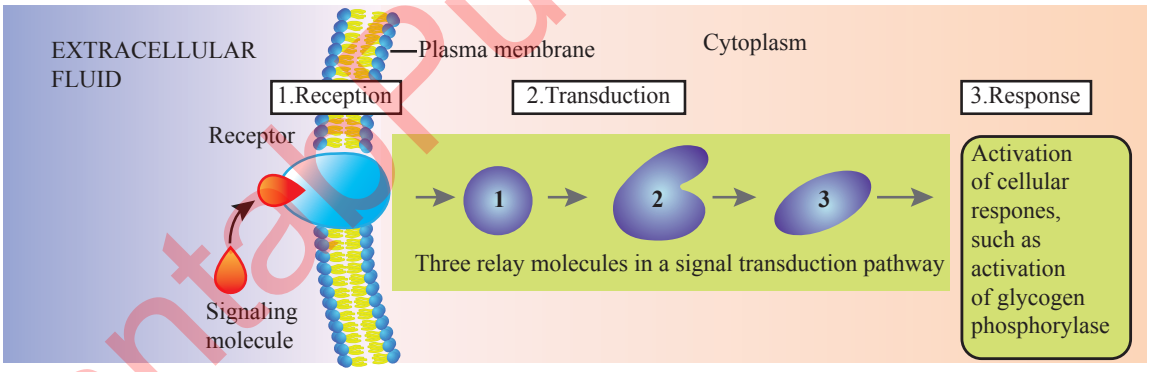


Figure 1.32: Protein signaling pathway through membrane receptor.

Steroid Signalling Pathway

Steroid hormones, being lipid-soluble (hydrophobic), can diffuse through the cell membrane and enter the cell easily. Once inside the cell, steroid hormones bind to specific intracellular receptors located in the cytoplasm or nucleus. These receptors are often transcription factors. The resulting hormone-receptor complex translocates into the nucleus and interacts with DNA (see Figure 1.33). The hormone-receptor complex binds to specific DNA sequences known as **hormone response elements** (HREs). This binding either stimulates or inhibits the transcription of specific genes, leading to changes in mRNA production. The altered mRNA levels result in changes in the synthesis of specific proteins. These newly synthesized proteins contribute to the cellular response induced by the steroid hormone. Estrogen, progesterone and testosterone are examples of steroid hormones (Chapter 2).

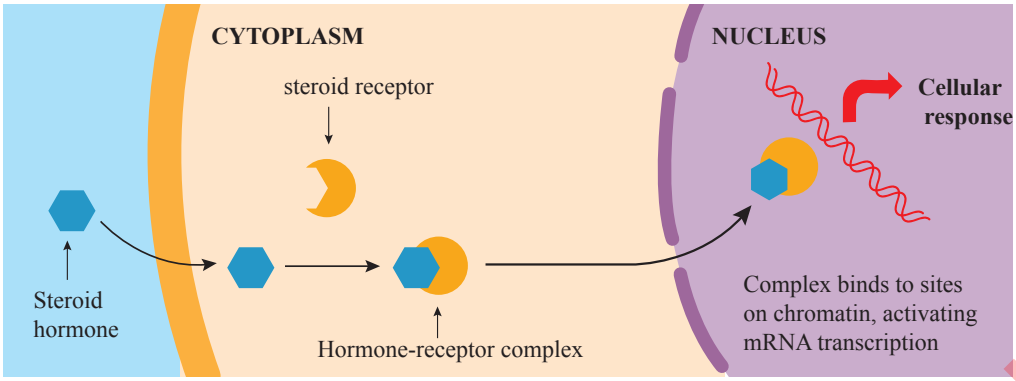


Figure 1.33: Steroid Signaling Pathway through mobile receptors

Skill:1.6

Objective:

- Define the concept of cell signalling and elaborate on the pathways of protein and steroid signals from their reception outside the cell to their effects inside the cell.

Test Yourself

Short answer-based questions

1. Define cell signaling. Name its key components.
2. Differentiate between steroid signalling and protein signalling pathways.
3. Name the second messengers involved in a protein signalling pathway.

Long answer-based questions:

1. Briefly describe the three stages of cell signalling.
2. Explain the mechanism involved in the steroid signalling pathway.

1.7 Knowledge

Stem Cells

Stem cells are undifferentiated cells with the unique ability to develop into various specialized cell types within the body. They have the capacity for self-renewal, enabling them to divide and produce more stem cells, as well as the potential to differentiate into specific cell types with specialized functions (see Figure 1.34).

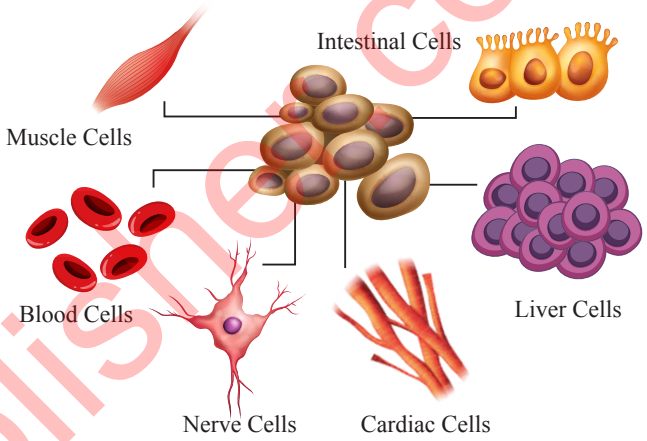


Figure 1.34: Stem Cells

Advantages of Stem Cells

Stem cells offer many advantages in various aspects;

- Stem cells can replace or repair damaged tissues and organs, offering hope for treating a wide range of diseases and injuries such as Parkinson's disease, type 1 diabetes, and heart disease.
- Stem cells provide a valuable tool for studying developmental processes and disease mechanisms.
- They allow scientists to observe how cells differentiate and mature, providing insights into normal development and disease progression.
- This understanding can lead to breakthroughs in predicting and possibly preventing developmental anomalies.
- Stem cells can be used in drug testing and screening to evaluate the safety and effectiveness of new drugs. This can streamline the process of drug development, making it faster and less costly.

Types of Stem Cells

Understanding the categorization of stem cells is important for studying their capabilities and applications in biology and medicine. Stem cells can be broadly categorized based on their origin and their potential to differentiate into other cell types (potency). Based on their potency, students have studied their types in grade 9. Here are the main types of stem cells based on their origin:

Embryonic Stem Cells (ESCs): These cells are derived from the inner cell mass of the blastocyst (early-stage embryo). They are **pluripotent** and can give rise to nearly all cell types in the body. Their use is often controversial due to ethical concerns regarding the source of embryonic tissue.

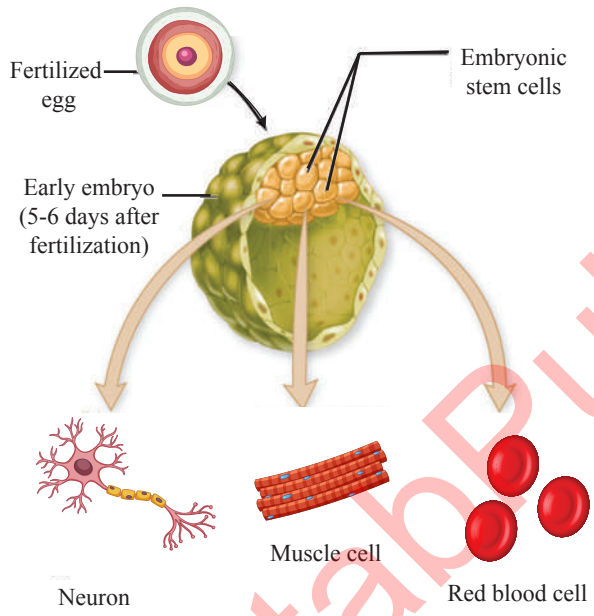


Figure 1.35: Human Embryonic stem cells

Adult Stem Cells (ASCs): These cells are found in various tissues or organs like the bone marrow, brain, and liver in the body and are also known as **somatic stem cells**. These cells are generally **multipotent**, capable of differentiating into a limited range of cell types related to their tissue of origin. They are used to maintain and repair the tissue in which they are found. Common examples include hematopoietic stem cells (found in bone marrow) and mesenchymal stem cells (in bone marrow, adipose tissue, etc.).

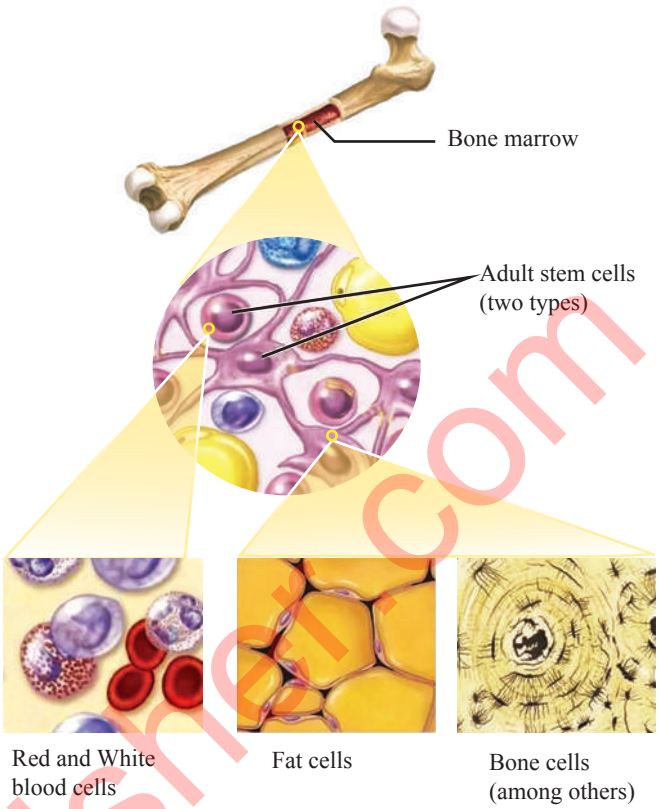


Figure 1.36: Adult stem cells in bone marrow

Knowledge Booster

Adult stem cells continue to divide throughout life. These include blood- forming cells in the bone marrow and basal cells of the skin and digestive tract. Continuous division of these cells is required because blood cells live only a short while, and cells that line the intestine and cells that form the outer layer of the skin are continually sloughed off.

Induced Pluripotent Stem Cells (iPSCs): These are cells that have been genetically reprogrammed to an embryonic stem cell-like state by being forced to express genes important for maintaining the defining properties of embryonic stem cells. iPSCs can be derived from adult cells and are **pluripotent,** being capable of differentiating into various cell types. They offer a promising source of stem cells without the ethical issues associated with ESCs.

Induced pluripotent stem cells (iPSCs) have revolutionized the field of regenerative medicine and research due to their unique properties. Here are the advantages and disadvantages associated with their use.

Advantages of Induced Pluripotent Stem Cells:

There are many advantages of using induced pluripotent stem cells;

- Unlike ESCs, which are derived from embryos, iPSCs avoid the ethical concerns associated with the destruction of human embryos, as they are generated from adult cells such as skin or blood cells.
- Since iPSCs can be derived from the patient's own cells, they are genetically identical to the original donor's cells. This personalization allows for minimized risks of immune rejection when used in therapies such as tissue transplants.
- iPSCs can be cultured indefinitely in the lab, providing an inexhaustible source of patient-specific cells for medical research or treatment.
- iPSCs enable the creation of cell models for various diseases, particularly those for which there is no adequate animal model. This aspect is crucial for studying disease mechanisms, and progression, and for screening potential therapeutic drugs.

Disadvantages of Induced Pluripotent Stem Cells:

Besides advantages, there are some disadvantages of induced pluripotent stem cells, which are;

- One of the significant risks associated with the use of iPSCs is their potential to form tumors. The reprogramming process can induce mutations that may increase the risk of cancerous growth if the cells are implanted in patients.
- Sometimes, the reprogramming process is incomplete, resulting in cells that retain some memory of their previous cellular identity. This memory could influence the cells' behaviour and efficiency in differentiating into other cell types.
- The production of iPSCs is a complex and time-consuming process that requires sophisticated equipment and high levels of expertise, which can be expensive. This may limit the availability of technologies based on iPSCs, especially in lower-resource settings.

Skill: 1.7

Objective:

- Define stem cells and assess the advantages of using stem cells in various applications, including medical therapies and research.
- Categorize different types of stem cells based on their origin and explain the characteristics that distinguish each type.
- Critically evaluate the advantages and disadvantages of using induced pluripotent stem cells.

Test Yourself

Short answer-based questions

1. What is a stem cell? What are its various types?
2. What are the differences between embryonic stem cells and adult stem cells?
3. What is the role of stem cells in drug testing?
4. What are the main sources of stem cells in the human body?

Long answer-based questions:

1. Highlight the advantages and disadvantages of Induced Pluripotent Stem Cells.

1.8 Knowledge

Mitosis and Meiosis

The cell cycle is a complex series of events that cells undergo to divide and produce new cells. This cycle is crucial for growth, development, and repair in multicellular organisms and consists of four main phases: G1 (Gap 1), S (Synthesis), G2 (Gap 2), collectively called Interphase, and M (Mitosis). In G1, the cell grows and carries out its normal functions. The S phase is where the cell duplicates its DNA, preparing for division. In G2, further growth occurs, and the cell ensures that it is ready for division. Mitosis, the final phase, involves the actual division of the parent cell resulting in two daughter cells. Throughout these phases, various checkpoints ensure the cell is properly prepared to move to the next stage, safeguarding the accuracy of cell division.

Mitosis

Mitosis is a process that allows a single eukaryotic cell to divide and produce two genetically identical daughter cells. This process is essential for growth, tissue repair, and the maintenance of the body's various tissues and organs. Mitosis is responsible for the proliferation of somatic (body) cells and occurs in multicellular organisms, including plants, animals, and fungi.

Mitosis is a continuous cellular process, but it is conventionally divided into two main phases:

Karyokinesis, which involves the division of the cell nucleus, and Cytokinesis, which encompasses the division of the entire cell.

Karyokinesis

Karyokinesis is the process of nuclear division during cell division. It involves the segregation and distribution of genetic material (chromosomes) into daughter nuclei, ensuring that each resulting cell has a complete and identical set of chromosomes.

The mitotic apparatus is important for chromosome movement and separation during mitosis, specifically in karyokinesis. It consists of microtubules, associated proteins, and centrosomes that organize within the cell to ensure accurate chromosome distribution. The main components include:

- **Spindle Microtubules:** Protein filaments made of **tubulin** that extend from centrosomes at opposite cell ends, forming the spindle framework.
- **Centrosomes:** Regions that organize microtubules. They duplicate and move to opposite poles, giving rise to spindle fibers.
- **Kinetochore Microtubules:** Attach to **kinetochores** (protein structures) on chromosome centromeres, separating sister chromatids during anaphase.
- **Non-Kinetochore Microtubules:** Extend from spindle poles to the cell center, interacting with microtubules from the opposite pole to push spindle poles apart during anaphase.
- **Astral Microtubules:** Radiate from centrosomes toward the cell cortex (the outer layer of the cytoplasm), helping position the spindle apparatus and orient cell division.

The mitotic apparatus ensures chromosomes are evenly distributed to daughter cells, maintaining genetic integrity and accuracy during cell division.

i. Prophase: During prophase, several significant events take place as the cell prepares for nuclear division. Firstly, the **chromatin**, a complex of DNA and proteins, begins to condense, transforming into visible and tightly coiled structures known as **chromosomes**. Each chromosome appears to have two sister chromatids attached at the centromere. The nucleoli disappear. Simultaneously, the nuclear envelope, which separates the nucleus from the rest of the cell, starts to break down, allowing access to the spindle fibers (see Figure 1.37). These fibers capture the condensed chromosomes by attaching to protein structures called **kinetochores** at the centromeres. The centrosomes start to migrate to opposite ends of the cell. The centrioles extend a radial array of microtubules towards the nearby plasma membrane when they reach the poles of the cell. This arrangement of microtubules is called an **aster.** Prophase sets the stage for subsequent mitotic stages, including metaphase, anaphase, and telophase, where further processes lead to the accurate segregation of genetic material into two daughter cells.

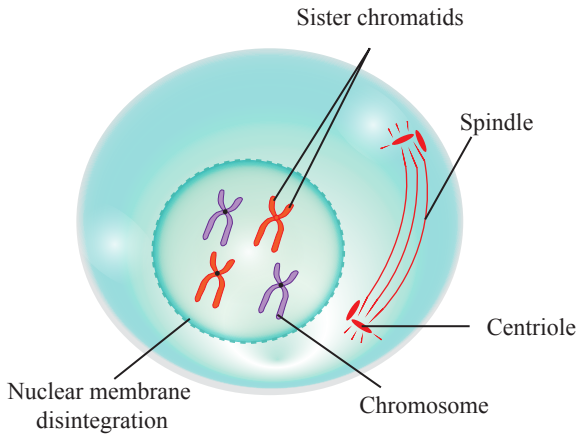


Figure 1.37: Prophase of mitosis

ii. Metaphase: It is a pivotal stage in mitosis where chromosomes align along the cell's center, known as the **metaphase plate** (see Figure 1.38). This alignment ensures the precise distribution of genetic material to daughter cells. It also serves as a critical checkpoint to confirm the correct chromosomal

attachment to the spindle fibers before progressing to anaphase, where sister chromatids are separated.

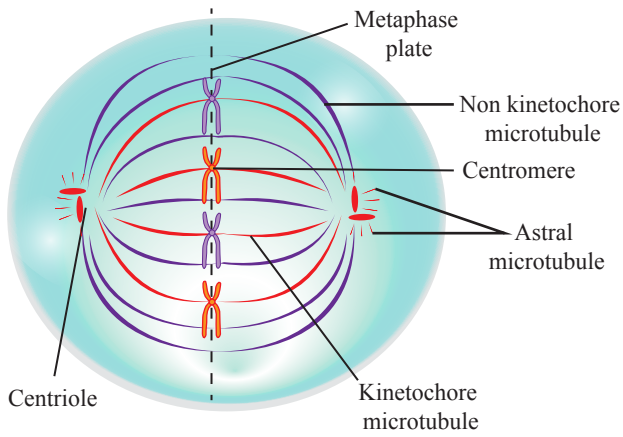


Figure 1.38: Metaphase of mitosis

iii. Anaphase: It is a crucial stage in mitosis, during which sister chromatids, previously held together at the centromere, are separated and pulled towards opposite poles of the cell (see Figure 1.39). This process ensures that each daughter cell receives an identical and complete set of chromosomes, contributing to genetic stability and the formation of two genetically identical daughter cells. Anaphase is marked by the rapid movement of chromatids along the spindle fibers, and it is a key step in the overall process of cell division.

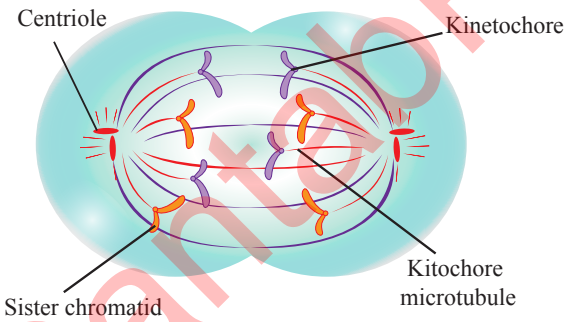


Figure 1.39: Sister chromatids are separating during anaphase of mitosis

iv. Telophase: It marks the near conclusion of mitosis, playing a vital role in the process of cell division. During this stage, the sister chromatids, which were separated and pulled towards opposite poles during anaphase, begin to decondense, transitioning from visible chromosomes back to their more relaxed chromatin form (see Figure 1.40).

Simultaneously, the cell starts to reform a new nuclear envelope around each set of chromatids, establishing two separate nuclei within the cell.

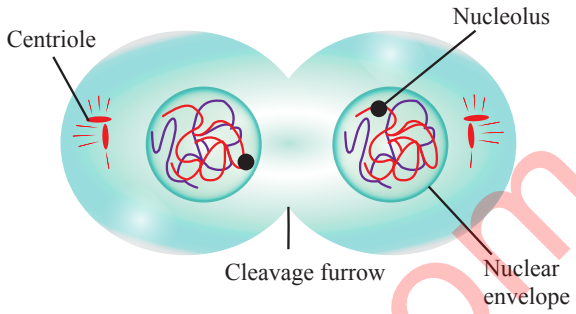


Figure 1.40: Telophase of mitosis

Cytokinesis

During the latter stages of telophase, astral microtubules convey signals to the central region of the cell. These signals initiate the activation of actin and myosin proteins, which come together to construct a **contractile ring**. Over time, this ring progressively contracts, giving rise to the development of a **cleavage furrow** that becomes more pronounced toward the center of the cell (see Figure 1.41). Ultimately, this sequence of events leads to the division of the original cell into two distinct daughter cells.

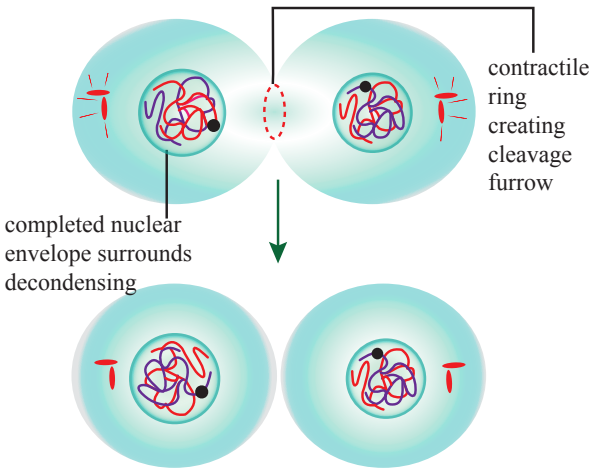


Figure 1.41: Cytokinesis in an animal cell

However, due to the cell wall in plant cells, the **phragmoplast,** a structure made of microtubules and proteins, directs the formation of the **cell plate** from Golgi vesicles, which gradually develops into the new cell wall that split the cell into two new cells (see Figure 1.42).

