بِسۡمِ اللّٰہِ الرَّحۡمٰنِ الرَّحِیۡمِ

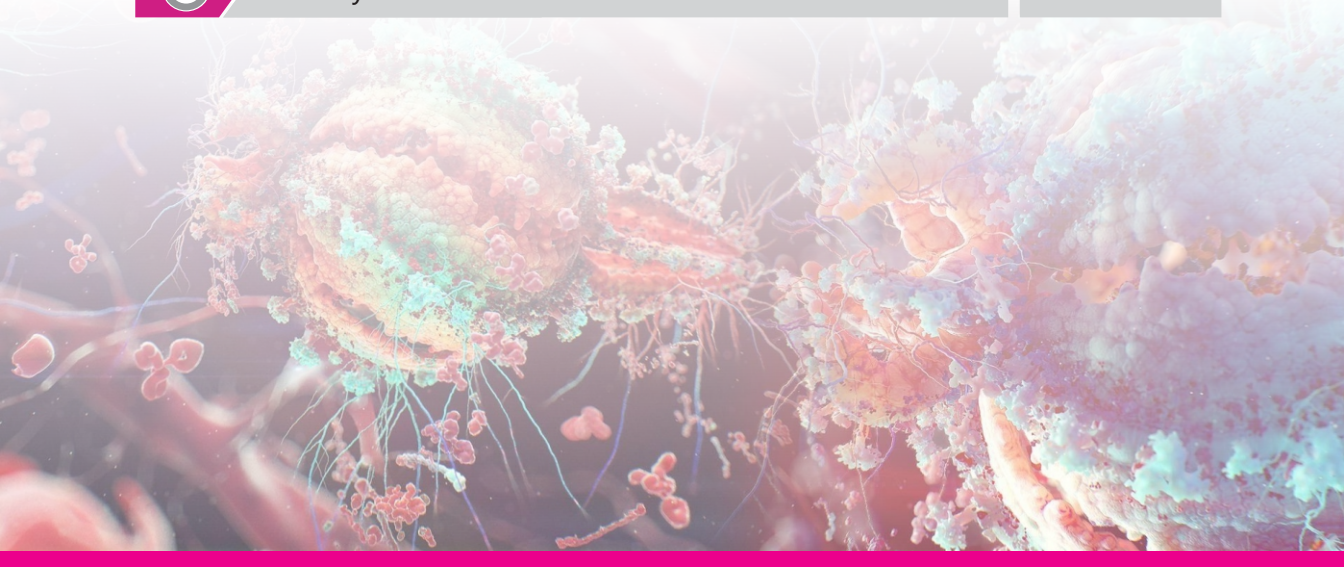
(In the Name of Allah, the Most Compassionate, the Most Merciful.)

Biology

11

Punjab Education, Curriculum, Training and Assessment Authority

Table of Contents



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Chapter 1

BIODIVERSITY & CLASSIFICATION

STUDENTS' LEARNING OUTCOMES

After studying this chapter, the students will be able to:

- Discuss the meaning of the terms species and speciation.
- Describe the classification of organisms into three domains: Archaea, Bacteria and Eukarya.
- Describe the classification of organisms in the Eukarya domain into the taxonomic hierarchy of kingdom, phylum, class, order, family, genus and species.
- Outline the characteristic features of the kingdoms Monera, Protoctista, Fungi, Plantae and Animalia.
- Outline how viruses are classified.
- Define the terms ecosystem and niche.
- Explain the different levels at which biodiversity can be assessed.
- Explain the importance of random sampling in determining the biodiversity of an area.
- Describe and use suitable methods to assess the distribution and abundance of organisms in an area.

Biodiversity and classification are fundamental concepts in biology that provide insight into the vast array of life forms on Earth and their evolutionary relationships. In this chapter, we will study the biodiversity, highlighting the variety of life at genetic, species, and ecosystem levels. We will also explore the principles and methods of biological classification, which scientists use to organize and categorize organisms.