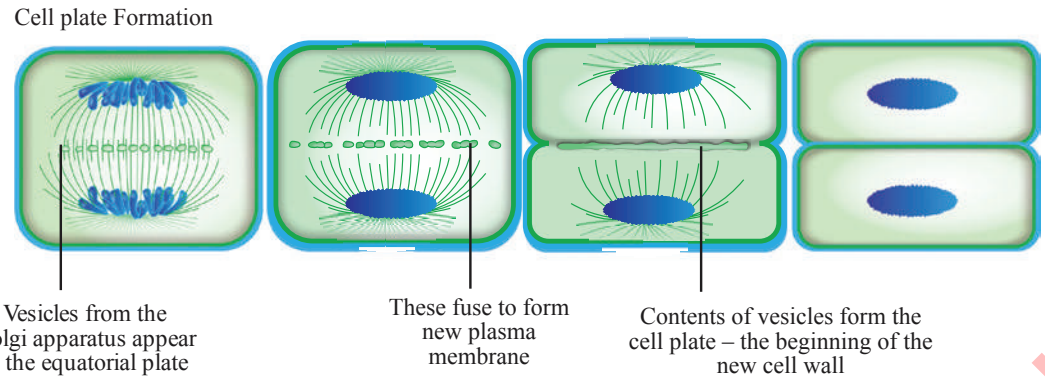


Figure 1.42: Cytokinesis in a plant cell

Meiosis

Meiosis is a unique form of cell division that halves the chromosome number in daughter cells compared to the parent cell. Meiosis exclusively occurs in diploid cells, taking place during gamete formation in animals and spore production in plants.

Following meiosis, each diploid cell generates four haploid cells, a process achieved through two consecutive divisions after a single DNA replication event. These divisions are referred to as meiosis I and meiosis II. The initial meiotic division, known as the **reduction division,** is responsible for reducing the chromosome count, while the second meiotic division closely resembles the process of mitosis.

Prophase I: Prophase I is a critical stage within meiosis I, which is the first round of meiotic cell division. It is a complex process with several distinct sub-stages, each contributing to the overall genetic diversity of offspring.

Prophase I consists of the following stages:

Here are the stages of Prophase I (also see Figure 1.43):

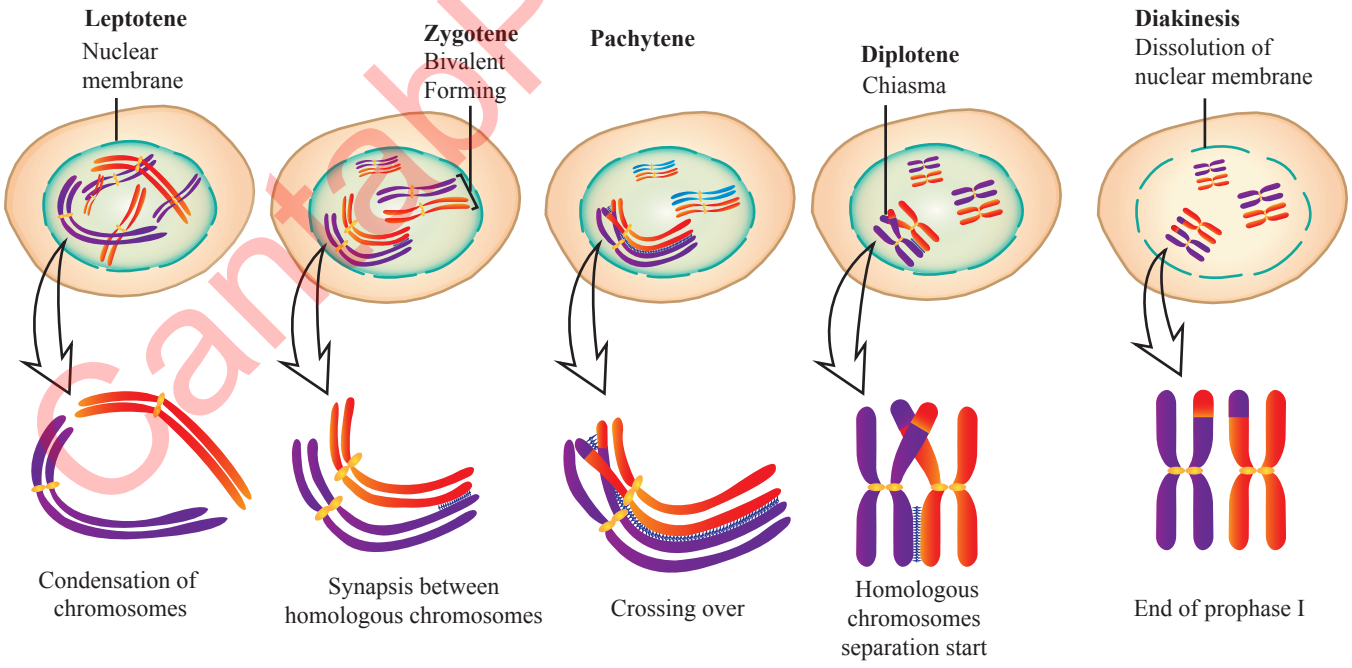


Figure 1.43: Stages of Prophase 1

- **Leptotene:** Chromatin within the nucleus begins to condense, and chromosomes become visible under a microscope. Each chromosome consists of two sister chromatids due to DNA replication in the preceding interphase.
- **Zygotene:** During this stage, homologous chromosomes start to pair up through a process called **synapsis**. This pairing results in the formation of a structure known as a **tetrad** or **bivalent**, which comprises four chromatids (two from each homologous chromosome).
- **Pachytene**: In this stage, the tetrads continue to condense and become more tightly aligned. A significant event in pachytene is crossing over, where genetic material is exchanged between non-sister chromatids of homologous chromosomes. This genetic recombination enhances genetic diversity.
- **Diplotene:** During diplotene, the paired homologous chromosomes begin to separate slightly, although they are still connected at the chiasmata (the sites where crossing over occurred). The chromosomes remain attached by these crossover points until the later stages of meiosis.
- **Diakinesis:** In the final stage of prophase I, the tetrads complete their condensation, and the nuclear envelope begins to break down. Chromosomes become fully visible, and spindle fibers start to interact with the condensed chromosomes, preparing for their eventual separation. Finally, nucleoli disappear.

Metaphase I: Before meiosis I, the homologous chromosomes (pairs of chromosomes, one from each parent) has already undergone replication in the S-phase of interphase I. The homologous chromosomes align themselves along the metaphase plate (also called the equatorial plate) at the center of the cell. Each homologous pair lines up side by side, with one chromosome from the maternal parent and one from the paternal parent (see Figure 1.44).
Spindle fibers attach to the centromere of chromosomes. Each chromosome of a homologous pair receives spindle fibers from one pole.

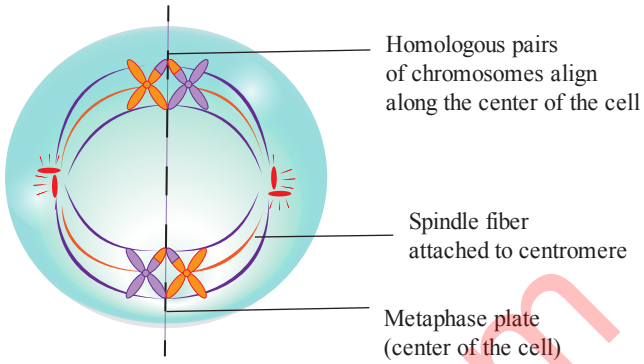


Figure 1.44: Events of metaphase I of meiosis I

Anaphase I: Anaphase I begins with the separation of homologous chromosomes. Each homologous pair is pulled apart and moved toward opposite poles of the cell (see Figure 1.45). This separation is accomplished by the contraction of microtubules that make up the spindle fibers attached to the centromeres of the chromosomes. As the homologous chromosomes move to opposite poles, the chromosome number in each daughter cell is reduced by half. This is a crucial step in meiosis because it ensures that the resulting daughter cells will have the haploid number of chromosomes, which is half the diploid number. In humans, the haploid number is 23, while the diploid number is 46.

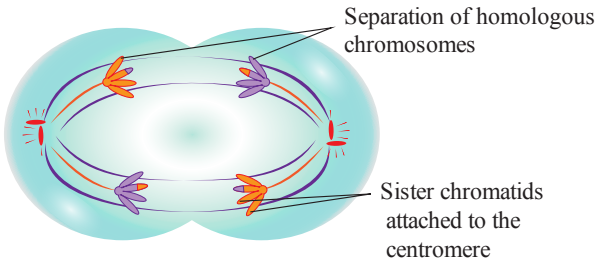


Figure 1.45: Anaphase I of meiosis I

Telophase I: During Telophase I, the separated homologous chromosomes, which were pulled apart during Anaphase I, continue to move towards opposite poles of the cell. This movement is facilitated by the contraction of microtubules that make up the spindle fibers. As the homologous chromosomes reach their respective poles, the nuclear envelopes or membranes that had disintegrated during an earlier stage of meiosis (Metaphase I) start to reform around each set of chromosomes. This reformation marks the

establishment of two nuclei in a cell. The chromosomes, which were highly condensed and visible during earlier stages, begin to decondense as they are enclosed within the newly formed nuclei. They become less compact and return to their extended, interphase-like state. Telophase I is followed by cytokinesis, which is the division of the cytoplasm and other cell organelles. In animal cells, a cleavage furrow forms, pinching the cell membrane and ultimately resulting in the separation of the two daughter cells. In plant cells, a cell plate directed by phragmoplast forms in the middle of the cell and develops into a new cell wall, leading to the formation of two distinct daughter cells.

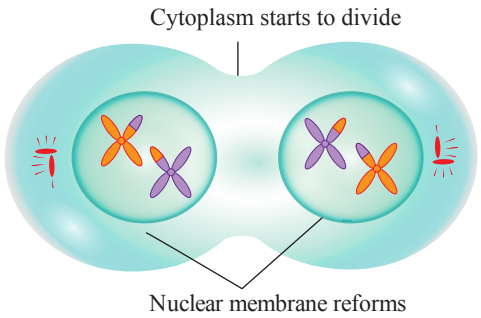


Figure 1.46: Telophase I

Meiosis II

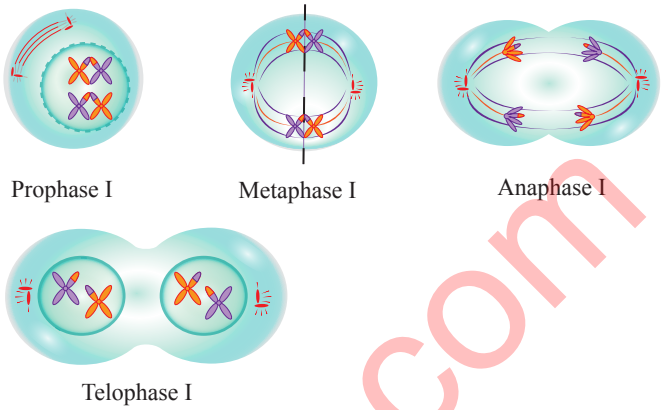
After meiosis I, two daughter cells go through a brief interphase, but unlike the interphase of mitosis, there is no replication of chromosomes. Prophase II, metaphase II, anaphase II, and telophase II closely resemble the respective phases of mitosis. During these stages, chromosomes condense, the mitotic apparatus forms, chromosomes align at the equator, individual or sister chromatids separate, and ultimately, four nuclei are formed at the respective poles of the two daughter cells formed after meiosis I (see Figure 1.47). Cytokinesis occurs, resulting in the formation of four haploid cells, each with half the number of chromosomes (chromatids).

Knowledge Booster

In males, meiosis produces sperm cells (spermatogenesis) and in females, it produces egg cells (oogenesis). Interestingly, oogenesis results in one viable egg and three polar bodies, whereas spermatogenesis results in four viable sperm cells.

Meiosis Phases

Meiosis I



Meiosis II

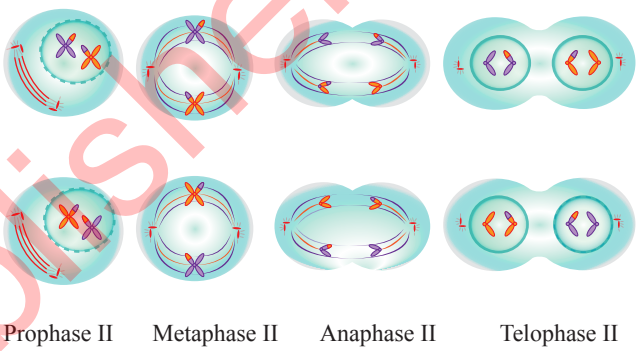


Figure 1.47: Stages of Meiosis I and Meiosis II

Skill:1.8

Objective:

- Illustrate and explain the steps involved in mitosis and meiosis, using detailed diagrams to highlight each phase.

Test Yourself

Short answer-based questions

1. Differentiate between Prophase I and Prophase II.
2. What do you know about synapsis?
3. Sketch the stages of Mitosis.
4. What does mitotic apparatus include?
5. What are the similarities and differences in the outcome of mitosis and meiosis?

Long answer-based questions:

1. Briefly describe the stages of prophase I of meiosis.

Key Points

- Cells demonstrate movement, respiration, homeostasis, growth, reproduction, excretion, and nutrition.
- Cell theory includes principles that all living things are made of cells, cells are the basic unit of life, and new cells arise from existing cells.
- Light microscopes use light for magnification with lower resolution, while electron microscopes offer higher resolution using electron beams.
- Animal cells lack cell walls and chloroplasts, while plant cells have these and other unique structures like a central vacuole.
- Each organelle, from mitochondria to ribosomes, has specific structures and roles in cell functioning.
- Cell membrane comprises phospholipid bilayer with embedded proteins, studied using various biochemical techniques.
- Phospholipids consist of a hydrophilic head and two hydrophobic fatty acid tails.
- Membrane transport mechanisms include simple diffusion, facilitated diffusion, osmosis, and active transport.
- Simple diffusion involves passive transport across the membrane, while facilitated diffusion requires transport proteins.
- Endocytosis and Exocytosis are cellular processes for taking in and expelling substances involving membrane vesicles.
- Prokaryotic cells lack a nucleus and organelles, while eukaryotic cells have both.
- Cell signaling is critical for cellular communication, involving the transmission of signals to regulate cellular activities.
- Methods of signal transduction from the cell surface to the interior, involving different pathways.
- Stem cells are undifferentiated cells with the potential for development and regeneration in various tissues.
- Stem cell types include embryonic stem cells, adult stem cells, and induced pluripotent stem cells (iPSCs).
- Embryonic stem cells offer versatility in use but raise ethical concerns and potential risks in medical applications.
- Processes of cell division, with mitosis for somatic cell replication and meiosis for gamete production.

Extensive Exercise

Encircle the most suitable answer

1. Which of the following is a requirement for osmosis to occur?

a) A semi-permeable membrane **b)** The presence of ATP

c) Equal concentration of solutes on both sides of the membrane

d) Movement of solutes down its electrochemical gradient

2. Which of the following features do prokaryotes and eukaryotes have in common?

a.	nucleus	plasma membrane	ribosomes
b.	mitochondria	cytoplasm	plasma membrane
c.	ribosomes	plasma membrane	cytoplasm
d.	ribosomes	nucleus	plasma membrane

3. A particular cell has a nucleus and lysosome in addition to the fundamental structures required by all cells. Based on this information, this cell could be ____.

a) a bacterium **b)** a cell from a pine tree
c) a cell from the intestinal lining of a cow **d)** A blue-green algae

4.Which of the following structures is not a component of the cell membrane?

a) Phospholipids Bilayer **b)** Ribosomes
c) Cholesterol **d)** Glycoproteins

5. Centrioles are most closely associated with:

a) Cellular respiration **b)** Cell division
c) Protein synthesis **d)** Lipid metabolism

6.The number of nuclei in a typical eukaryotic cell is:

a) One **b)** Two
c) Multiple **d)** None

7.Which of the following statements is FALSE with respect to eukaryotic cells?

a) Eukaryotic cells have membrane-bound organelles.
b) Eukaryotic cells have genetic material in a defined nucleus.
c) Eukaryotic cells only use sexual reproduction.
d) Eukaryotic cells have a cytoskeleton for support and movement.

8.Which of the following groups is primarily involved in synthesizing molecules needed by the cell?

a) lysosome, vacuole, ribosome **b)** vacuole, RER, SER
c) RER, lysosome, vacuole **d)** ribosome, RER, SER

9.Which of the following categories best describes the function of the rough endoplasmic reticulum?

a) Energy production **b)** Protein synthesis
c) Lipid metabolism **d)** Waste elimination

10. A cell with an extensive Golgi apparatus is likely to ____?

a) move rapidly **b)** secrete large amounts of protein
c) make large amounts of ATP **d)** absorb nutrients in the GI tract

Restricted Response Questions

1. Write differences between Prokaryotic and eukaryotic cell
2. Compare the roles of rough and smooth endoplasmic reticulum in cellular metabolism and processing.
3. How do stem cells contribute to tissue regeneration?
4. Name a cell in which you would expect to find a large number of lysosomes and why.
5. What features of cells are observed by electron microscopy that are not visible by light microscopy?
6. Give a comparative account of light microscopy and electron microscopy.
7. Define the term peroxisome and glyoxysomes.
8. What are the characteristic structural features of mitochondria that aid in their identification?
9. Compare the functions of mitochondria and chloroplast.
10. How many types of RNA are found in the nucleus?

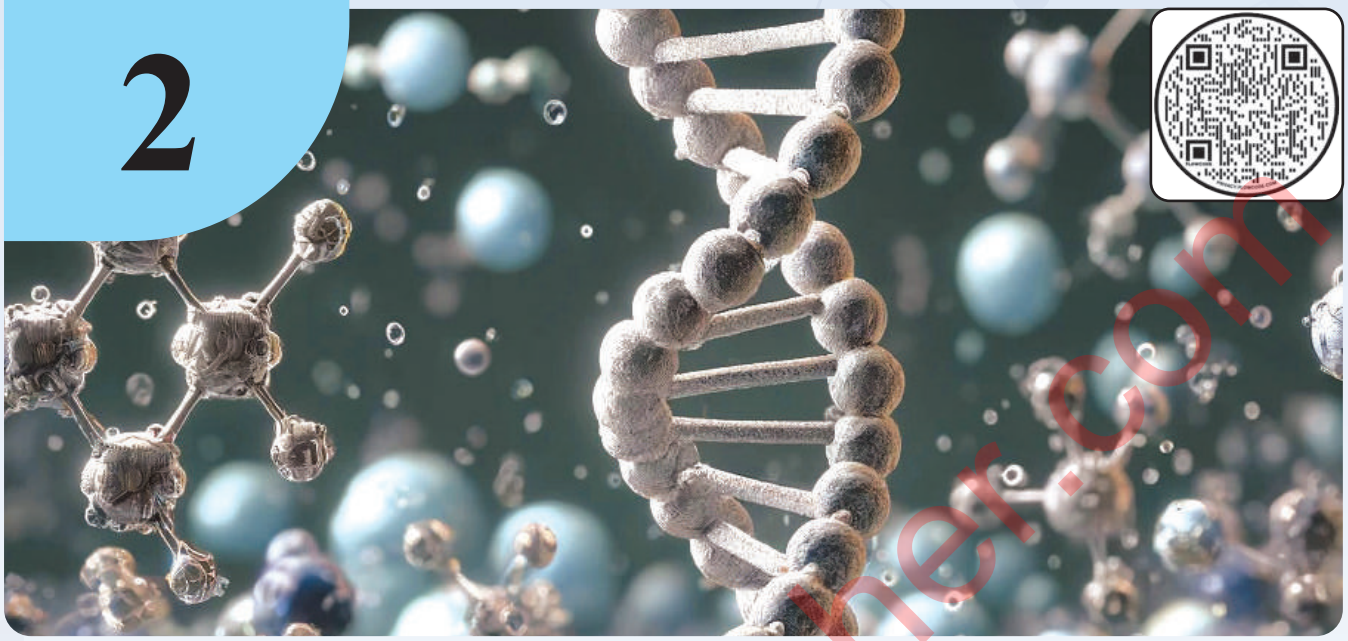
Extended Questions

1. Outline the sequence of events that must take place for a protein to be manufactured and then secreted from the cell.
2. What are the characteristics of active transport? Give the types of active transport.
3. What steps are involved in the signalling pathway of cells?
4. Describe the differences between embryonic, adult, and induced pluripotent stem cells.
5. Elaborate on the various stages of the Prophase I of meiosis.