1.1- THREE-DOMAIN SYSTEM OF CLASSIFICATION

According to the five-kingdom classification system, proposed by American ecologists **Rebert Whittaker** in 1969, all organisms were divided into five kingdoms i.e., Monera, Protista, Fungi, Plantae, and Animalia. According to this system, the kingdom Monera included prokaryotes while all the other four kingdoms included eukaryotes. In 1990, American microbiologist **Carl Woese** suggested that there are two separate groups of prokaryotes i.e., Archaea and Bacteria. On the basis, he classified living organisms into three domains i.e., domain Archaea, domain Bacteria and domain Eukarya. According to his three-domain

The evolutionary relationship among organisms is called **phylogeny**. The diagram to show phylogeny, is called phylogenetic or evolutionary tree.

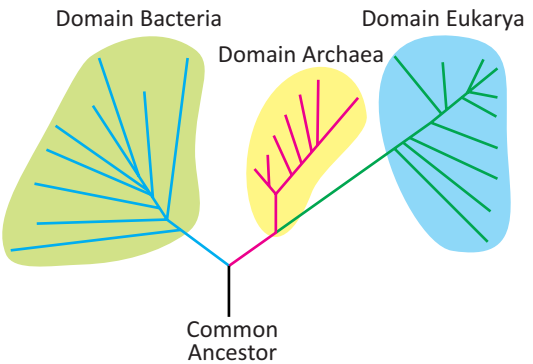


Figure 1.1: Evolutionary tree of the three domains

system, domain Archaea and domain Bacteria contain prokaryotes but they differ in a number of features.

Now biologists believe that Archaea and Bacteria evolved independently from some common ancestor. Molecular evidence suggests that archaea are more closely related to eukaryotes than to bacteria. In other words, Eukarya evolved from Archaea, after archaea split off from the Bacteria (Figure 1.1).

Domain Archaea

In the five-kingdom system, this domain was included in kingdom Monera. The name Archaea comes from the Greek *archaios* ("ancient"). They are prokaryotes which diverged from bacteria in very ancient times. Individual archaeans range from 0.1 µm to over 15 µm in diameter. Some form aggregates or filaments up to 200 µm in length. They occur in various shapes, such as spherical, rod-shape, spiral, lobed, or rectangular. Archaea reproduce asexually by binary or multiple fission, fragmentation, or budding. Mitosis and meiosis do not occur in archaea.

Archaea were initially classified as a group of bacteria, and were called archaebacteria.

How are Archaea unique?

Cell Membrane:

Their cell membrane contains lipids with ether-linkage between glycerol and fatty acid chains. The fatty acid chains are branched. That's why their cell membranes are more resistant to extreme conditions.

On the other hand, bacteria and Eukarya have membrane lipids with fatty acids attached to glycerol by ester linkages. The fatty acid chains are unbranched.

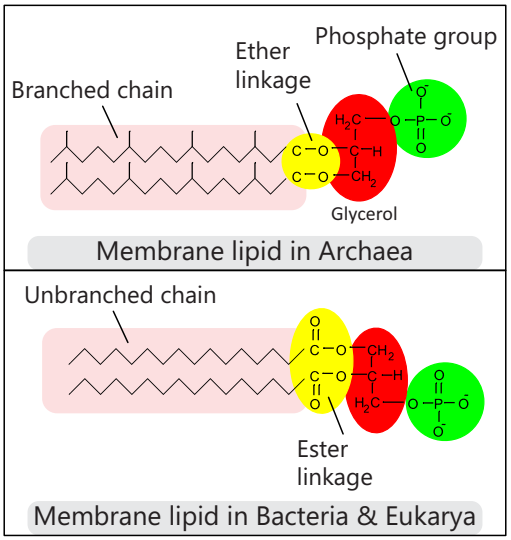


Figure 1.2: Difference in membrane lipids of Archaea and other organisms

Cell Wall Composition:

The cell walls of archaea lack cellulose and peptidoglycan. Instead, they contain distinct polysaccharides and proteins. Some archaea have pseudopeptidoglycan.

On the other hand, bacterial cell walls contain peptidoglycan, a polymer consisting of sugars and amino acids that provides structural support. In Eukarya, the cell walls, if present, are composed of cellulose (in plants) or chitin (in fungi).

Genetic Differences:

Archaea share several genetic sequences and regulatory features with eukaryotes, highlighting their closer evolutionary relationship.

Significance of Archaea

The archaeans which live in high acidity and alkalinity are a source of enzymes that can function under harsh conditions. For example, the enzymes of DNA replication have been extracted from such archaeans. These enzymes can work best at high temperatures and allow rapid cloning of DNA in laboratory. Similarly, the methanogen archaeans are a vital part of sewage treatment. They carry out anaerobic digestion and produce biogas. Acidophillic Archaea are used to extract metals such as gold, cobalt and copper from ores in mineral processing.