CHAPTER

2

Biological Molecules



2.1 Knowledge

Introduction to Biochemistry

Student Learning Outcomes

SLO:B-11-C-01: *Define biochemistry/molecular biology*

2.2 Knowledge

Different types of Bonds and Interactions in Biology

Student Learning Outcomes

SLO:B-11-C-02: *Describe Briefly the different types of bonds found in biology (hydrogen bonds, covalent bonds, interactions, Ionic, hydrophobic and hydrophilic interactions etc)*

2.3 Knowledge

Biological Molecules in Protoplasm

Student Learning Outcomes

SLO:B-11-C-03: *Distinguish carbohydrates, proteins, lipids and nucleic acids as the four fundamental kinds of biological molecules.*

2.4 Knowledge

Condensation and Hydrolysis

Student Learning Outcomes

SLO:B-11-C-04: *Describe and draw sketches of the condensation-synthesis and hydrolysis reactions for the making and breaking of macromolecule polymers.*

2.5 Knowledge

Water as a Medium of Life

Student Learning Outcomes

SLO:B-11-C-05: *State the properties of water (high polarity, hydrogen bonding, high specific heat, high heat of vaporization, cohesion, hydrophobic exclusion, ionization and lower density of ice) allow it to be the medium of life.*

2.6 Knowledge

Carbohydrates

Student Learning Outcomes

SLO:B-11-C-06: *Define carbohydrates and classify them.*

SLO:B-11-C-07: *Compare and contrast the properties and roles of monosaccharides and write their formula.*

SLO:B-11-C-08: *Compare the isomers and stereoisomers of glucose.*

SLO:B-11-C-09: *Distinguish the properties and roles of disaccharides.*

SLO:B-11-C-10: *Describe glycosidic bonds in disaccharides.*

SLO:B-11-C-11: *Describe the structure properties and roles of polysaccharides starch, glycogen, cellulose and chitin.*

2.7 Knowledge

Proteins

Student Learning Outcomes

SLO:B-11-C-12: *Define protein, amino acid and*

recognized essential amino acid and structural formula of amino acid.
SLO:B-11-C-13: *Outline the synthesis and breakage of peptide linkages.*
SLO:B-11-C-14: *Justify the significance of the sequence of amino acids through the example of sickle cell hemoglobin.*
SLO:B-11-C-15: *Classify proteins as globular and fibrous proteins.*
SLO:B-11-C-16: *List the roles of structural proteins and functional proteins with 3 examples*

2.8 Knowledge

Lipids

Student Learning Outcomes

SLO:B-11-C-17: *Define lipids*
SLO:B-11-C-18: *Describe the properties and roles of acylglycerols, phospholipids, terpenes and waxes.*
SLO:B-11-C-19: *Illustrate the molecular structure (making and breaking) of an acylglycerol, a phospholipid and a terpene.*
SLO:B-11-C-20: *Evaluate steroids and prostaglandins as important groups of lipids*

2.9 Knowledge

Nucleic Acids

Student Learning Outcomes

SLO:B-11-C-21: *Describe nucleic acids and molecular structure of nucleotides.*
SLO:B-11-C-22: *Distinguish among the nitrogenous bases found in the nucleotides of nucleic acids.*
SLO:B-11-C-23: *Outline the examples of a mononucleotide (ATP) and a dinucleotide (NAD).*
SLO:B-11-C-24: *Illustrate the formation of phosphodiester bond.*
SLO:B-11-C-25: *Explain the double helical structure of DNA as proposed by Watson and Crick.*
SLO:B-11-C-26: *Explain the general structure of RNA.*
SLO:B-11-C-27: *Distinguish in terms of functions and roles, the three types of RNA.*

2.10 Knowledge

Central Dogma

Student Learning Outcomes

SLO:B-11-C-28: *Discuss the Central Dogma.*

2.11 Knowledge

Conjugated Molecules

Student Learning Outcomes

SLO:B-11-C-29: *Define conjugated molecules and describe the roles of common conjugated molecules i.e. glycolipids, glycoproteins, lipoproteins and nucleoproteins.*

"Let's embark on an exciting journey through the Student Learning Outcomes (SLOs) outlined in the curriculum. These SLOs serve as your roadmap to mastering essential knowledge and honing core skills. To make your learning experience seamless and interactive, you'll find QR codes embedded within the main text. These codes provide instant access to test skills, skill sheets, and worksheets, all thoughtfully designed to help you apply what you've learned effectively."

Introduction

Biological molecules, or biomolecules, are essential organic compounds that form the structure, function, and regulation of all living organisms. This chapter explores the four key classes of biomolecules—carbohydrates, proteins, lipids, and nucleic acids—highlighting their roles in life processes. We will examine the types of bonds that hold these molecules together and the processes of condensation synthesis and hydrolysis that build and break down macromolecules. Water, with its unique properties, such as high polarity, cohesion, and the ability to form hydrogen bonds, makes it indispensable for biological functions. We will explore how water's properties enable it to support life at the molecular level. By the end of this chapter, you will understand the fundamental biological molecules that underpin all biological functions.

2.1 Knowledge

Introduction to Biochemistry

Biochemistry is a branch of biology that explores the chemical processes and substances that occur within living organisms. By combining biology and chemistry, biochemistry seeks to understand and describe how biological molecules contribute to the processes that occur within living cells and between cells, which in turn influences the function and growth of the organism. A basic knowledge of biochemistry is essential for understanding various life processes like photosynthesis, respiration, digestion, muscle contraction, etc.

Molecular biology is the branch of biochemistry that covers the study of the molecular mechanisms by which genetic information encoded in DNA leads to the processes essential for life. Central to this is the synthesis of proteins from this genetic code, a process that involves transcription and translation.

Skill:2.1

Objective:

- Ability to accurately define and explain the fundamental concepts and importance of biochemistry and molecular biology.

Test Yourself

Short answer-based questions

1. What is biochemistry and why is it important?
2. How does molecular biology relate to biochemistry?

2.2 Knowledge

Different types of Bonds and Interactions in Biology

In biology, different types of bonds and interactions are formed between atoms and molecules, which are essential for the structure and function of biological molecules.

Covalent Bonds

These are strong bonds formed when two atoms mutually share one or more electrons. They are very stable and require a significant amount of energy to break. Covalent bonds are fundamental in biology, forming the backbone of molecules like DNA and proteins. In DNA, covalent bonds form the sugar-phosphate backbone in the form of phosphodiester linkages between nucleotides.

In proteins, covalent bonds are primarily represented by peptide bonds formed during protein synthesis by linking the carboxyl group of one amino acid to the amino group of another, creating a backbone for the polypeptide chain (see Figure 2.1).

Ionic Bonds

An **ionic bond** is the type of chemical bond that results from the electrical attraction between two ions with opposite charges. These bonds form when one atom donates electrons to another, leading to the creation of positively charged **cations** and negatively charged **anions**. The electrostatic attraction between these oppositely charged ions holds them together in a stable compound. In biological systems, ionic bonds are often found in different salts, between oppositely charged side chains of amino acids to stabilize the tertiary and quaternary structures of proteins, metal ions and enzymes and between enzyme and substrate.

Hydrogen bonds

Hydrogen bonding is a type of intermolecular force that occurs when a hydrogen atom, which is covalently bonded to a highly electronegative atom such as nitrogen, oxygen or fluorine, attracts another electronegative atom from a different molecule that has a lone pair of electrons. This attraction links the atoms of two different molecules or atoms of the same molecule, thus significantly influencing the properties and behaviours of various molecules.

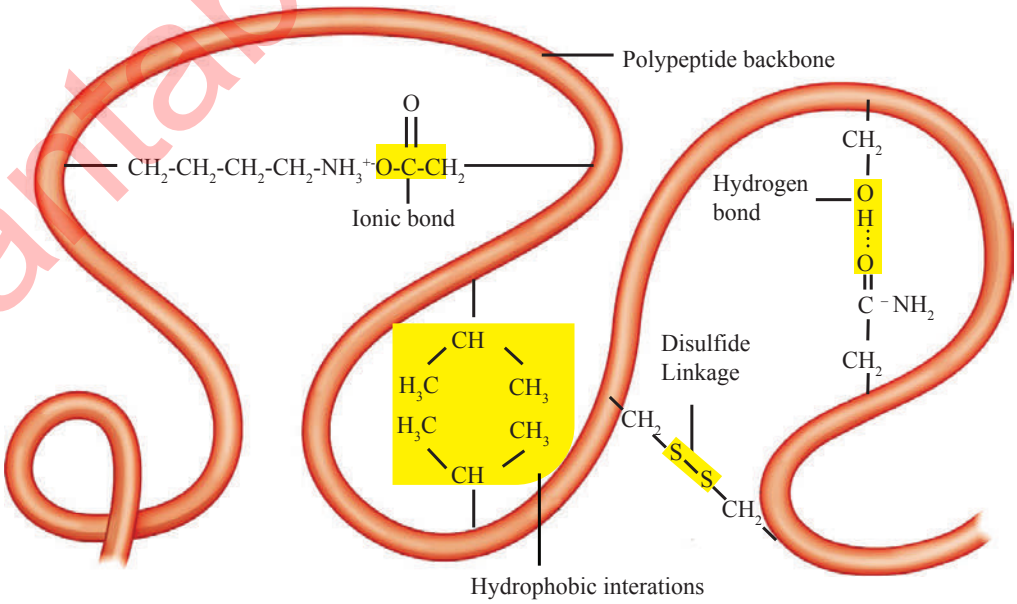


Figure 2.1: Structure of a Polypeptide, showing various types of bonding and interactions.

Hydrogen bonds, while weaker compared to ionic and covalent bonds, are still strong enough to stabilize the characteristic structures of large biological molecules such as DNA. In DNA, the two strands of the double helix are connected by hydrogen bonds between specific complementary bases on each strand. In proteins, hydrogen bonds help stabilize the tertiary structure critical for the protein's function. These bonds can form between amino acid side chains, maintaining the structure necessary for the protein to work effectively.

Hydrophobic Interactions

Hydrophobic interactions play a critical role in the structure and function of biological molecules, especially in the organization of biological membranes and the folding of proteins. These interactions are not true bonds in the chemical sense but are significant forces that influence how molecules arrange themselves in aqueous environments.

Hydrophobic interactions occur between nonpolar molecules or nonpolar regions of molecules, which tend to aggregate in aqueous (water-containing) environments to minimize their exposure to water. The term "hydrophobic" means "**water-fearing**," indicating how these nonpolar substances behave in water.

Hydrophobic interactions are pivotal in biological structures, particularly in protein folding and the formation of cell membranes. In protein folding, nonpolar amino acids within a protein tend to cluster internally, away from the aqueous environment, driving the protein to fold into its functional three-dimensional shape. This is essential for establishing the protein's tertiary structure. Similarly, in cell membranes, which are composed mainly of phospholipids with hydrophilic heads and hydrophobic tails, the hydrophobic tails orient themselves inward, forming a bilayer that effectively acts as a barrier to most polar substances (see Figure 2.2).

This bilayer structure is stabilized by hydrophobic interactions among the fatty acid tails, ensuring the integrity and functionality of the membrane.

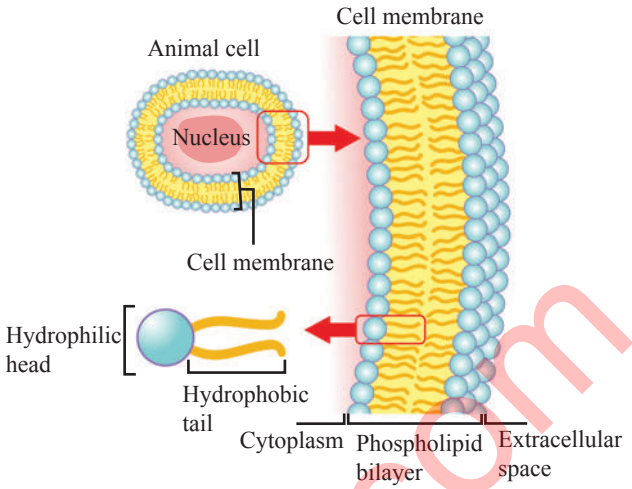


Figure 2.2: The orientation of hydrophobic tails in aqueousenvironment

Hydrophilic Interactions

The term "hydrophilic" means "**water-loving**," indicating the affinity these molecules or parts of molecules have for water. These interactions are crucial for the solubility, stability, and activity of many biomolecules in aqueous environments, such as within cells or bodily fluids.

Hydrophilic interactions occur primarily due to the polar nature of the interacting groups. These groups can form hydrogen bonds with water molecules, facilitating solubility and interaction with other polar substances. Common hydrophilic groups include hydroxyl (-OH), carbonyl (>C=O), carboxyl (-COOH), amino ($-NH_2$), and phosphate ($-PO_4$) groups.

In proteins, hydrophilic interactions are critical for proper protein functionality and the maintenance of its secondary, tertiary, and quaternary structures (see Figure 2.3). For cell membranes, the hydrophilic heads of phospholipids interact with the internal and external aqueous environments, stabilizing the membrane structure and facilitating interactions with water-soluble molecules and ions. In the case of nucleic acids like DNA and RNA, the negatively charged, hydrophilic phosphate backbone allows these molecules to interact effectively with the cellular aqueous environment, which is essential for vital processes such as transcription and replication, where enzyme and substrate solubility are required.

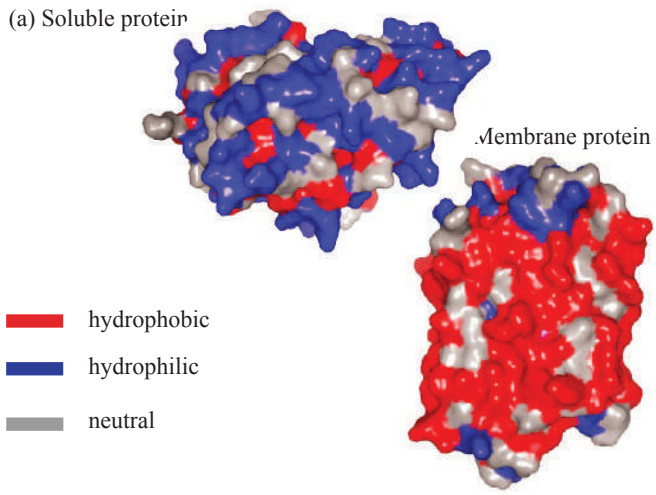


Figure 2.3: The orientation of hydrophobic and hydrophilic side chains of amino acids in soluble protein and membrane protein.

Enzymatic reactions often occur in aqueous solutions and the hydrophilic nature of substrates and enzymes facilitates these reactions by improving solubility and interaction rates. Similarly, many signalling molecules and their receptors are hydrophilic, which allows them to operate in the extracellular fluid or cytosol effectively. These interactions are essential for the recognition and binding of hormones, neurotransmitters, and other signalling molecules.

Skill:2.2

Objective:

- Ability to describe and illustrate the different types of chemical bonds and their roles in biological structures and functions.

Test Yourself

Short answer-based questions

1. What is a covalent bond, and why is it significant in biology?
2. What is a hydrogen bond and its significance in biological molecules?
3. How do hydrophilic and hydrophobic interactions differ?

Long Question

1. Elaborate on the different types of bonds essential for biological molecules and their importance.

2.3 Knowledge

Biological Molecules in Protoplasm

The molecules which are found in living organisms are called bio-molecules or biological molecules. Biomolecules contain mainly carbon with other important bioelements like H, O, N, P and S. Carbonin biomolecules behaves in the same manner as in other organic compounds, i.e. forming four bonds, usually with a tetrahedral arrangement and forming carbon-carbon long chains, which may be linear, branched, cyclic, or aromatic (see Figure 2.4).

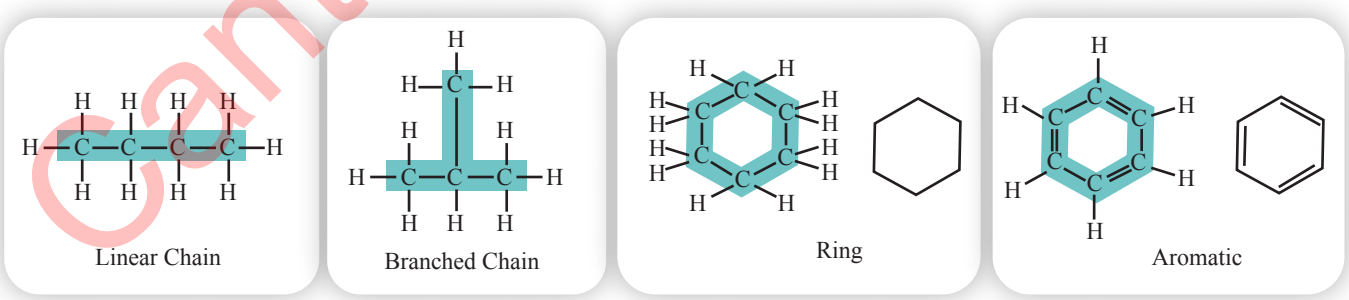


Figure 2.4: Linear, branched, ring, and aromatic structures formed by C-C bonds

The following are the major types of biological molecules:

i.Carbohydrates: They are the compounds made up of carbon, hydrogen and oxygen. They provide energy for various metabolic activities of the cells.

ii. Proteins: They are chemically composed of carbon, hydrogen, oxygen and nitrogen. They are the building

blocks of the cell. Proteins are essential for various cell structures like membranes, ribosomes, enzymes, cytoskeletons, etc.

iii. Lipids: They are present in cell membranes. These are the source of reserved energy and provide shape and protection to the cell.

iv. Nucleic Acid: They are called molecules of heredity. Nucleic acids are of two types. DNA (Deoxyribonucleic acid) and RNA (Ribonucleic acid). DNA is found mainly in the chromosomes, whereas most of the RNA is present in the cell cytoplasm and a little in the nucleus.

Skill:2.3

- **Objective:** Skill in distinguishing and categorizing each type of biological molecule based on their structure and function.

Test Yourself

Short answer-based questions

1. List the main elements that makeup biomolecules.
2. Describe how carbon behaves in biomolecules regarding its bonding.

2.4 Knowledge

Condensation and Hydrolysis

Condensation (Dehydration synthesis)

It is the process in which two or more small units combine together to form a large molecule releasing water. It is also called dehydration synthesis because it involves the removal of water and results in the synthesis of new molecules. The large molecule is called a **polymer** (macromolecule), while the individual units are called **monomers**. It is the basis for the synthesis of all the important biological molecules (carbohydrates, proteins, lipids and nucleic acids). During condensation, when two monomers join, a hydroxyl (OH^-) group is removed from one monomer and hydrogen (H^+) is removed from the other; for example, two glucose units condense together to form a dimer, maltose, releasing water (see Figure 2.5). This dimer formation is a fundamental step toward creating larger polymers, as additional monomers can continuously join through similar reactions, progressively building up complex structures.

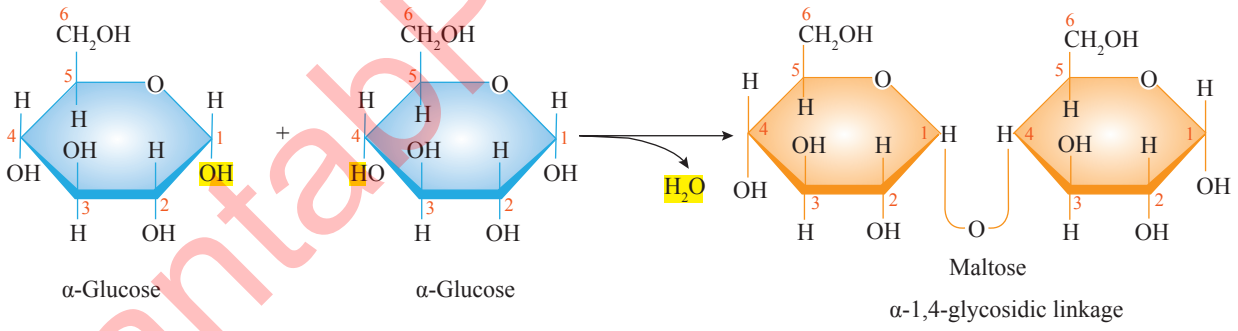


Figure 2.5: Condensation reaction between two glucose units to form maltose

Hydrolysis

It is the process in which a large molecule is broken down into smaller units involving the addition of water. It is the reverse of condensation. During hydrolysis, hydrogen (H^+) and hydroxyl (OH^-) groups from water are added to different monomers. Hydrolysis plays a vital role in various biological processes, including digestion, where it helps in breaking down complex molecules into simpler forms that cells can absorb and use. For example, maltose on hydrolysis gives rise to two glucose units (see Figure 2.6).

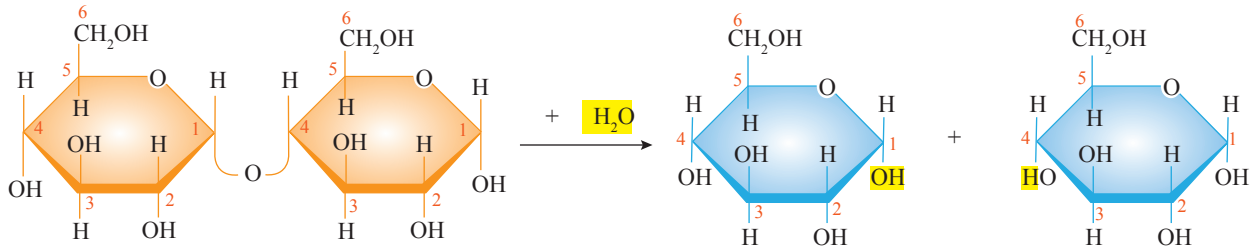


Figure 2.6: Hydrolysis of Maltose yields two glucose units

Skill:2.4

- **Objective:** Ability to describe and sketch condensation and hydrolysis reactions, demonstrating the formation and breakage of macromolecular bonds.

Test Yourself

Short answer-based questions

1. What is condensation, and why is it also called dehydration synthesis?
2. Provide an example of a molecule undergoing hydrolysis and the resulting products.

2.5 Knowledge

Water as a Medium of Life

Water is a crucial component of all living organisms, typically constituting about 70–90% of their total weight. In humans, the brain and heart are composed of 73% water, and the lungs are about 83% water. The skin contains 64% water, muscles and kidneys are 79%, and even the bones are 31% watery (H.H. Mitchell, Journal of Biological Chemistry). Water is the medium of life and is an essential requirement, as no life can exist without it. The physical and chemical properties of water make it an ideal medium for supporting life activities. Some of the key properties of water are as follows:

High polarity

Water is often called the universal solvent because of its highly polar nature. The oxygen atom in a water molecule is more electronegative than hydrogen, causing the shared electrons to be more attracted to oxygen. This creates partial positive and negative charges, making water molecules highly polar (see Figure 2.7). This polarity allows water molecules to attract and surround various solute particles, effectively separating and dissolving them. This high polarity makes water an excellent solvent, allowing many substances to dissolve and ionize, which then participate in reactions (metabolism). Without the dissolving power of water, aquatic organisms could not take up the substances they need from the water.

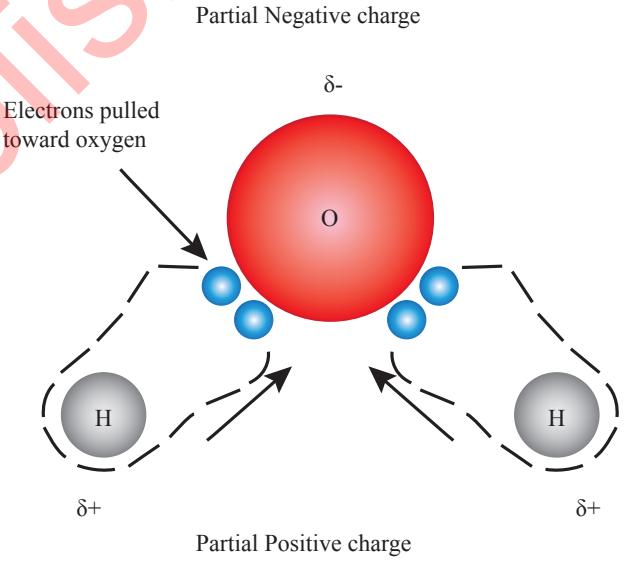


Figure 2.7: Polar nature of water molecule

Hydrogen bonding

Because of the polar nature of water molecules, the oxygen atom and a hydrogen atom on neighbouring water molecules attract each other. This results in the formation of a weak bond, which is called a **hydrogen bond,** represented by the dotted line (see Figure 2.8). Hydrogen bonding is responsible for many of the unusual properties of water that are essential for life, such a stronger cohesive and adhesive forces.

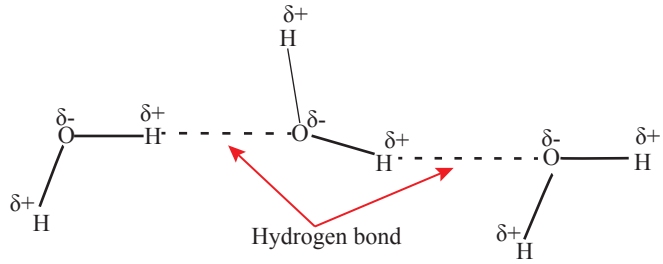


Figure 2.8: Schematic structure of water molecules, indicating the hydrogen bonding between water molecules

Cohesion and Adhesion

Water molecules attract each other due to relatively strong hydrogen bonding. As a result, water exhibits high **cohesion**, meaning the molecules tend to stick closely together. A related property of water is **adhesion**, the tendency to form hydrogen bonds with other polar substances. This ability allows water to stick to various surfaces, creating a thin film. Together, cohesion and adhesion make water an excellent transport medium, both outside and within living organisms (see Figure 2.9).

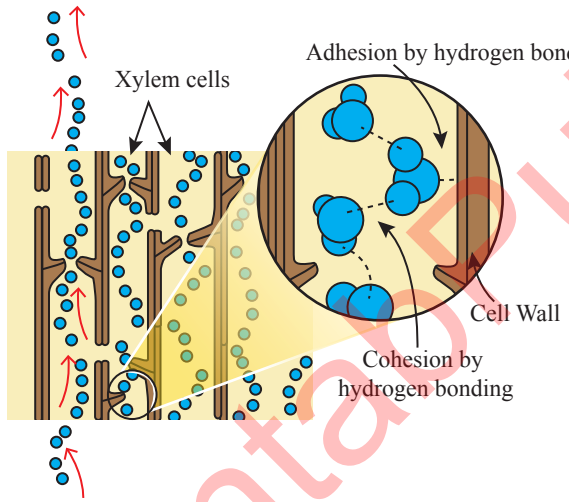


Figure 2.9: Water transport in plant xylem due to adhesion and cohesion of water molecules.

High specific heat capacity

The specific heat capacity of water is the amount of heat required to raise the temperature of one gram of water by 1°C. The specific heat of water is 4.184 J/g°C, higher than all other substances except liquid ammonia. This means that water maintains a large amount of heat with a relatively small increase in its temperature. Water has a high heat capacity due to its ability to form hydrogen bonds. These bonds are relatively strong and require significant energy to break. This property of water is important for all living organisms as water protects them from rapid thermal change and helps them maintain their normal internal body temperature by acting as **temperature stabilizer.**

High heat of vapourization

The heat of vapourization of water is the energy required to convert one gram of liquid water to its gaseous form. The **heat of vapourization** of water is approximately 574 Cal/g. Evaporation from the moist surface of organisms causes cooling. This is the reason when sweat is vapourized by the body heat, the surface becomes cool. Such heat loss in the form of sweating and transpiration (in plants) is important in regulating body temperature.

Hydrophobic exclusion

Hydrophobic exclusion, or the **"hydrophobic effect",** describes how water interacts with non-polar substances. When non-polar substances that cannot form hydrogen bonds are introduced into water, water molecules orient to maximize hydrogen bonding among themselves. Consequently, non-polar molecules are excluded and pushed together. This leads to phenomena like **micelle** formation, where hydrophobic tails cluster away from water (see Figure 2.10), or protein folding, where hydrophobic side chains are buried away from the water-rich environment.

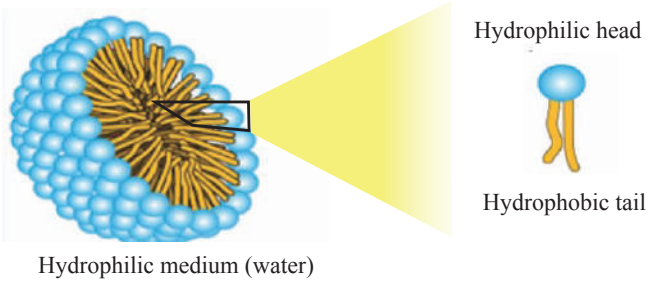


Figure 2.10: Hydrophobic exclusion of lipid molecules

Ionization

Water ionizes into hydrogen (H^+) and hydroxide (OH^-) ions according to the given reversible reaction:

$$H\text{–}O\text{–}H \longrightarrow H^+ + OH^-$$

At 25°C, this process maintains a state of equilibrium. The H^+ and OH^- ions play crucial roles in numerous cellular reactions, such as facilitating enzymatic activities and participating in metabolic

pathways. Additionally, the ionization of water is important in regulating the pH levels of various mediums.

Lower density of ice: Water exhibits anomalous behaviour at lower temperatures. It expands upon freezing. During freezing, water molecules align themselves into a hexagonal crystalline structure, causing ice to be less dense compared to liquid water. In colder temperatures, a thin layer of water freezes at the surface of a pond, creating a layer of ice that acts as an insulator, preventing the water below from freezing (see Figure 2.11). It allows aquatic organisms to survive in winter. If ice became denser upon freezing, it would sink to the bottom, causing the lake to freeze from the bottom up, trapping the organisms that reside there.

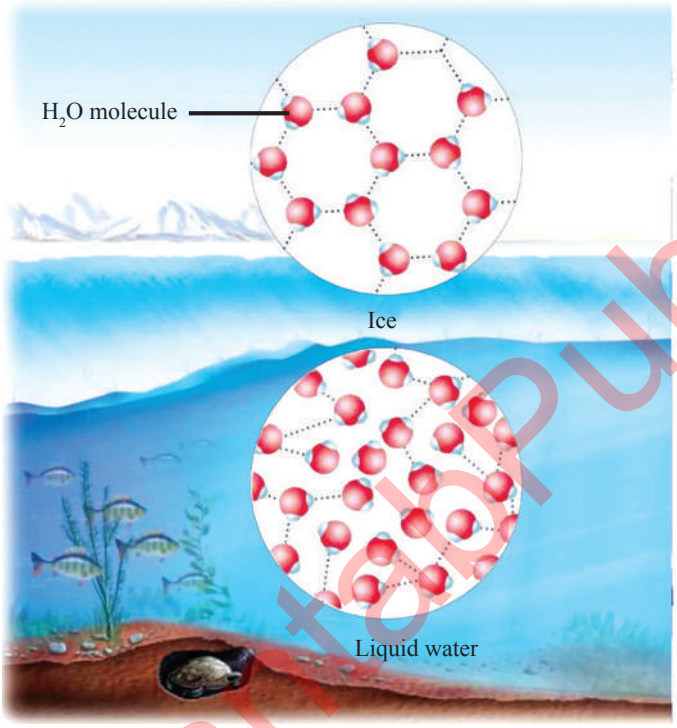


Figure 2.11: Arrangement of water molecules in ice and liquid water.

Skill:2.5

- **Objective:** Ability to state and explain how properties like high polarity, hydrogen bonding, high specific heat, high heat of vaporization, cohesion, hydrophobic exclusion, ionization and lower density of ice contribute to water's role as the medium of life.

Test Yourself

Short answer-based questions

1. Why is water's high specific heat important for living organisms?
2. How does the high polarity of water molecules contribute to their ability to
3. dissolve various substances?
   How does the lower density of ice affect aquatic life?

Long answer-based questions

1. Discuss the multifaceted role of water in biological systems.

2.6 Knowledge

Carbohydrates

Carbohydrates are among the most abundant biomolecules on Earth and are central to the nutrition and energy systems of living organisms. Composed of carbon, hydrogen, and oxygen, carbohydrates are commonly referred to by the general formula $C_x(H_2O)_y$, where "x" is a whole number from three to many thousand, while "y" may be the same or a different whole number. The general formula suggested that these are the compounds of carbon with hydrogen and oxygen in the same elemental ratio as in the water. This is the reason they are called hydrated carbons. Chemically, carbohydrates are defined as polyhydroxy aldehydes or polyhydroxy ketones or their derivatives or complex substances that yield these substances on hydrolysis.

Classification of carbohydrates

Carbohydrates, which include sugars and polymers of sugars, are generally classified into three groups.

i. Monosaccharides

Monosaccharides (Greek mono, single, sacchar, sugar) are the simplest form of carbohydrates, consisting of a single sugar molecule. They cannot be hydrolyzed into simpler units. They serve as monomers or building blocks of more complex carbohydrates, such as disaccharides and polysaccharides. They have a general formula $(CH_2O)_n$, where n refers to the whole number. In

monosaccharides number of carbon atoms ranges from 3 to 7. The monosaccharides with the aldehyde group are called aldoses, and those containing ketone group are known as ketoses (see Figure 2.12).

Classification: The monosaccharides are classified into trioses (3C), tetroses (4C), pentoses(5C), hexoses (6C) and heptoses (7C) depending upon the number of carbon atoms they possess. The following figure illustrates the structure of various monosaccharides.

Molecules of pentoses, hexoses and heptoses assume ring form when dissolved in water. If the ring is five-cornered, it is called **furanose,** and if it is six-cornered, then it is called **pyranose.** For example, glucose forms a six-cornered ring, known as glucopyranose, while fructose forms a five-cornered ring, called fructofuranose (see Figure 2.13).

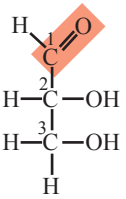
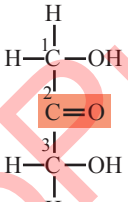
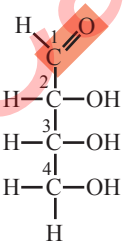
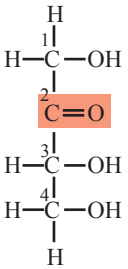
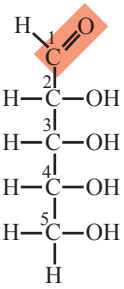
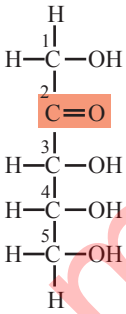
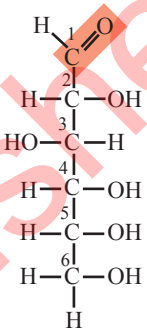
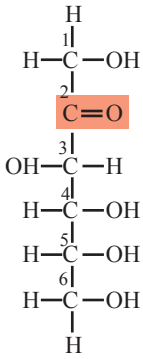
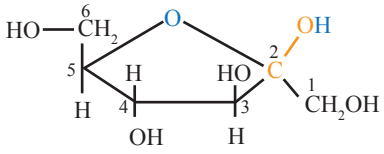
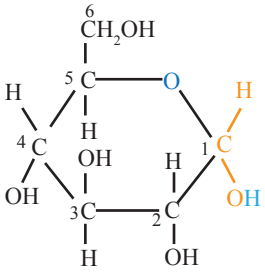
Aldoses (Aldehyde Sugars) Carbonyl group at end of carbon skeleton	**Ketoses (Ketone Sugars)** Carbonyl group within carbon skeleton
Trioses: three-carbon sugars ($C_3H_6O_3$)	
 **Glyceraldehyde** An intermediate of glucose breakdown	 **Dihydroxyacetone** An intermediate of glucose breakdown
Tetroses: four-carbon sugars ($C_4H_8O_4$)	
 **Erythrose** An intermediate in photosynthesis	 **Erythrulose** An intermediate in bacterial photosynthesis
Pentoses: five-carbon sugars ($C_5H_{10}O_5$)	
 **Ribose** A component of RNA	 **Ribulose** An intermediate in photosynthesis
Hexoses: six-carbon sugars ($C_6H_{12}O_6$)	
 **Glucose** Energy sources for organisms	 **Fructose** An energy source for organisms

Figure 2.12: Structure of various monosaccharides.



D-Fructofuranose



D-Glucopyranose

Figure 2.13: Structures of glucopyranose and fructofuranose.

Properties of monosaccharides:

- Monosaccharides are generally highly soluble in water due to their multiple hydroxyl groups that can form hydrogen bonds with water molecules.
- They are sweet in taste, with fructose being the sweetest natural sugar, much sweeter than glucose and galactose.
- At room temperature, most monosaccharides are crystalline solids.
- Most monosaccharides are reducing sugars, meaning they can act as reducing agents due to the free aldehyde or ketone group. This property is used in biochemical tests like Benedict's test for reducing sugars.
- Monosaccharides exhibit isomerism, where compounds with the same chemical formula differ structurally. This includes optical isomerism due to asymmetric carbon atoms, leading to multiple stereoisomers.

Role of monosacccharides: Monosaccharides have two major functions. First, they are mainly used as a source of energy in respiration. This is due to a large number of carbon-hydrogen bonds. These bonds can be broken to release a lot of energy, which is transferred to help make ATP (adenosine triphosphate) from ADP (adenosine diphosphate) and phosphate. The most important monosaccharide in energy metabolism is glucose.

Secondly, monosaccharides are important as building blocks for larger molecules. For example, glucose is a precursor to the formation of starch, glycogen, and cellulose. In addition, ribose (a pentose) is used in the formation of RNA (ribonucleic acid). Deoxyribose (also a pentose) is one of the building blocks of DNA.

Isomerism in Glucose

Isomers are compounds that have the same chemical formula but differ in the structure of their molecules. There are two main types of isomers: structural isomers and stereoisomers.

Structural isomers: Structural isomers are molecules that have the same molecular formula but differ in the way their atoms are arranged within the molecule. For example, glucose and fructose have the same molecular formula ($C_6H_{12}O_6$) but different structures. Glucose is an aldose, meaning it has an aldehyde group (-CHO) at one end of the carbon chain. Fructose is a ketose, meaning it contains a ketone group (-CO) typically positioned at the second carbon atom in the chain. That is why they fall under the category of **functional group isomers** (differ in the placement of their functional groups as shown in Figure 2.14).

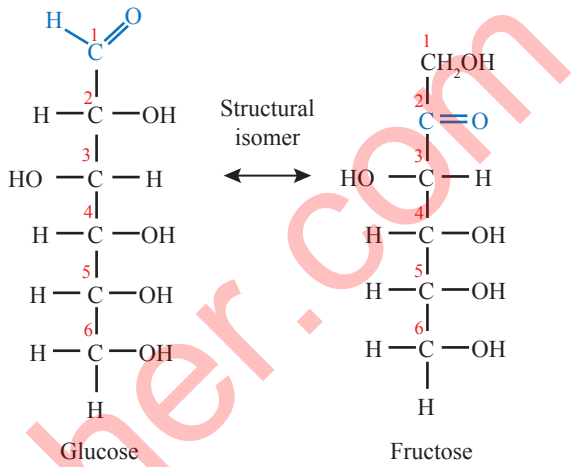


Figure 2.14: Structural isomerism between glucose and fructose.

Stereoisomers of Glucose: Stereoisomers are molecules that have the same molecular formula and sequence of bonded atoms but differ in the three-dimensional orientations of these atoms in space. In the case of glucose, its stereoisomers would differ in the spatial arrangements of hydroxyl group (OH) at the chiral carbon atoms. A **chiral/asymmetric carbon atom** is a carbon atom that is attached to four different groups or atoms, creating a molecule that is non-superimposable on its mirror image. Glucose has four chiral carbon atoms, namely C-2, C-3, C-4 and C-5. The number of stereoisomers increases exponentially with the number of chiral centers in the molecule, calculated as 2^n where n is the number of chiral carbons. It means glucose has 16 stereoisomers.

Stereoisomers are further classified into:

Enantiomers: These are mirror-image isomers. For instance, D-glucose and L-glucose are enantiomers of each other. In D-glucose, the hydroxyl group is on the right side on the penultimate (second to last) carbon (C-5) in the chain while in L-glucose, the hydroxyl group on the penultimate carbon is on the left side (see Figure 2.15).

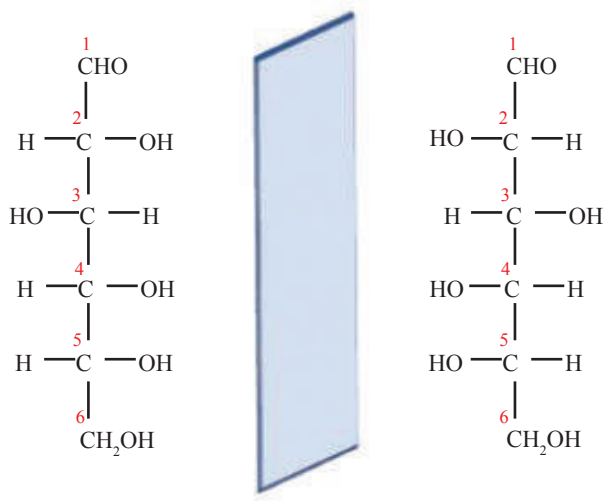


Figure 2.15: Enantiomers of glucose.

Do you Know?

D-glucose (also known as dextro glucose) is naturally occurring and metabolically active, whereas L-glucose (levo glucose) is not metabolized by humans and is synthetically produced.

Diastereomers: These are isomers that are not mirror images of each other. They differ in the configuration of the hydroxyl group at one or more but not all chiral centers. Diastereoisomers of glucose are shown in Figure 2.16.

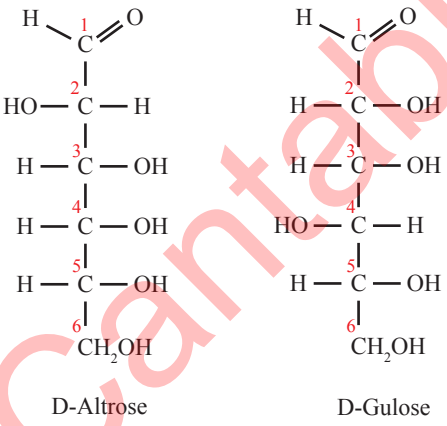


Figure 2.16: Diastereoisomers of glucose.

Epimers: These are a type of diastereoisomers that differ in the arrangement of OH group at only one chiral carbon among several. For example, D-glucose and D-mannose differ for OH group only at the C-2 position and are therefore epimers (see Figure 2.17).

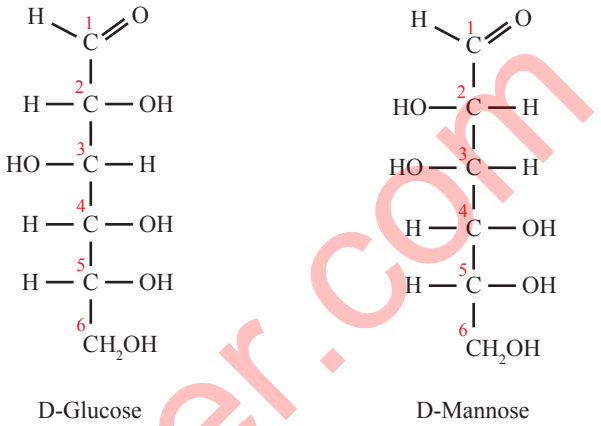


Figure 2.17: Epimers of glucose.

Anomers: These are a special case of diastereoisomers that occur when the arrangement of OH group changes around the anomeric carbon. The **anomeric carbon** is a carbon atom in a monosaccharide that becomes a new chiral center upon cyclization of the sugar from its linear form to its ring form. This carbon is originally the carbonyl carbon (either part of an aldehyde or ketone group) in the linear form of the sugar.

These configurations are termed **alpha (α)** and **beta (β)**. For glucose, α-Glucose has the OH group on C-1 below the plane of the ring, while β-Glucose has it above the plane of the ring as shown in Figure 2.18.

Knowledge Booster

Isomerization plays a crucial role in vision. The retinal molecule in our eyes undergoes isomerization when it absorbs light, triggering the visual signal to the brain.

Do you Know?

The alpha configuration has the hydroxyl group attached to the anomeric carbon trans to the CH_2OH side group (opposite side of the ring), while the beta configuration has it cis to the CH_2OH side group (same side of the ring).