Metabolism:

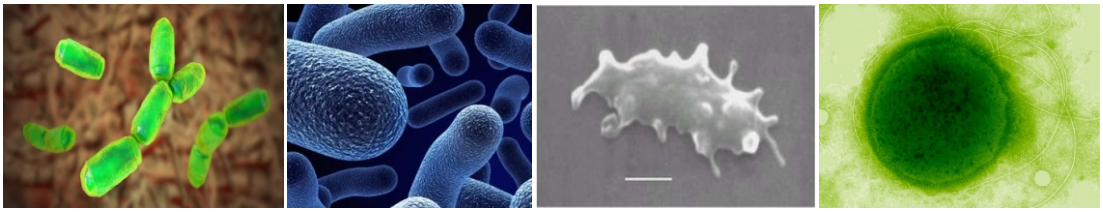
Archaea have unique metabolic processes like methanogenesis (production of methane), which is not found in bacteria or Eukarya.

On the other hand, bacteria exhibit metabolic pathways, including photosynthesis, nitrogen fixation, and fermentation. In Eukarya, the metabolic processes are often more complex and include cellular respiration, photosynthesis (in plants and algae), and various forms of fermentation.

Major Groups of Archaea

The major groups of Archaea include Methanogens (produce methane as a metabolic by-product), Halobacteria (live in extremely saline environments), Thermococci (found in hot environments), and Thaumarchaeota (involved in nitrogen cycle).

In humans, intestinal gas is largely the result of the metabolism of methanogens.



Methanogens Halobacteria Thermoplasmata Thermococci

Figure 1.3: Major groups of Archaea

Domain Bacteria

In the five-kingdom system, this domain was included in kingdom Monera. They are the true bacteria. They possess several distinct characteristics that differentiate them from other domains i.e., Archaea and Eukarya. Here are the general characteristics of the domain Bacteria:

1. Cell Structure: Like archaea, bacterial possess prokaryotic cell i.e., lack a true nucleus and membrane-bound organelles.

2. Cell Wall Composition: Bacteria have a cell wall composed of peptidoglycan, a unique polymer that provides structural support and shape.

3. Genetic Material: Like Archaea bacteria possess a single, circular chromosome composed of DNA, located in the nucleoid region.
4. Plasmids: Most bacteria have small, circular DNA molecules that can be transferred between bacteria, aiding in genetic diversity and adaptation.
5. Reproduction: Bacteria primarily reproduce asexually through binary fission, a process where a single cell divides into two identical daughter cells.
6. Nutritional Modes : Include autotrophs (self-feeding, e.g., photosynthetic bacteria) and heterotrophs (feeding on organic matter, e.g., decomposers).
7. Morphology : Bacteria exhibit a variety of shapes, such as cocci (spherical), bacilli (rod-shaped), spirilla (spiral-shaped), and vibrios (comma-shaped).
8. Arrangement: Cells may be found singly, in pairs (diplococci), chains (streptococci), clusters (staphylococci), or other arrangements based on species-specific characteristics.
9. Flagella: Many bacteria have one or more flagella, whip-like structures that enable movement.
10. Pili and Fimbriae: These are hair-like structures in some bacteria. They help in attachment to surfaces and in exchange of genetic material with other bacteria.
11. Respiration: Bacteria can be obligate aerobes, obligate anaerobes, facultative anaerobes, microaerophiles, or aerotolerant anaerobes. Some bacteria perform fermentation to produce energy in the absence of oxygen.
12. Extremophiles: Some bacteria thrive in extreme conditions, such as high temperatures (thermophiles), high salinity (halophiles), and low pH (acidophiles).
13. Pathogenicity: Some bacteria cause diseases in humans, animals, and plants, producing toxins or other virulence factors.
14. Symbiosis Many bacteria live in symbiotic relationships with other organisms, including mutualism (both benefit) and commensalism (one benefits, the other is not harmed).