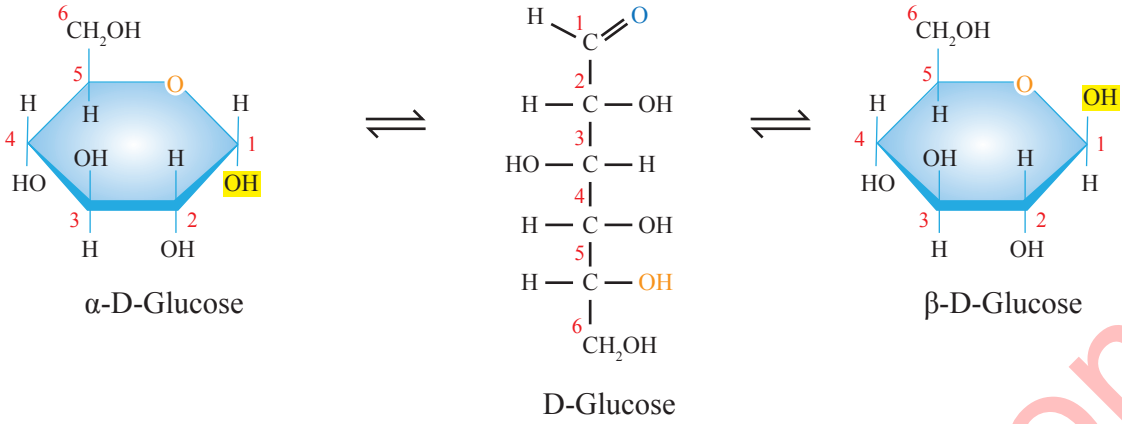


Figure 2.18: Anomers of glucose.

ii. Disaccharides

Disaccharides consist of two monosaccharide rings joined by a **glycosidic linkage;** a covalent bond between two monosaccharides. Common disaccharides such as sucrose, maltose, and lactose are derived from hexose sugars and share the general formula $C_{12}H_{22}O_{11}$. Disaccharides can be hydrolyzed into their constituent monosaccharides by specific enzymes. Compared to monosaccharides, disaccharides are less sweet and less soluble in water.

Sucrose: Sucrose, commonly known as **table sugar**, is the most abundant disaccharide and consists of glucose and fructose units. It occurs naturally in many fruits and vegetables, particularly in sugar cane and sugar beets, which are major commercial sources. Sucrose is synthesized through a condensation reaction between the anomeric carbons of **α-glucose** (C-1) and the **β-fructose** (C-2), forming an **α-1, β-2- glycosidic bond** (see Figure 2.19). This unique bond involves both anomeric carbons, thus rendering sucrose a **non-reducing sugar.**

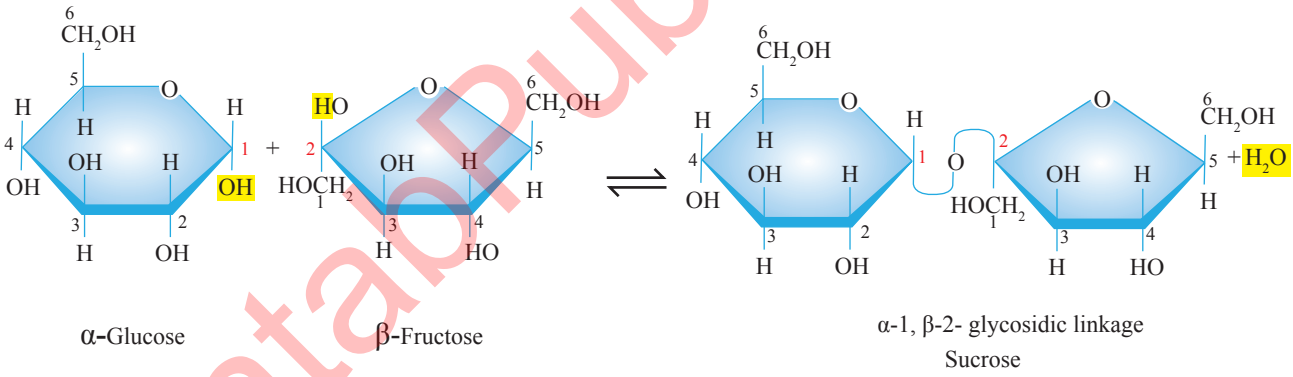


Figure 2.19: Formation of a sucrose molecule.

Sucrose is highly soluble in water, with solubility increasing at higher temperatures. Sucrose serves as the transport carbohydrate transported from leaves to other non-photosynthetic parts of plants. Additionally, sucrose is used in the fermentation industry.

Maltose: Maltose, also known as **malt sugar,** comprises two glucose units. Maltose is a breakdown product of starch and glycogen by an enzyme **amylase**, which is then converted into glucose by the action of the enzyme **maltase**. It also occurs in germinating seeds and serves as an energy source. Maltose is formed through a condensation reaction between the anomeric carbon of α-glucose (C-1) and the C-4 of the other α-glucose, resulting in a glycosidic bond known as an **α -1,4-glycosidic bond** (see Figure 2.20). The second glucose unit in maltose retains a free anomeric carbon (C-1) that is not involved in the glycosidic bond, so maltose is a **reducing sugar.**

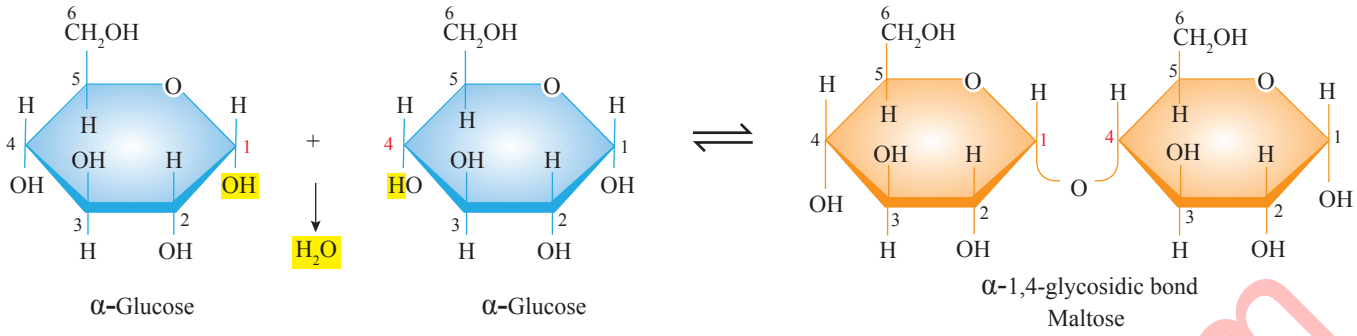


Figure 2.20: Formation of a maltose molecule.

Though less sweet than sucrose, maltose is ideal for syrups, requiring moderate sweetness and high solubility. In brewing, maltose derived from barley malt is the primary sugar fermented by yeast to produce alcohol and carbon dioxide in beer production.

Lactose: When glucose is linked to the stereoisomer galactose, the resulting disaccharide is lactose or **milk sugar.** It is found in milk and dairy products such as yogurt and cheese. Lactose is formed when the -OH group at **anomeric carbon** (C-1) of the β-galactose molecule reacts with the H of -OH at the fourth carbon (C-4) of the β-glucose molecule, creating a **β-1,4-glycosidic bond** (see Figure 2.21). Like maltose, lactose is also a **reducing sugar** because it retains an anomeric carbon of glucose unit.

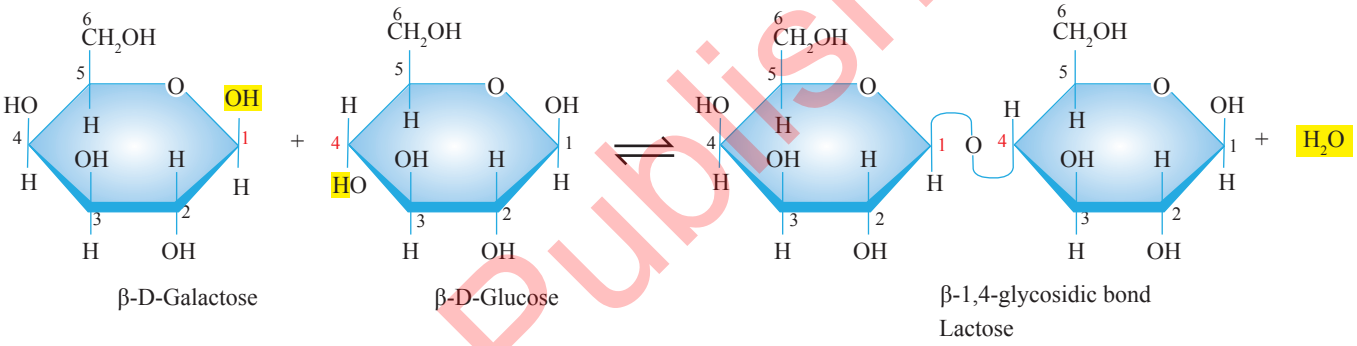


Figure 2.21: Formation of a lactose molecule.

Lactose is formed by the mammary glands and is an important source of energy for infants. It is broken down into glucose and galactose by the enzyme lactase, which is then used by the body for energy.

iii. Polysaccharides

Polysaccharides, also known as **glycans**, are complex carbohydrates composed of long chains of monosaccharide units linked by glycosidic bonds. Polysaccharides, being large and complex molecules, generally exhibit limited solubility in water, with their solubility depending significantly on their molecular structure and branching. They vary in their monosaccharide composition, chain length, and degree of branching. Polysaccharides are classified into two main types: **homopolysaccharides** e.g., starch, cellulose, which contain only one type of monosaccharide, and **heteropolysaccharides** e.g., agar, pectin, which contain two or more different types of monosaccharides repeated throughout the chain. Based on function, they are categorized into storage polysaccharides and structural polysaccharides as well.

Storage polysaccharides: Storage polysaccharides function as reserves of monosaccharides to be used as fuel. Typically, these are homopolysaccharides composed of glucose units. Examples include starch and glycogen.

Starch: Starch is a polymer of **α-D-glucose** linked by glycosidic bonds and serves as a major energy reserve in plants. Starch molecules accumulate to form visible grains in many plant cells. It is crucial in the

human diet and is found predominantly in potatoes, wheat, maize (corn), and rice. Starch gives blue colour with iodine. Starches are of two types; amylose and amylopectin.

Amylose: About 20-30% of starch, amylose is a linear polymer of α-D-glucose units connected by **α-1,4** glycosidic bonds (see Figure 2.22). It is soluble in hot water.

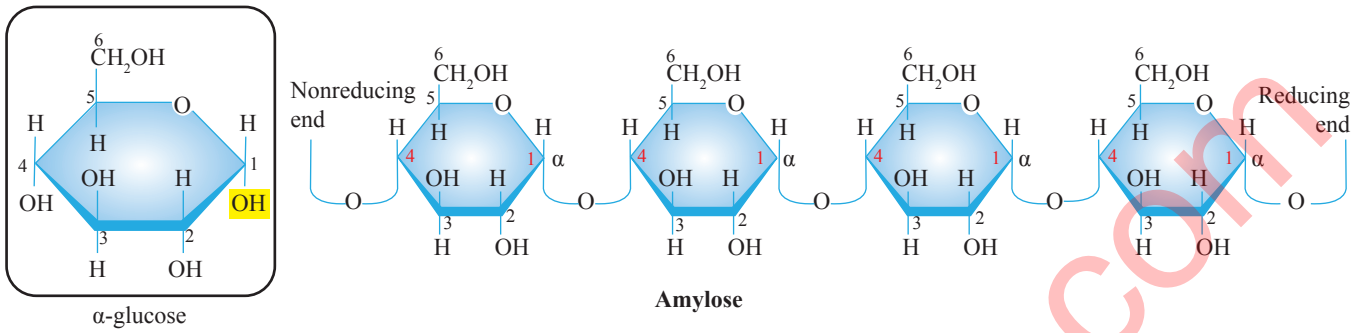


Figure 2.22: Structure of amylose.

Amylopectin: Constituting about 70-80% of starch, amylopectin is a highly branched molecule. Its branches, formed by α-1,6 glycosidic bonds, appear every 24 to 30 glucose units along the α-1,4 linked chains (see Figure 2.23). It is completely insoluble in hot or cold water.

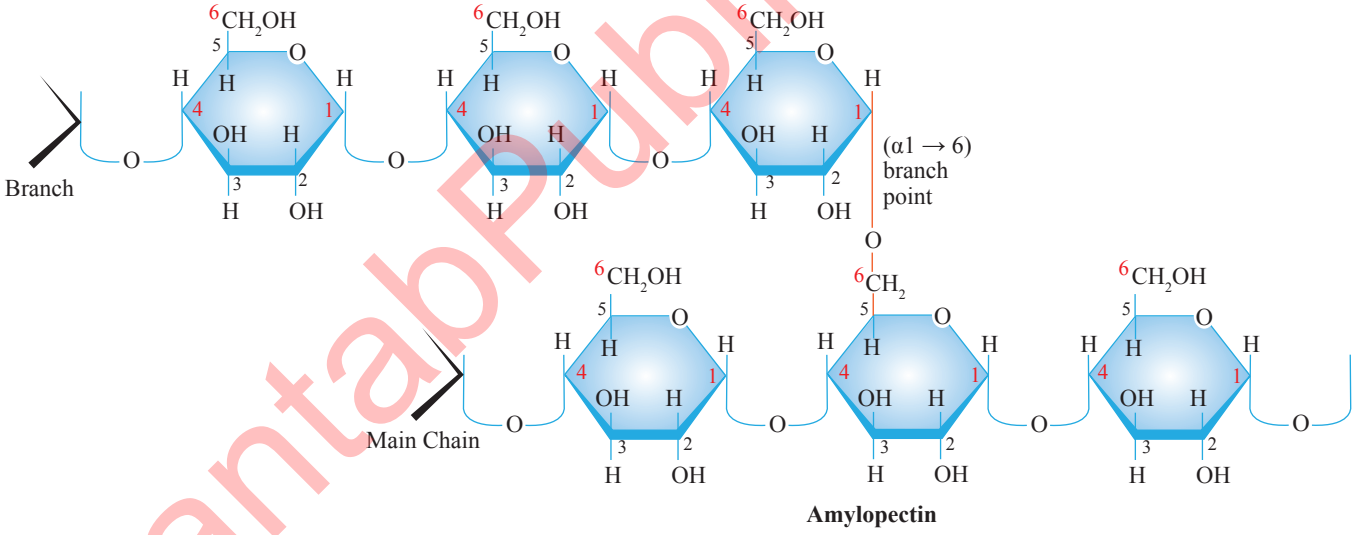


Figure 2.23: A short segment of amylopectin polymer

Both amylose and amylopectin are rapidly hydrolyzed by α-amylase, secreted by salivary glands and the pancreas, into maltose and eventually into glucose units by maltase enzyme.

Glycogen: Glycogen, also known as **animal starch**, is the main storage polysaccharide of animal cells and many fungi. Like amylopectin, glycogen is a polymer of **α-1,4** linked D-glucose units with **α-1,6** linked branches. However, it is more extensively branched (every 8 to 12 units) and more compact than starch (see Figure 2.24). Glycogen is particularly abundant in the liver and skeletal muscle and gives a red colour with iodine.

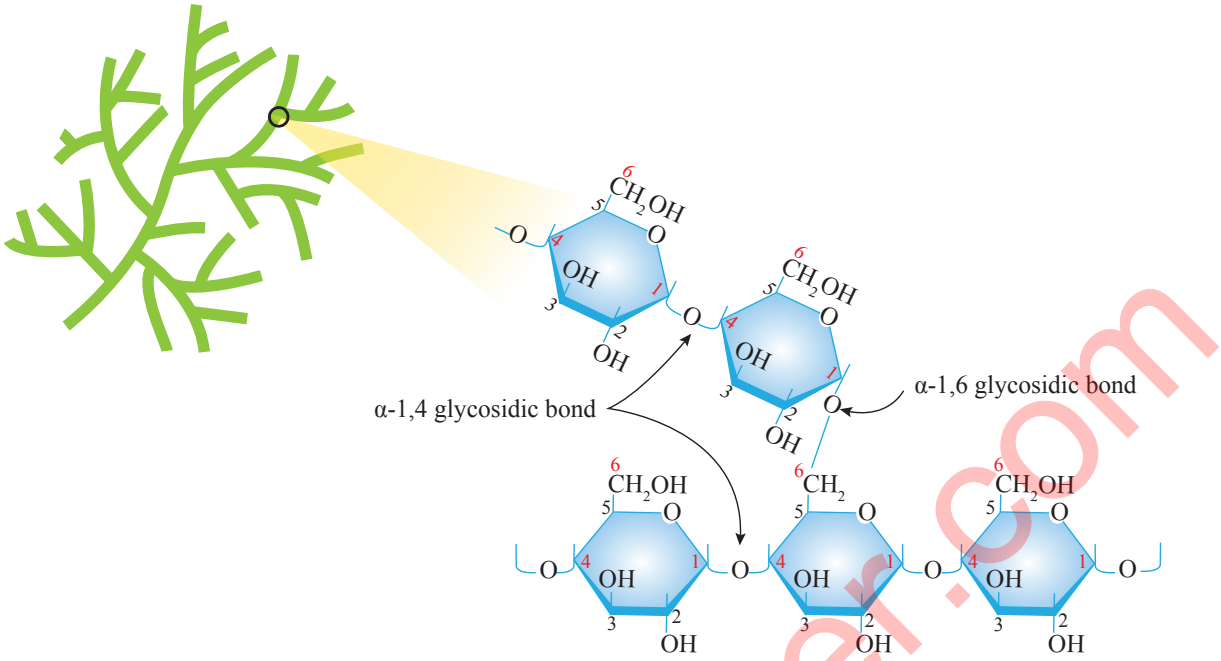


Figure 2.24: A short segment of glycogen

Structural Polysaccharides: Structural polysaccharides provide support in plant cell walls and animal exoskeletons. Examples include cellulose and chitin, which are also homopolysaccharides composed of glucose molecules.

Cellulose: Cellulose, found in plant cell walls, provides structural support and constitutes a significant portion of wood and cotton, the pure form of cellulose. It is composed of 10,000 to 15,000 **β-D-glucose** units linked by β-1,4 glycosidic bonds (see Figure 2.25). Enzymes that digest starch by breaking down its α linkages are unable to hydrolyze the β linkages of cellulose, thereby remaining indigestible to humans. However, ruminant animals, such as sheep and cattle, possess symbiotic gut microbes that can break down cellulose, allowing them to digest cellulose as a major component of their diet. Cellulose gives no colour with iodine.

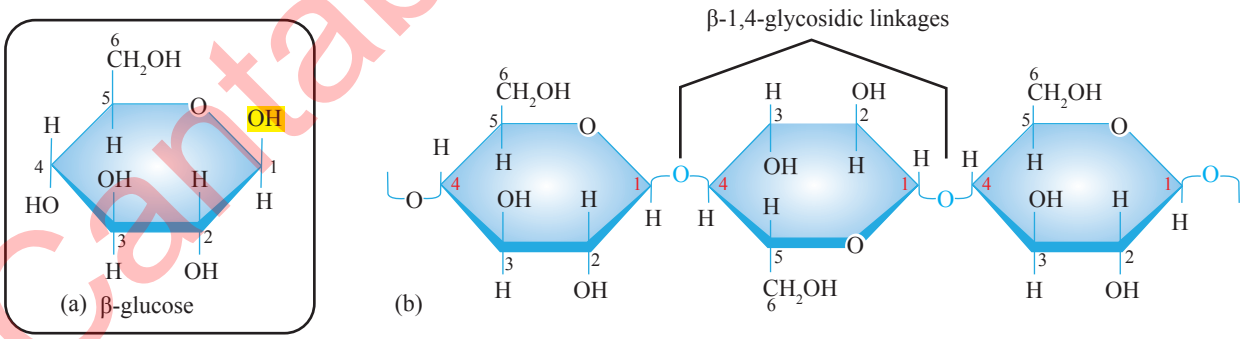


Figure 2.25: Structure of Cellulose

Chitin: Chitin is a linear homopolysaccharide composed of **N-acetylglucosamine** units linked by **β-1,4** glycosidic bonds. It differs from cellulose only in the replacement of the hydroxyl group at C-2 with an acetylated amino group in D glucose (see Figure 2.26). Chitin is a structural component in the exoskeletons of crustaceans and insects and in the cell walls of fungi providing rigidity and protection.

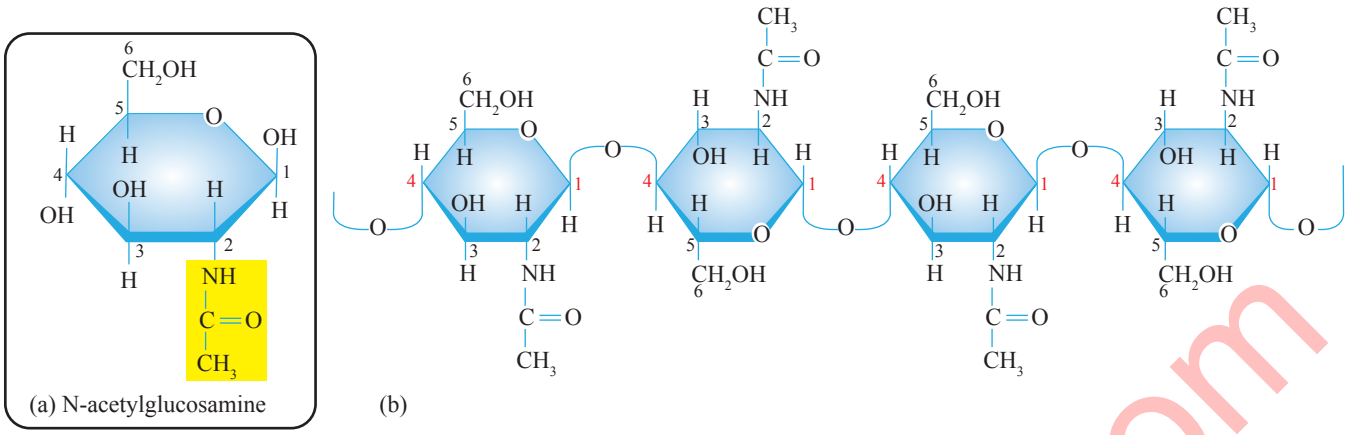


Figure 2.26: A short segment of chitin

Skill:2.6

Objective:

- Skill in classifying carbohydrates into their respective groups based on structure and complexity.
- Ability to compare and contrast different monosaccharides, including writing their chemical formulas.
- Analyze and compare the structural differences between isomers and stereoisomers of glucose.
- Ability to distinguish between different disaccharides based on their structure and function.
- Ability to describe and illustrate the formation of glycosidic bonds in disaccharides.
- Ability to describe and illustrate the structural differences and functional roles of these polysaccharides.

Test Yourself

Short answer-based questions

1. Define carbohydrates and their general formula.
2. Distinguish between enantiomers, epimers and anomers of glucose.
3. Differentiate between amylose and amylopectin in starch.
4. What is the role of glycogen in animals?
5. Explain the structural significance of cellulose in plants.

Long answer-based questions

1. Discuss the structure and biological importance of monosaccharides, including their role in different metabolic processes.
2. Elaborate on the structure, types, and biological roles of polysaccharides in living organisms.

2.7 Knowledge

Proteins

Proteins are polymers composed of one or more polypeptide chains of amino acids, which are linked together through peptide bonds. These are the most abundant and diverse organic molecules found in living organisms. They make up over half of the dry weight of most organisms and play a crucial role in mediating or assisting physiological processes. In fact, a single cell can contain thousands of proteins, each with a unique structure and function.

Structure of Amino Acids

Amino acids serve as the building components of proteins. All amino acids contain carbon, hydrogen, oxygen and nitrogen, while some contain phosphorus and sulphur. A few amino acids also have iron, iodine and magnesium in their structure. There are hundreds of naturally occurring amino acids known, but only 20 of these serve as the common building blocks for proteins. The molecule of amino acids has a central carbon called **α** (alpha) carbon. Four different groups are attached to this carbon. Three of them, i.e. an amino group, a carboxyl group and hydrogen, are present in each amino acid, while the fourth group, known as the R group, is variable and can be alkyl, aryl or other type of side chain (see Figure 2.27). Each of the 20 standard amino acids has a unique R group. It may be a simple hydrogen atom as in

glycine, or CH_3 as in **alanine**, or any other group. The R group determines the individual chemical properties of amino acids.

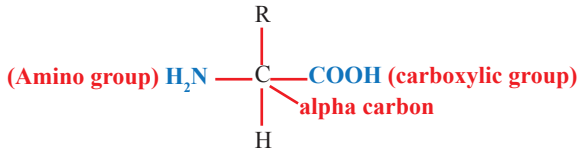


Figure 2.27: Generalized structure of an amino acid

The amino acids are classified based on the body's capability to synthesize them into two categories: essential amino acids and non-essential amino acids.

Essential amino acids are a group of amino acids that are important for human health but cannot be synthesized by the human body. Therefore, they must be obtained through diet. There are nine essential amino acids: histidine, isoleucine, leucine, lysine, methionine, phenylalanine, threonine, tryptophan, and valine. High-quality protein sources such as meat, fish, poultry, eggs, dairy products, and some plant-based sources like soy products contain all nine essential amino acids and are thus referred to as complete proteins. These amino acids are vital for various bodily functions such as protein synthesis, tissue repair, neurotransmitter synthesis and nutrient absorption. Failure to consume enough essential amino acids can lead to symptoms like muscle weakness, fatigue, hair loss, and immune system impairments.

Non-essential amino acids are those that the human body can synthesize on its own, meaning they do not need to be obtained directly through diet. There are 11 non-essential amino acids: alanine, glutamine, arginine, glycine, asparagine, proline, aspartic acid, serine, cysteine, tyrosine, and glutamic acid. The body makes these amino acids from other amino acids or through normal metabolic processes.

Synthesis and breakage of Peptide linkage

Two amino acids are linked together through a covalent bond known as a peptide bond. This bond forms when the hydrogen atom from the amino group ($-NH_2$) of one amino acid reacts with the hydroxyl group from the carboxyl group (-COOH) of another, releasing a water molecule in a condensation reaction (see Figure 2.28). This linkage creates a dipeptide, which has a free amino group at one end (the N-terminal) and a free carboxyl group at the other end (the C-terminal).

By continuously adding new amino acids to the carboxyl end, the chain can be extended to form a tripeptide, tetrapeptide, and eventually a polypeptide.

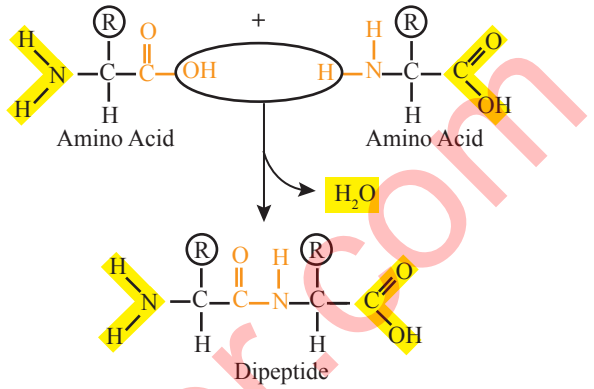


Figure 2.28: Two amino acids are linked together through a peptide bond to form a dipeptide.

Peptide bonds are hydrolyzed by the addition of water. The water molecule splits into H and OH, which attack the peptide bond, breaking the link between amino acids. This hydrolysis is typically catalyzed by enzymes known as proteases or peptidases. In the digestive system, these enzymes break down proteins into shorter peptides and free amino acids as shown in Figure 2.29, for easy absorption and assimilation by the body. Inside cells, proteases ensure that damaged or unneeded proteins are degraded and their amino acids recycled for new protein synthesis.

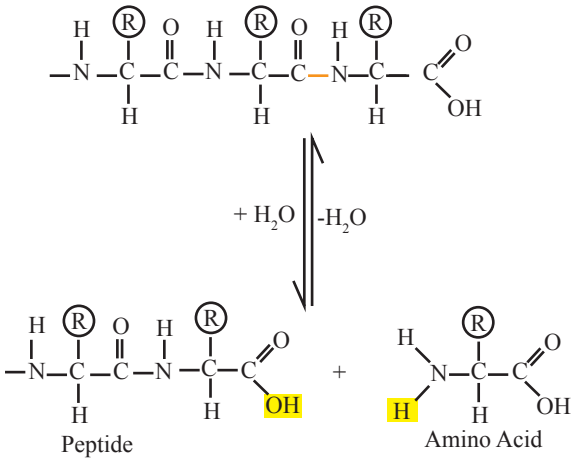


Figure 2.29: Synthesis and breakage of Peptide linkage

Level of Organization of Protein

Proteins are complex molecules whose properties are determined by the number, type and sequence of amino acids they contain. There are four levels of organization in a protein as shown in Figure 2.30.

Primary structure: The primary structure of a protein is the specific linear sequence of amino acids linked together by peptide bonds in a polypeptide chain. This sequence is determined by the genetic code. F. Sanger was the first to work out the sequence of amino acid residues in insulin. Primary structure is crucial for protein function, and many genetic diseases, such as sickle cell anaemia, are caused by defects in these sequences.

Secondary structure: The linear polypeptide chains in a protein molecule usually coil to obtain different regular configurations. The most common types of secondary structures are the **α helix** and the **β pleated sheet**. Both structures are held together by hydrogen bonds between the oxygen of the carbonyl group (-CO-) of one amino acid and the hydrogen of the amino group (-NH-) of the other amino acid.

Tertiary structure: This level is formed when the secondary structure twists and folds further through hydrogen bondings, ionic bondings, and disulphide bridges into a more complex three-dimensional globular arrangement.

Quaternary structure: Finally, we have the quaternary structure. Two or more polypeptide chains come together to form a functional protein. Each of hese chains is referred to as a subunit of the protein. The quaternary structure is crucial as it allows for the formation of complex protein with specific function. The protein subunits are held together by various interactions, including hydrophobic interaction, hydrogen bonds, and ionic bonds. This specific aggregation of polypeptide chains is what we call a quaternary structure.

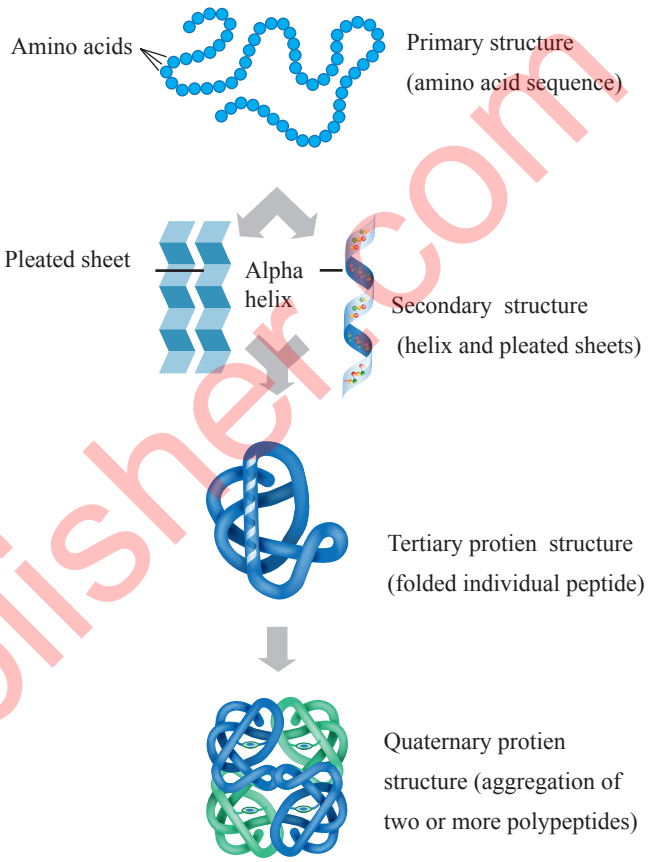


Figure 2.30: Four levels of a protein's structural organization

Significance of the sequence of Amino acids

The number of amino acids in a polypeptide chain can vary from a few to over 3000. All amino acids must be in the correct position in the chain. If even one amino acid is out of place, the protein's function can be lost. For example, in sickle cell anaemia, a single amino acid changes the haemoglobin protein.

Normally, red blood cells have a biconcave disc shape, which allows them to be flexible and travel smoothly through blood vessels. They carry oxygen from the lungs to the body's tissues due to the presence of a protein called haemoglobin. **Normal haemoglobin (Hb^A)** contains 574 amino acids in four polypeptide chains, two α and two β chains. Each α chain consists of 141 amino acids, and each β chain consists of 146 amino acids.

In sickle cell anaemia, a **point mutation** in the gene (in which a single nucleotide adenine is replaced by a thymine) encoding the beta-globin chain causes the substitution of a single amino acid, **glutamic acid**, with another amino acid, **valine**, at position 6 in the protein chain (see Figure 2.31).This results in the formation of **sickle cell haemoglobin** (Hb^S). Just this one replacement of a single amino acid, out of 574 amino acids, changes the entire structure and function of the haemoglobin. In a person with sickle cell disease, the red blood

cells are sickle-shaped due to the polymerization of haemoglobin molecules (see Figure 2.31). These sickle-shaped cells can clump together and block blood flow, leading to various complications, including pain, organ damage, and anaemia.

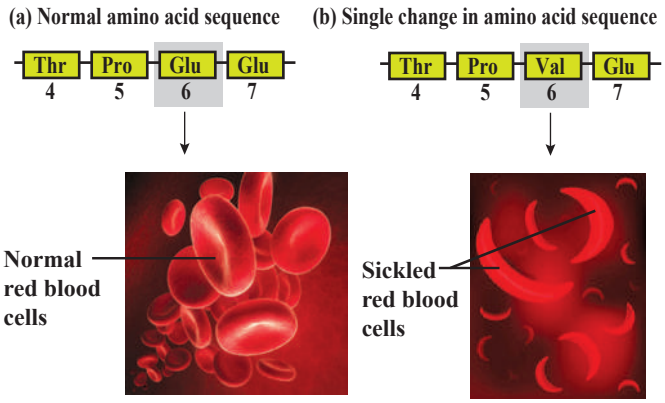


Figure 2.31: Sickle cell anaemia due to point mutation in gene.

Classification of Proteins

The shapes of protein molecules are in accordance with their functions. On the basis of shapes and structure, proteins are of two types.

i. **Fibrous proteins** have long parallel polypeptide chains, cross-linked at intervals, forming long fibres or sheets. These have a secondary structure and are insoluble in water. They cannot be crystallized. Fibrous proteins play the structural role in cells and organisms, e.g. Collagen, keratin, actin and myosin (see Figure 2.32 a).

ii. **Globular proteins** consist of polypeptide chains that are tightly folded to form spherical or globular shapes. They possess tertiary or quaternary structures and are soluble in water. Unlike fibrous proteins, globular proteins can be crystallized. Examples of globular proteins include enzymes, antibodies, haemoglobin, and some hormones, such as insulin (see Figure 2.32 b).

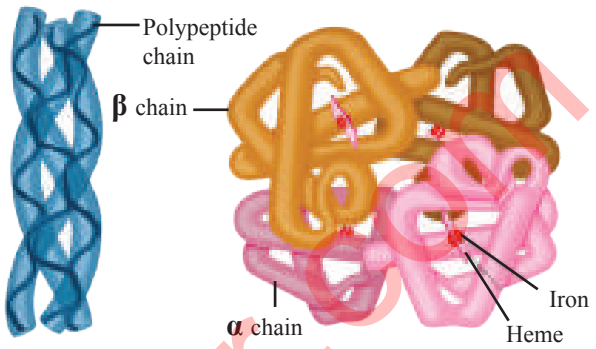


Figure 2.32: (a) Fibrous structure of collagen protein (b) Globular quaternary structure of haemoglobin.

Role of Proteins

Proteins are essential biomolecules that play important roles in maintaining the structure and function of all living organisms. They are classified into structural and functional proteins based on their role in the body. This classification helps in understanding their diverse functions and how they contribute to the biology of organisms.

Structural Proteins: Structural proteins provide support and shape to cells, tissues and organs, forming the framework of various structures within the body. They are usually fibrous with repetitive amino acid sequences for stability and strength. Important examples include collagen, keratin and elastin (see Table 2.1).

Table 2.1: Types and roles of Structural proteins

Types	Role of Structural proteins
Collagen	It is the most abundant protein in the body and forms the main component of connective tissues such as bones, cartilage, tendons and ligaments.
Keratin	This protein forms the protective layers of hair, nails, feathers, horns and hooves.
Elastin	It is found in various connective tissues that require elasticity, including the lungs, arteries and skin.

Functional Proteins: Functional proteins are involved in carrying out the biochemical and physiological activities necessary for life processes. Often globular, these proteins are designed for a wide range of functions including catalysis, transport, regulation, and motion. Key examples are enzymes, hormones and Fibrinogen (see Table 2.2).

Table 2.2: Types and roles of Functional proteins

Types	Role of Functional proteins
Enzymes	Most of the enzymes are proteins and act as biological catalysts. They speed up chemical reactions in the body without being consumed in the process.
Hormones	Some hormones are proteins and serve as chemical messengers to regulate various physiological processes and maintain homeostasis within the body.
Fibrinogen	A blood plasma protein involved in the blood clotting process by forming a mesh that helps to stop bleeding.

Skill:2.7

Objective:

- Skill in identifying essential amino acids and illustrating the structural formula of an amino acid.
- Ability to outline the process of peptide bond formation and hydrolysis.
- Justifying the significance of amino acid sequences in determining protein function and characteristics.
- Skill in classifying proteins based on their structural characteristics as either globular or fibrous proteins, while understanding their role in biological systems.
- Ability to list and provide examples of structural and functional proteins, highlighting their specific roles.

Test Yourself

Short answer-based questions

1. Define the term 'peptide bond'.
2. How does a change in amino acid sequence affect protein function?
3. What is the primary structure of a protein?
4. Differentiate between alpha-helix and beta-pleated sheet.
5. Differentiate between fibrous and globular proteins.

Long Question

1. Elaborate on the four levels of protein structure and their importance.

2.8 Knowledge

Lipids

Lipids are a chemically heterogeneous group of organic compounds that are insoluble in water but soluble in organic solvents like acetone, alcohol, and ether. They are composed of carbon, hydrogen and oxygen. However, they contain relatively less proportion of oxygen than carbon and hydrogen. Lipids store almost double the amount of energy per gram than carbohydrates or proteins due to their high content of energy-rich C-H bonds, which allows them to yield more energy upon metabolism. Biologically important groups of lipids include acylglycerols, phospholipids, terpenes, steroids and waxes.

Classification of Lipids

Lipids are classified on the basis of their chemical structure and the role they perform in biological systems. Lipids have been classified as:

1. Acylglycerol: Acylglycerols, also known as glycerides, are esters formed by the combination of glycerol and fatty acids. An ester is a compound formed by the reaction of an alcohol with an acid, resulting in the elimination of a water molecule. **Glycerol** is a three-carbon alcohol molecule containing three OH groups. A **fatty acid** is a long, straight chain of an even number of carbon atoms from 2 to 30 with a COOH group at one end. Depending on the number of fatty acid chains attached to glycerol, acylglycerols can be classified as **monoglycerides** (one fatty acid chain), **diglycerides** (two fatty acid chains), or **triglycerides** (three fatty acid chains). Triglycerides or triacylglycerols are the most abundant lipids in living organisms and are commonly known as **neutral lipids** (see Figure 2.33).

Fact

Excess acylglycerols in the diet can lead to health issues like obesity and cardiovascular disease, as they are stored in adipose tissue and can accumulate if not used for energy.

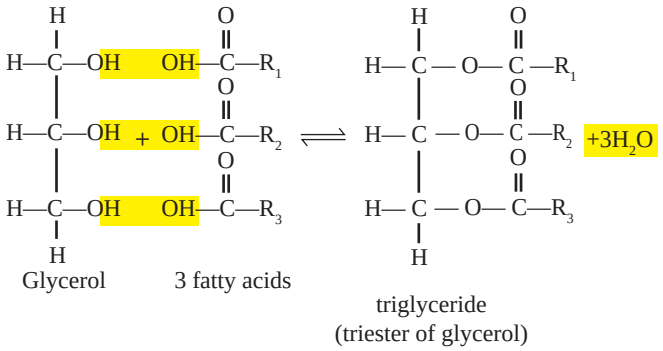


Figure 2.33: Formation and breakdown of triglyceride molecule.

Types of fatty acids: The physical state and properties of acylglycerols depend on the types of fatty acids present. Fatty acids with all the single bonds and no double bonds between carbon atoms in their hydrocarbon chain are called **saturated fatty acids.** They tend to be solid at room temperature and are more common in animal lipids such as butter. **Unsaturated fatty acids** are characterized by the presence of one or more double bonds between carbon atoms in their hydrocarbon chain. Depending on the number of double bonds, these fatty acids can be classified as either **monounsaturated**, which contains one double bond, or **polyunsaturated**, which has two or more double bonds. They are liquid at room temperature and are typically found in plant lipids like olive oil, canola oil, and soybean oil (see table 2.3).

Table 2.3: Comparison of Saturated and Unsaturated Fatty Acids.

Features	Saturated fatty acids	Unsaturated fatty acids
Type of bonds	All single, no double	One or more double
Physical state	Solid	Liquid
Occurrence	Animals	Plants

Properties of Acylglycerols

Some properties of acylglycerol are given below:

- Acylglycerols generally have lower densities than water, which is why oils float on water. The density of these lipids usually decreases as the number of double bonds in the fatty acid chains increases.
- Acylglycerols are hydrophobic, meaning they are insoluble in water but soluble in organic solvents such as ether, chloroform, and benzene.
- The melting points of acylglycerols vary based on their fatty acid composition and length. Lipids containing long and saturated fatty acids (fats) have higher melting points than those containing short and unsaturated fatty acids. For example, butter has approximately 32°C to 35°C melting point, while olive oil has a melting point of around -6°C to 0°C.
- Acylglycerols are relatively stable molecules under normal conditions, but they can become rancid due to oxidation in fats and oils.

Roles of Acylglycerols

Following are some roles of acylglycerols in biological systems.

- Acylglycerols, especially triglycerides, have a high energy content. In fact, each gram of triglyceride provides more than twice the energy of carbohydrates or proteins.
- Acylglycerols, especially monoglycerides, show excellent **emulsifying properties** and are widely used in the food, cosmetic, pharmaceutical, and chemical industries.
- Acylglycerols are stored in the body as energy storage compounds. Humans and other mammals stock their long-term food reserves in **adipose cells.**

- In addition to storing energy, adipose tissue cushions vital organs like the kidneys, and a layer of fat beneath the skin insulates the body. This subcutaneous layer is incredibly thick in whales, seals, and most other marine mammals, insulating their bodies in cold ocean water.

ii. Phospholipids: Phospholipids are lipid molecules that make up the membrane of cell and are derivatives of phosphatidic acid. Phosphatidic acid is a molecule similar to triglyceride and consists of a glycerol backbone with two fatty acid tails attached to the first and second carbons of glycerol. These tails can be saturated or unsaturated. The head of the molecule is made up of a phosphate group that is attached to the third carbon of the glycerol. Phospholipid is derived from phosphatidic acid when an organic molecule (such as choline, ethanolamine, inositol or the amino acid serine) is linked to the phosphate group (see Figure 2.34 a).

The most common example of a phospholipid is **phosphatidylcholine**, also known as **lecithin**. It is one of the most abundant phospholipids in cell membrane and contains a **choline** molecule attached to the phosphate group of phosphatidic acid (see Figure 2.34 b).

Properties of Phospholipids: Phospholipids are **amphipathic** in nature, meaning they contain both hydrophobic (non-polar) and hydrophilic (polar) regions. The head of the phospholipid molecule is polar and readily soluble in water due to its phosphate group, while the other end, continuing the fatty acid side chains, is hydrophobic and insoluble in water. In water, phospholipid molecules orient themselves into a bilayer so that their polar heads face the water and their non-polar tails face each other. This arrangement forms the basic structure of cell membrane.