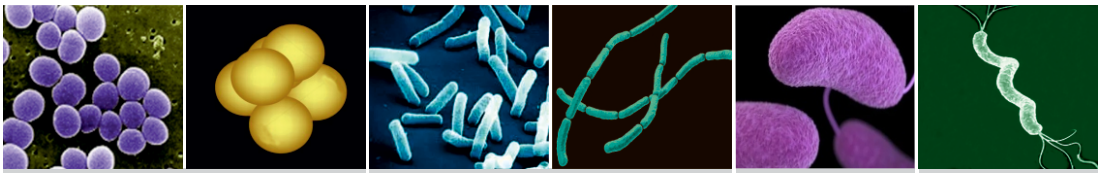


Figure 1.4: Different forms of Bacteria

Major Groups of Bacteria

The domain Bacteria is divided into numerous groups. For example;

- Proteobacteria e.g., *Escherichia coli*, *Rhizobium*, *Helicobacter pylori*.
- Firmicutes e.g., *Bacillus subtilis*, *Lactobacillus*, *Clostridium botulinum*.

- Actinobacteria e.g., *Streptomyces*, *Mycobacterium tuberculosis*
- Cyanobacteria e.g., *Anabaena*, *Spirulina*.
- Spirochaetes e.g., *Treponema pallidum*,
- Acidobacteria e.g., *Acidobacterium*.
- Aquificae e.g., *Aquifex pyrophilus*.

Domain Eukarya

The domain Eukarya encompasses all organisms with eukaryotic cells, which are fundamentally different from the prokaryotic cells of Bacteria and Archaea. Here are the general characteristics of the domain Eukarya that justify its classification as a separate domain:

1. Cell Structure: They possess eukaryotic cells - with true nucleus enclosed by a nuclear membrane. Cells have membrane-bounded organelles e.g., mitochondria, chloroplasts (in plants and algae), endoplasmic reticulum, Golgi apparatus, lysosomes, and peroxisomes. Cells also have cytoskeleton i.e., a complex network of microtubules, microfilaments, and intermediate filaments that provides structural support, enables cell movement, and facilitates intracellular transport.

2. Genetic Material: Their DNA is organized into multiple linear chromosomes within the nucleus. DNA is associated with histone proteins, which help in the organization and regulation of genetic material.

3. Reproduction: Most eukaryotes undergo sexual reproduction involving meiosis and fertilization, leading to genetic diversity. Some eukaryotes can also reproduce asexually through mitosis, producing genetically identical offspring.

5. Complex Cellular Organization: In multicellular eukaryotes, cells differentiate into specialized types forming tissues and organs with specific functions.

6. Evolutionary Relationships: Eukaryotes are believed to have originated through endosymbiosis, where certain prokaryotic cells (such as mitochondria and chloroplasts) were engulfed by a host cell, leading to a symbiotic relationship.

1.2- Taxonomic Hierarchy

The classification of living organisms is organized into a hierarchical system that allows scientists to categorize and understand the relationships between different forms of life. This system includes several levels, known as **taxa** (singular: taxon), each representing a rank in the biological classification system. The primary levels of this hierarchy are: kingdom, phylum, class, order, family, genus, and species. Below is a detailed description of each level.

1. Domain

It is the highest level of classification. Currently, there are three domains: Archaea, Bacteria, and Eukarya.

2. Kingdom

The kingdom is one of the highest taxonomic ranks, just below domain. It groups together all forms of life that share fundamental characteristics.

- Example: In the domain Eukarya, there are several kingdoms, such as Animalia (animals), Plantae (plants), Fungi (fungi), and Protista (protists).

3. Phylum

Phylum is the next level of classification below kingdom. Organisms within a phylum share a basic body plan and significant structural features.

- **Example:** In the kingdom Animalia, the phylum Chordata includes all animals with a notochord, such as mammals, birds, reptiles, amphibians, and fish.

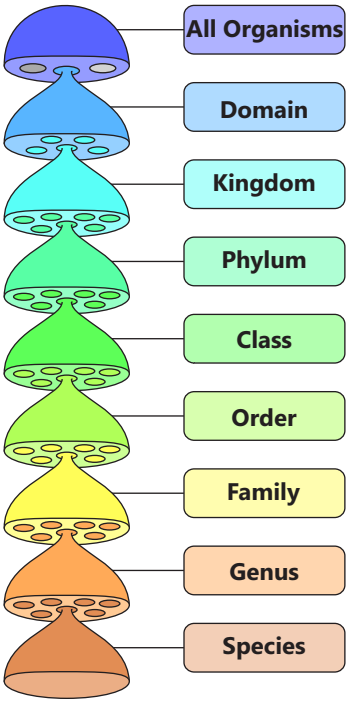


Figure 1.5: Taxonomic hierarchy

4. Class

Class further divides organisms within a phylum based on more specific common traits.