Role of Phospholipids: Phospholipids form semi-permeable barriers that regulate the entry and exit of substances in and out of cells and organelles. In the lungs, phospholipids are a major component of the surfactant that reduces surface tension in the alveoli, preventing the lungs from collapsing. In the digestive system, phosphatidylcholine is secreted by the liver into the bile, where it helps emulsify dietary fats, aiding in their digestion and absorption. Some phospholipids also participate directly in cell signalling pathways.

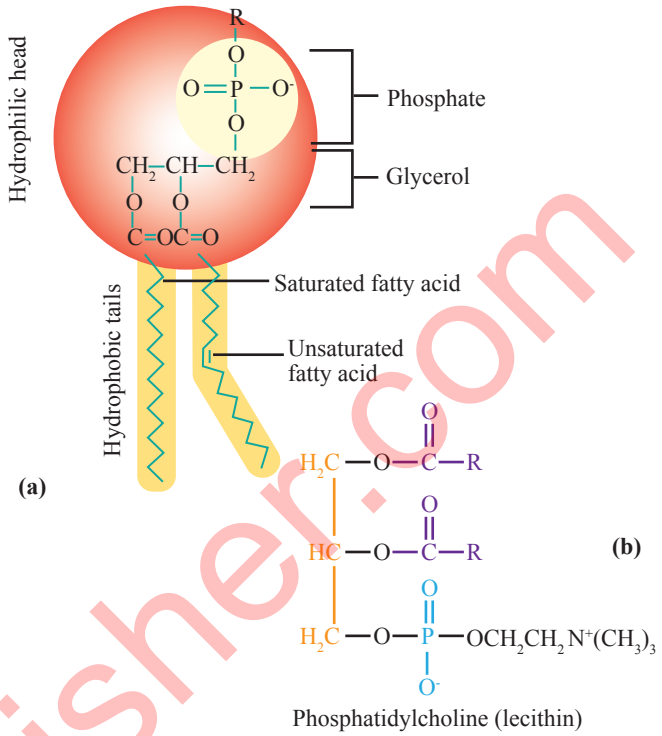


Figure 2.34: (a) Structure of phospholipid (b) Phosphatidylcholine, a phospholipid with choline nitrogenous base.

iii. Terpenes: Terpenes are a large and diverse class of organic compounds synthesized from a five-carbon building block known as an **isoprene unit** (see Figure 2.35). These units condense in different ways to form many compounds.

Properties of Terpenes: Terpenes are highly volatile compounds with characteristic odours. They can exhibit various structural arrangements, including linear chains and rings. Terpenes are widely recognized for their antimicrobial, anti-inflammatory, and antioxidant properties. They are also known for their thermal stability and are often used in traditional and modern medicine.

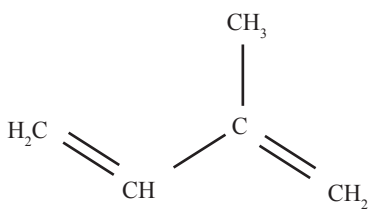


Figure 2.35: Isoprene unit of terpenes

Role of Terpenes: Terpenes play diverse roles in foods, drugs, hormones, and vitamins. They are responsible for the unique scents and tastes of fruits, vegetables, and other plants. Some terpenes are being studied for their potential anti-cancer properties and in the treatment of neurodegenerative diseases.

iv. Waxes: Waxes are esters of long chain (C_{14} to C_{36}) saturated and unsaturated fatty acids with long chain (C_{16} to C_{30}) alcohols.

Properties of Waxes: These are chemically inert and resistant to atmospheric oxidation. Waxes are highly hydrophobic. This property makes them excellent for waterproofing. Waxes have a higher melting point than fats, but they are still malleable at slightly higher temperatures, which allows them to stay solid at room temperature and melt when heated moderately. There are two types of waxes: natural waxes and synthetic waxes. **Natural waxes** are derived from plants (e.g., Cuticular wax), animals (e.g., beeswax), or minerals (e.g., ozokerite) (see Figure 2.36). On the other hand, **synthetic waxes**, like paraffin wax and polyethylene wax, are produced through chemical processes from petroleum or other sources.

Plant wax Animal wax

Figure 2.36: Natural waxes in plants and animals

Waxes serve multiple roles:

- They act as protective coatings. For example, cuticle wax is found on the surface of leaves, preventing excessive water loss. Bees use beeswax to build and protect honeycomb cells.
- Waxes repel water and prevent moisture from penetrating surfaces.
- Waxes also provide lubrication in various applications, such as in crayons; the waxy material allows for smooth colouring.
- Synthetic waxes such as paraffin and polyethylene wax are used in various applications, including candles, coatings, and plastics.

v. Steroids: Steroids are high molecular weight crystallizable lipids. They consist of a 17 carbon atoms nucleus arranged in four fused rings - three six-carbon rings (cyclohexane) and one five-carbon ring (cyclopentane) as shown in Figure [2.37(a)]. The length and structure of the side chains that extend from the nucleus differentiate one steroid from another. These structures are synthesized from isoprene units.

Importance of Steroids: Some of the steroids that are biologically important include cholesterol, bile salts, male sex hormone testosterone, female sex hormones progesterone and estrogen, etc. **Cholesterol** is a structural component of animal cell membranes as shown in Figure [2.37(b)], and serves as a precursor for other steroids like sex hormones. It is synthesized in the liver and can also be obtained from the diet. However, high levels of cholesterol in the blood may contribute to atherosclerosis.

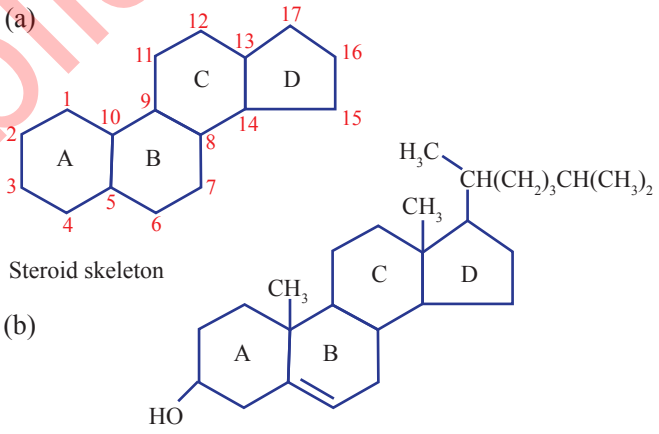


Figure 2.37: (a) 17 carbon nucleus of steroid (b) structure of cholesterol molecule

vi. Prostaglandins: Prostaglandins are a group of lipid compounds derived from fatty acids, usually arachidonic acid, found in the cell membrane's phospholipids. They are characterized by a **5-carbon ring** that is part of a larger structure that includes long hydrocarbon tails. There are different types of prostaglandins, each classified according to the structure of this cyclopentane ring and the functional groups attached to it.

Importance of Prostaglandins: Prostaglandins act

as local hormones and are present in almost all mammalian tissues. Depending on the tissue, prostaglandins have various functions, such as lowering or raising blood pressure, inducing fever and inflammation and intensifying pain sensation. They also help regulate the aggregation of platelets in the early step of the formation of blood clots. The ability of aspirin to reduce fever and decrease pain depends on the inhibition of prostaglandin synthesis.

Skill:2.8

Objective:

- Skill in defining lipids and categorizing them based on their structure and properties.
- Ability to describe the structure and function of acylglycerols, phospholipids, terpenes and waxes as major lipid types and their significance in biological systems.
- Skill in illustrating the molecular structure of acylglycerol, a phospholipid and a terpene while elaborating their formation and breaking.
- Ability to evaluate and explain the importance of steroids and prostaglandins in biological processes.

Test Yourself

Short answer-based questions

1. Define Acylglycerol.
2. What are the two main types of fatty acids?
3. Describe the role of phospholipids.
4. What are terpenes and their significance?
5. How do steroids differ in structure from other lipids?

Long answer-based questions

1. Explain the role and structure of different types of lipids in biological systems.

2.9 Knowledge

Nucleic Acids

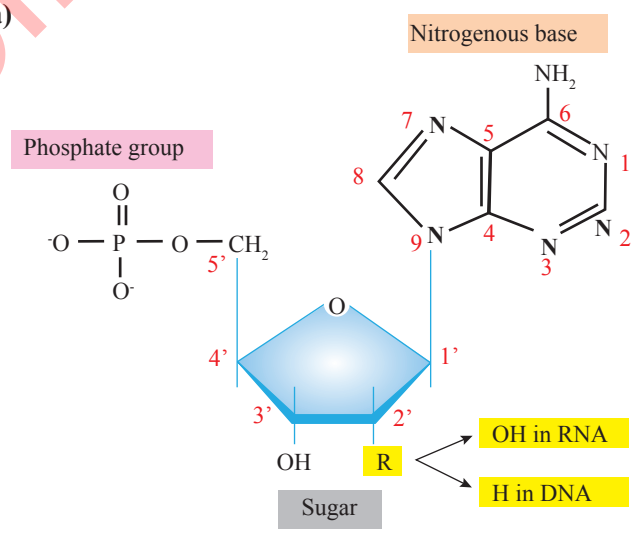
Swiss biochemist **Friedric Miescher** isolated a substance from the nucleus of pus cells (white blood corpuscles) in 1869 and named it **nuclein**. Later, it was found that the nuclein had acid properties and hence **Altmann**, in 1899, introduced the term nucleic acid to replace nuclein.

Structure of Nucleic Acids

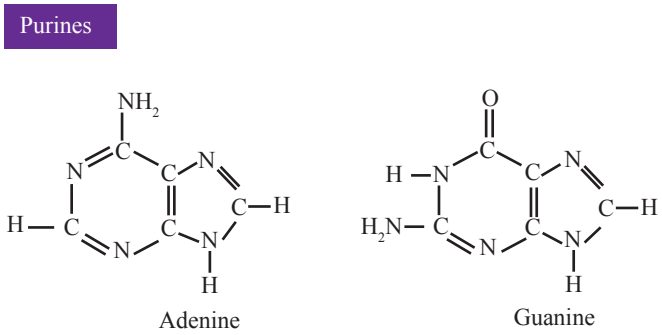
Nucleic acids are long, unbranched linear polymers of repeating subunits called **nucleotides.** Each nucleotide consists of three components as shown in Figure 2.38 (a).

- A five-carbon **pentose sugar**.
- A **phosphate** ($-PO_4$) group, which gives an acidic nature to nucleic acids and is attached to carbon no. 5 of pentose sugar. Together, the pentose sugar and phosphate group form the backbone of the nucleic acid polymer.
- A nitrogen-containing **base** attached to carbon no. 1 of the pentose sugar. The resulting base and sugar compound is called a **nucleoside.** When a phosphate group is added to a nucleoside, it becomes a nucleotide.
- Nitrogen bases are grouped as **purine** and **pyrimidine.** Purines are double-ringed structures and include **adenine** and **guanine.** Pyrimidines are single-ringed and include **cytosine**, **thymine** and **uracil** (see Figure 2.38 b).

(a)



(b)



Pyrimidines

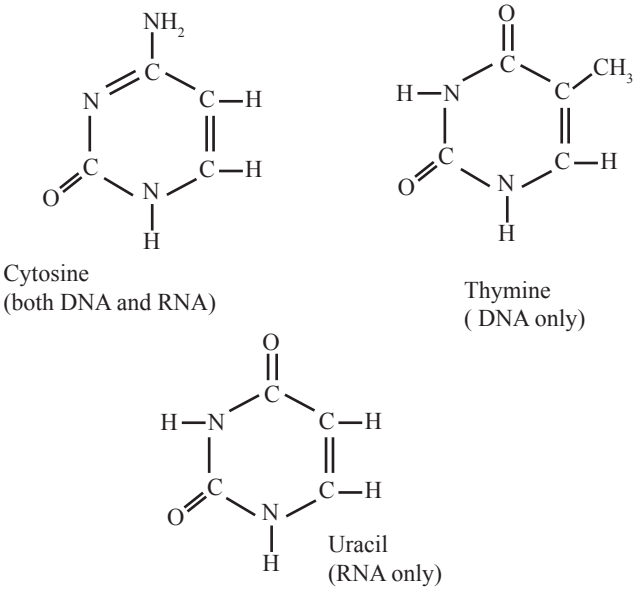


Figure 2.38: (a) The structure of a nucleotide molecule (b) The molecular structure of nitrogen-containing purines and pyrimidines.

Classification of Nucleic Acids

Nucleic acids with polynucleotide chains are of two types:

i. Deoxyribonucleic acids (DNA)
ii. Ribonucleic acids (RNA)

Deoxyribonucleic acid contains deoxyribonucleotides, while ribonucleic acid contains ribonucleotides. In a deoxyribonucleotide, pentose sugar is deoxyribose, while in a ribonucleotide, it is ribose. Among the four nitrogenous bases, adenine, guanine and cytosine are common in DNA and RNA, while the fourth base, thymine, is only present in DNA and uracil only in RNA.

A nucleotide can attach one to three phosphate groups to its sugar molecule. If it is one phosphate group, the nucleotide is named nucleoside monophosphate; with two phosphate groups, it is called nucleoside diphosphate and finally, with three phosphate groups, the nucleotide is called nucleoside triphosphate. To study the names of nucleosides and nucleotides see table 2.4.

Table 2.4: List of nucleosides and nucleotides present in RNA and DNA

Nitrogenous base	RNA		DNA	
	Ribonucleosides (ribose + nitrogenous base	Ribonucleotides (ribose + nitrogenous base + phosphate group)	Deoxyribonucleosides (deoxyribose + nitrogenous base	Deoxyribonucleotides (deoxyribose + nitrogenous base + phosphate group)
Adenine	Adenosine	AMP, ADP, ATP	d-Adenosine	dAMP, dADP, dATP
Thymine			d-Thymidine	dTMP, dTDP. dTTP
Guanine	Guanosine	GMP, GDP, GTP	d-Guanosine	dGMP, dGDP. dGTP
Cytosine	Cytidine	CMP, CDP, CTP	d-Cytidine	dCMP, dCDP, dCTP
Uracil	Uridine	UMP, UDP, UTP		

Phosphodiester Bond and Polymerization of Nucleic Acids

The polymerization of nucleic acids begins with a polymerase enzyme incorporating deoxyribonucleoside triphosphates (dNTPs) into the growing nucleic acid chain through a catalyzed reaction where the 3' hydroxyl group of the last nucleotide in the growing strand attacks the alpha phosphate of the NTP, forming a **phosphodiester bond** (see Figure 2.39). This bond formation simultaneously results in the cleavage of the outer two phosphates (beta and gamma) of the dNTP as pyrophosphate (PPi). The release and subsequent hydrolysis of PPi to two inorganic phosphate molecules provides the energy needed to drive the polymerization reaction forward.

In this way, nucleotides continue to add to the growing nucleic acid chain to form a polymer of nucleotides.

The resultant polynucleotide chain again has a free 5' phosphate group at one end and a free 3' hydroxyl group at the other end.

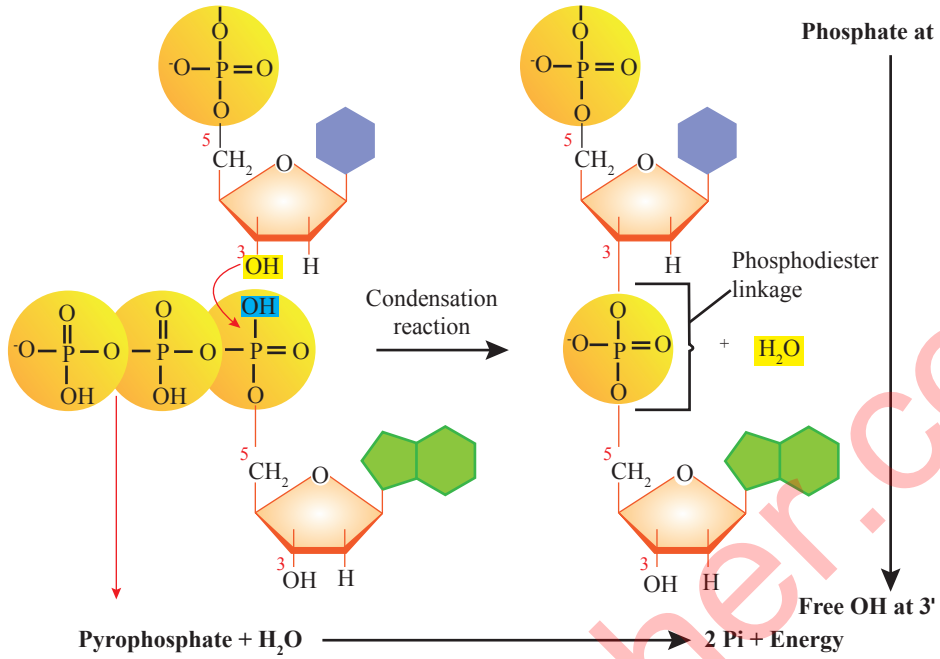


Figure 2.39: Formation of a phosphodiester bond

Let us now discuss a biologically important mononucleotide and a dinucleotide.

Mononucleotide: Adenosine triphosphate (ATP) is a mononucleotide and is known as the energy currency of cells. ATP, being a nucleotide, has three parts connected by covalent bonds: (a) adenine, a purine base; (b) ribose, a five-carbon sugar; and (c) three phosphates, which are attached sequentially to the 5' carbon of the ribose sugar (see Figure 2.40). The two covalent bonds linking the three phosphates are called high-energy bonds. ATP can be hydrolyzed into ADP (adenosine diphosphate) and an inorganic phosphate (Pi), releasing energy that can be used by the cell.

$$ATP + H_2O \rightleftharpoons ADP + Pi + 7.3\ Kcal/mole$$

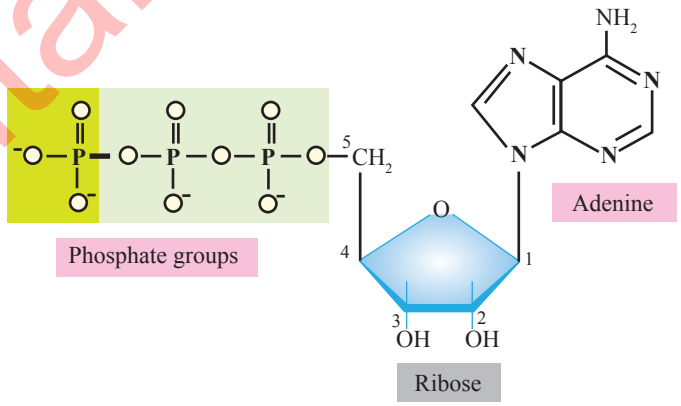


Figure 2.40: Structure of ATP

This process is reversible, so energy can be stored in ATP by reattaching a phosphate group to ADP .through condensation. The addition of inorganic phosphate to an organic molecule is called **phosphorylation.**

Dinucleotide: Cells contain several dinucleotides that play a vital role in metabolic processes. One such dinucleotide is **Nicotinamide adenine dinucleotide** (NAD), which comprises two nucleotides. One nucleotide of NAD contains a base called nicotinamide, sugar and phosphate while the other nucleotide contains a base called adenine, sugar and phosphate. The two nucleotides are joined by their phosphate groups to create a dinucleotide. It exists in two forms: oxidized (NAD^+) and reduced (NADH) as shown in Figure 2.41. When NAD^+ accepts two electrons and one H^+, it is converted into NADH. As a coenzyme, NADH acts as a carrier of electrons and protons in numerous oxidation-reduction (redox) reactions within the cell.

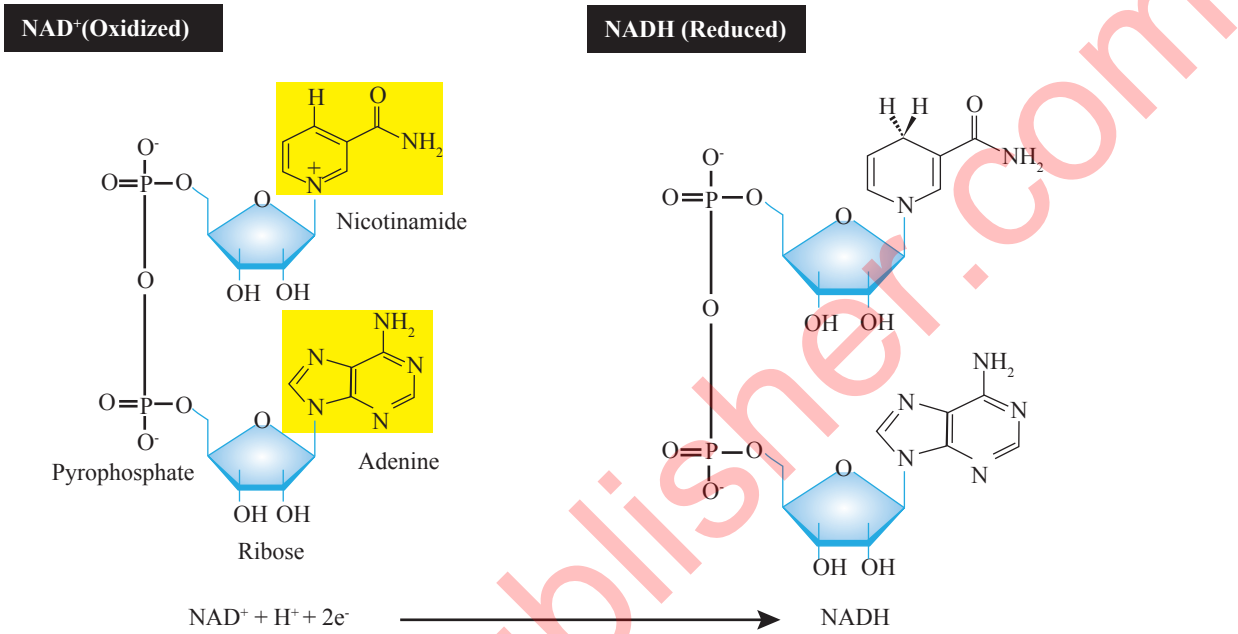


Figure 2.41: The chemical structure of oxidized (NAD^+) and reduced NADH

Watson and Crick's Model of DNA

DNA is the heredity material. It controls the properties and potential activities of a cell. It is made of four kinds of nucleotides, namely d-adenosine monophosphate (d-AMP), d-guanosine monophosphate (d-GMP), d-cytidine monophosphate (d-CMP), and d-thymidine monophosphate (d-TMP). These nucleotides are united with one another through phosphodiester linkages in a specific sequence to form long chains known as polynucleotide chains. Scientists who played an important role in the understanding of DNA structure are discussed below.

James Watson and Francis Crick proposed the double helical structure of DNA in 1953 (see Figure 2.42). They proposed that:

- The DNA molecule is made up of two polynucleotide strands that twist around each other, forming a double helix shape.
- The two strands of DNA are antiparallel, i.e. run in opposite directions, with one strand oriented 5' to 3' and the other 3' to 5'. This is important for DNA replication and transcription into RNA.
- The backbone of each strand of DNA is composed of sugar (deoxyribose) and phosphate groups. The phosphate group of one nucleotide forms a covalent bond with the 3' carbon atom of the sugar of the next nucleotide, forming a sugar-phosphate backbone. The bases extend from this backbone like the rungs of a ladder.A double-ring base, purine, always pairs with a single-ringed base, pyrimidine, on the opposite strand.
- The base pairing is specific: guanine (G) always pairs with cytosine (C), and adenine (A) always pairs with thymine (T). This is known as complementary base pairing.
- The base pairs are held together by hydrogen bonds. Three hydrogen bonds form between

guanine and cytosine, while adenine and thymine are held together by two hydrogen bonds.

- The helix is 2 nm in diameter and makes a complete spiral turn every ten base pairs, with a length of 3.4 nm. The distance between the two base pairs is 0.34 nm.

Do you Know?

Maurice Wilkins and Rosalind Franklin provided key physical evidence for the three-dimensional structure of DNA. Franklin used X-ray diffraction techniques to capture critical images, including the famous "Photo 51," which revealed the helical structure of DNA with a diameter of 2 nm and a turn length of 3.4 nm.

Nobel Prize:

In 1962, Watson, Crick, and Wilkins were awarded the Nobel Prize in Physiology or Medicine for their discoveries concerning the molecular structure of nucleic acids and its significance for information transfer in living material. Notably, the prize was not shared with Rosalind Franklin; she had passed away in 1958, and the Nobel Prize is not awarded posthumously.

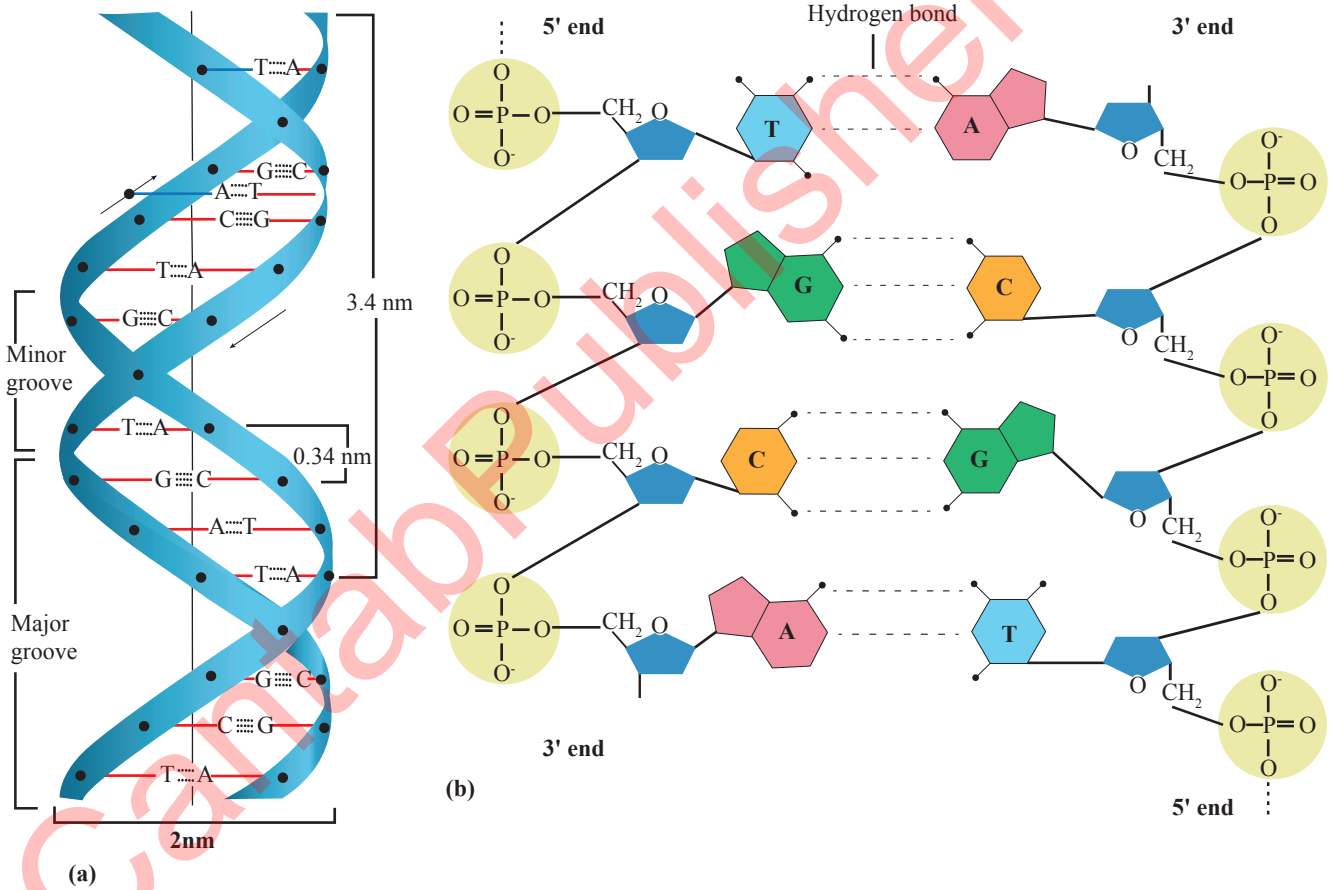


Figure 2.42: (a) Watson and Crick model of DNA (b) shows details of the DNA double helix.

Ribonucleic Acid (RNA)

Like DNA, RNA is also a polymer of nucleotides. Unlike DNA, RNA contains uracil instead of thymine and ribose sugar in place of deoxyribose sugar. Therefore, the four types of nucleotides present in RNA are adenosine monophosphate (AMP), guanosine monophosphate (GMP), cytidine monophosphate (CMP) and uridine monophosphate (UMP). These nucleotides combine through phosphodiester bonds to form a **single-stranded RNA** molecule with a linear sequence of nucleotides (see Figure 2.43).

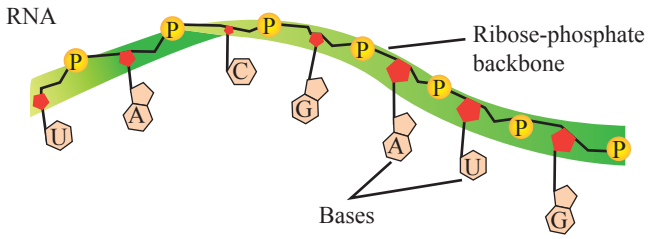


Figure 2.43: Single-stranded RNA structure

In some instances, complementary regions within a single RNA molecule can base pair with each other, leading to the formation of double-stranded RNA (dsRNA) regions. Each RNA molecule can have a unique sequence of nucleotides, which determines its structure and function within the cell. There are three general types of RNA, each with a specific function in protein synthesis. These include:

Messenger RNA (mRNA): It is a single-stranded molecule that can vary in length due to different numbers of ribonucleotides. Its length depends on the gene size and the specific protein it encodes for. During transcription, a mRNA molecule is synthesized in the nucleus based on the DNA template. It carries genetic information from the DNA in the cell's nucleus to the ribosomes in the cytoplasm. The mRNA code is read in sets of three nucleotides called codons. Each codon specifies a particular amino acid, which determines the sequence of amino acids in the protein being synthesized. mRNA is about 3 to 4% of the total RNA in the cell.

Ribosomal RNA (rRNA): It is a structural component of ribosomes and is found in both the small and large subunits of ribosomes. It is synthesized in a specialized region of the cell nucleus called the nucleolus, which contains genes encoding rRNA. Ribosomal RNA is combined with a variety of proteins to form ribosomal subunits. These molecules are typically single-stranded rRNA, which folds into complex three-dimensional structures that catalyze the formation of peptide bonds between amino acids, facilitating the synthesis of polypeptide chains. Ribosomal RNA comprises about 80% of total RNA.

Transfer RNA (tRNA): It is the smallest of the RNA molecules, typically around 75-90 nucleotides in length, and constitutes about 20% of the total RNA. tRNA is a single-stranded nucleic acid that folds back on itself to create regions where complementary bases are bonded, adopting a flat cloverleaf shape (see Figure 2.44).

Each tRNA molecule has a CCA sequence at the 3' end, which serves as the attachment site for amino acids. The attachment of an amino acid to tRNA molecule is catalyzed by an enzyme known as **aminoacyl-tRNA** synthetase.

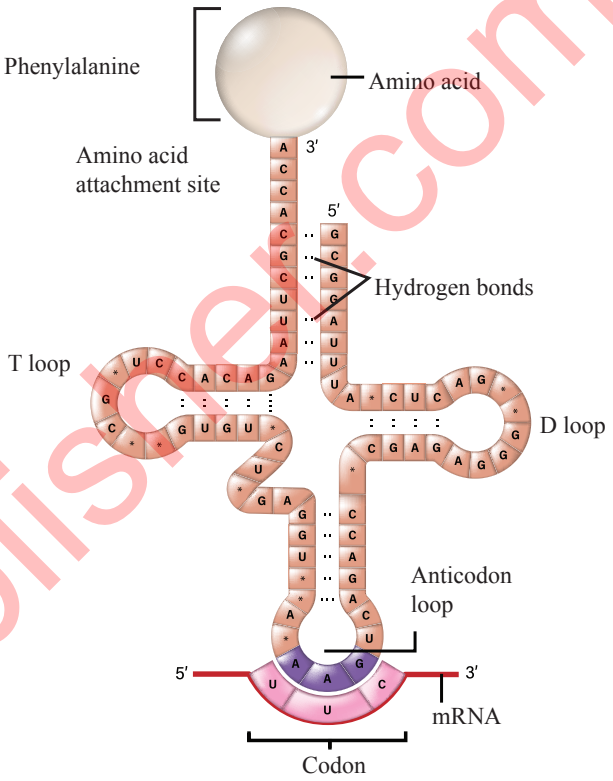


Figure 2.44: Structure of tRNA

Skill:2.9

Objective:

- Ability to describe the structure and function of nucleic acids and nucleotides.
- Skill in distinguishing among different nitrogenous bases based on their structure and pairing rules.
- Ability to outline the structure and role of mononucleotides and dinucleotides.
- Ability to illustrate the formation of phosphodiester bonds in DNA and RNA.
- Ability to explain and depict the double helical structure of DNA proposed by Watson and Crick, including its components.
- Ability to explain the structural differences between RNA and DNA.
- Skill in distinguishing the functions and roles of RNA types.

Test Yourself

Short answer-based questions

1. What are the three components of a nucleotide?
2. What is the difference between purines and pyrimidines?
3. What is the role of ATP in cells?
4. Name two types of RNA and their functions.
5. How are nucleotides linked in a polynucleotide chain?

Long answer-based questions

1. Explain the Watson and Crick model of DNA and its significance.

2.10 Knowledge

Central Dogma

The genetic information is stored in DNA, which serves as the primary source. This information is transcribed into RNA and then translated into proteins. This process is known as the central dogma (see Figure 2.45).

Transcription

The first step of the central dogma involves the transfer of genetic information from DNA to RNA. This process begins when an enzyme called **RNA polymerase** binds to a specific binding site on DNA known as a **promoter** located upstream of the gene. The enzyme progresses along the DNA strand, synthesizing a complementary mRNA copy of the gene. Transcription continues until RNA polymerase encounters a stop signal at the end of the gene, at that point it detaches from the DNA and releases the newly formed RNA.

Translation

The second step of the central dogma is the translation of RNA into proteins. During translation, a ribosome reads the sequence of the mRNA to synthesize a protein, converting the sequence of nucleotides into a sequence of amino acids. This step utilizes transfer RNA (tRNA) molecules, which bring amino acids in accordance with the codons on the mRNA.

Together, the two steps of central dogma (transcription and translation) serve as a means of gene expression.

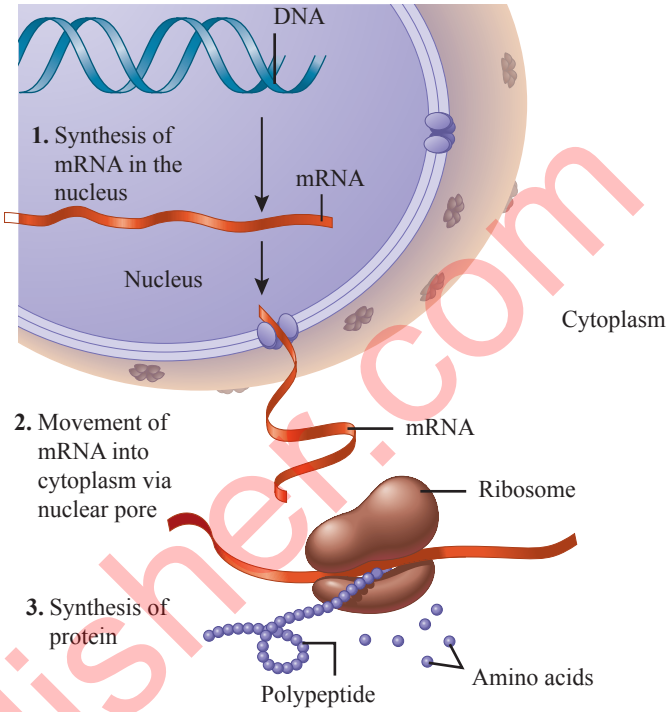


Figure 2.45: The central dogma (transcription and translation)

Skill:2.10

Objective:

- Ability to discuss and explain the processes of transcription and translation as outlined in the Central Dogma.

Test Yourself

Short answer-based questions

1. What is the central dogma of molecular biology?
2. Explain the role of tRNA during the translation process.

2.11 Knowledge

Conjugated Molecules

Two different molecules belonging to different categories combine together to form **conjugated molecules**. These conjugated structures play critical roles in biological systems, enabling more diverse

and specialized functions than the individual components alone could achieve. Following are some types of conjugated molecules:

Glycoproteins

Carbohydrates combine with proteins to form glycoproteins. These are integral components of plasma membrane and are involved in cellular secretions, immune responses, and hormone signalling.

Glycolipids

Carbohydrates combine with lipids to form glycolipids. These are also structural components of plasma membrane and are involved in cell signalling, cell recognition, and cell adhesion.

Lipoproteins

Lipoproteins are formed by the combination of lipids and proteins. These travel through the bloodstream, delivering lipids to cells throughout the body. They are the basic structural frameworks of cell membrane.

Nucleoproteins

Nucleic acids have a special affinity for basic proteins. When they combine, they form nucleoproteins. The nucleohistones (nucleic acid and histone proteins) are present in chromosomes. These conjugated proteins are not only of structural significance but also play an important role in the regulation of gene expression.

Skill:2.11

Objective:

- Ability to describe the roles and significance of common conjugated molecules in biological systems.

Test Yourself

Short answer-based questions

1. What is the function of nucleoproteins in cells?

Key Points

- Biochemistry is the branch of biology that deals with biochemical basis of life.
- The structural integrity and function of biological molecules are governed by various bonds and interactions, including hydrogen bonds, covalent bonds, ionic bonds, and hydrophobic/ hydrophilic interactions, each contributing uniquely to the complexity and diversity of life.Water is one of the best solvents, regulate temperature of the body and has high absorbing capacity.
- Condensation is a process in which large organic molecules are synthesized and water molecules is removed.
- Hydrolysis is a process in which large organic molecules is broken down and involves the addition of water molecules.
- Carbon is present in all organic compound with a covalent bonding capacity of four.
- Carbohydrates are generally the hydrated carbons which are composed of carbon, hydrogen and oxygen.
- Carbohydrates are classified into monosaccharides, disaccharide and polysaccharides.
- Starch is a common polysaccharides found in plants.
- Carbohydrates provide energy, a building material of different body structure and are
- storage molecules.
- Proteins contain carbon, hydrogen, oxygen and nitrogen. Proteins are made up of amino acids.
- The amino acids bond together by peptide linkage which produce polypeptides chains.
- Proteins molecules may be fibrous e.g. keratins or globular e.g. haemoglobin.
- Proteins may be primary, secondary, tertiary and quaternary depending on their different level of structural organization.
- Lipids are mainly composed of carbon, hydrogen and oxygen.
- The most abundant lipids in living things are the triglycerides.
- Triglycerides are with three fatty acid chains bonded to one molecules of glycerol.
- Fatty acid may be saturated or unsaturated.
- Lipids are important as storage molecules, building material and as insulators.
- Monoucleotides may have single phosphate group e.g. adenosinemonophosphate (AMP), two phosphate groups e.g. Adenosine di phosphate (ADP) or three phosphate group e.g. Adenosine triphosphate (ATP).

- When more than two nucleotides join together they form polynucleotides e.g. DNA and RNA.
- The two nucleic acid are deoxyribonucleic acid (DNA) and ribonucleic acid (RNA).
- DNA is the heredity material. It controls the properties and potential activities of a cell. It is made of four kinds of nucleotides namely adenosine monophosphate (AMP), guanosine monophosphate (GMP), cytidine monophosphate (CMP), and thymidine monophosphate (TMP).
- RNA is a polymer of nucleotides like DNA but in it thymine is replaced by uracil nitrogenous base.
- Three types of RNA are transfer RNA (tRNA), messenger RNA (mRNA) and ribosomal RNA (rRNA).
- Conjugated molecules are glycoproteins, nucleoproteins, glycolipids and lipoproteins.

Extensive Exercise

Encircle the most suitable answer

1.What is the nature of the bond formed between two water molecules in liquid water?

a) Ionic bond **b)** Covalent bond
c) Hydrogen bond **d)** Hydrophobic interaction

2.Which type of interaction helps stabilize the structure of proteins by attracting water molecules to their polar regions?

a) Hydrophobic interactions **b)** Hydrogen bonds
c) Ionic bonds **d)** Hydrophilic interactions

3. Which of the following is a disaccharide?

a) Glucose **b)** Ribose
c) Sucrose **d)** Glyceraldehyde

4.What type of linkage is found in cellulose?

a) α 1,4-glycosidic linkage **b)** β 1,6-glycosidic linkage
c) β 1,4-glycosidic linkage **d)** α 1,6-glycosidic linkage

5. What is the significance of the R group in an amino acid?

a) It determines the peptide bond. **b)** It determines the individual chemical properties of amino acids.
c) It is always a hydrogen atom. **d)** It is the same in all amino acids.

6. Which type of bonding is crucial in maintaining the α-helix structure of proteins?

a) Peptide bonds **b)** Disulfide bridges
c) Hydrogen bonds **d)** Ionic bonds

7. What is the primary component of cell membranes among lipids?

a) Steroids **b)** Terpenes
c) Phospholipids **d)** Waxes

8. Which of the following is true about prostaglandins?

a) They are a type of phospholipid.
b) They act as local hormones in various tissues.
c) They are primarily energy storage molecules.
d) They are insoluble in organic solvents.

9. Which molecule is essential for the transfer of genetic information from DNA to proteins?

a) tRNA **b)** mRNA
c) rRNA **d)** ATP

10. What is the structural basis of DNA according to the Watson and Crick model?

a) Single helix **b)** Triple helix
c) Double helix **d)** Quadruple helix

Restricted Response Questions

1. Define the following terms:

a) Biochemistry
b) Molecular biology
c) Specific heat capacity
d) Heat of vapourization
e) Acylglycerol
f) Terpenes
g) Waxes
h) Steroids
i) Prostaglandins
j) phosphodiester bond
k) aminoacyl-tRNA
l) Central Dogma
m) Conjugated molecules

2. Differentiate between the following terms:

a) Hydrophobic interactions & Hydrophilic interactions
b) Condensation & Hydrolysis
c) Aldoses & Ketoses
d) Furanose & Pyranose
e) Structural isomers & Stereoisomers
f) α-glucose & β- glucose
g) Reducing sugar & non reducing sugar
h) Homopolysaccharides & Heteropolysaccharides
i) Essential amino acids & non-essential amino acids
j) Fibrous proteins & Globular proteins
k) Structural Proteins & Functional proteins
l) Nucleoside & Nucleotide

3. How do hydrophobic interactions contribute to the structure of cellular membranes?
4. What is isomerism? Give isomers of glucose.
5. Give the role of a structural and a functional protein.
6. Describe the peptide bond formation between two amino acids.
7. What unique properties of water make it essential for life?
8. What determines the primary structure of a protein?
9. Explain the difference between saturated and unsaturated fatty acids.
10. Describe the structure of a nucleotide and its components.
11. Define conjugated molecules and give an example of such a molecule in biological systems.
12. Discuss the importance of phosphodiester bonds in the structure of nucleic acids.

Extended Questions

1. Explain the Condensation and Hydrolysis process with examples of formation and breaking of maltose.
2. Describe different isomers and sterioisomers of glucose
3. Write a detailed note on disaccharides with examples.
4. What is Acylglycerol? Describe its properties in detail.
5. Write an extensive note on Ribonucleic Acid (RNA) and its types.