- **Example:** Within the phylum Chordata, the class Mammalia includes all mammals, which are characterized by having hair and mammary glands.

5. Order

Order categorizes organisms within a class based on additional shared characteristics and evolutionary history.

- **Example:** Within the class Mammalia, the order Primates includes humans, monkeys, and apes, characterized by their large brains and opposable thumbs.

6. Family

Family groups organisms within an order that are even more closely related, sharing more precise common attributes.

- **Example:** Within the order Primates, the family Hominidae includes great apes and humans.

7. Genus

Genus is a more specific rank within a family, grouping species that are very closely related and often visually similar.

- **Example:** Within the family Hominidae, the genus Homo includes humans and our closest extinct relatives.

8. Species

Species is the most specific level of classification, representing a single type of organism. Members of a species can interbreed and produce fertile offspring.

- **Example:** Within the genus Homo, the species Homo sapiens refers to modern humans.

Taxonomic Rank	Human (*Homo sapiens*)	Sparrow (*Passer domesticus*)	Onion (*Allium cepa*)
Domain	Eukarya	Eukarya	Eukarya
Kingdom	Animalia	Animalia	Plantae
Phylum	Chordata	Chordata	Angiosperms
Class	Mammalia	Aves	Monocots
Order	Primates	Passeriformes	Asparagales
Family	Hominidae	Passeridae	Amaryllidaceae
Genus	Homo	Passer	Allium
Species	*Homo sapiens*	*Passer domesticus*	*Allium cepa*

1.3- Salient Features of Kingdoms of Domain Eukarya

Eukarya consists of kingdoms protista, fungi, plantae and animalia. It includes all eukaryotes which consist of complex, eukaryotic cells containing nucleus and other membrane-bound organelles.

1. Kingdom Protista

Kingdom Protista includes eukaryote which are unicellular or colonial or filamentous or simple multicellular. Simple multicellular means that they do not have multicellular sex organs. There are three types of protists.

Certain protists are parasitic and cause diseases like malaria (Plasmodium), amoebic dysentery (Entamoeba histolytica), and sleeping sickness (Trypanosoma).

Major Groups or Protists

- The group Protozoa includes animal-like protists. They are unicellular and are heterotrophic. Examples are Paramecium, Amoeba, .Plasmodium, and Trypanosoma.
- The group Algae includes plant-like protists. They have cell walls made of cellulose. They have chlorophyll and are autotrophs. Examples include *Euglena*, diatoms.
- The groups Myxomycota and Oomycota include Fungi-like protists. They have hyphae-like structure and are saprophytic e.g., slime molds and water molds.

Figure 1.6: Common protists

2. Kingdom Fungi

Fungi are eukaryotic, heterotrophic organisms that are unicellular or multicellular. Their cells are covered by cell wall made of chitin (a polysaccharide). Fungi get nutrients in a unique way. They do not ingest food like animals and some protists. They absorb food from surroundings. Examples are mushrooms, rusts, smuts and molds.

Some fungi are used in the production of bread, cheese and beer. Others have medicinal properties, such as penicillin, an antibiotic derived from the fungus *Penicillium*.

Makro Groups of Fungi

There following are the major groups of fungi:

- Zygomycota includes the fungi which lack septa in their hyphae. Examples are Rhizopus (bread molds), which grow on moist bread, fruits etc.
- Ascomycota includes the largest groups of fungi. They have septate hyphae. Examples include common molds, morels, truffles, cup fungi, Neurospora and yeasts.
- Basidiomycota includes the fungi with septate hyphae. Examples are mushrooms, toadstools, puffballs, jelly fungi and bracket/shelf fungi, rusts and smuts.

There are about 100,000 known species of fungi. Most of the Ascomycetes are found in lichens and some are found in mycorrhizae.

Figure 1.7: Common fungi

3. Kingdom Plantae

It includes plants which are eukaryotic, multicellular organisms with cell walls made of cellulose.They are autotrophic and prepare food through photosynthesis. All

plants develop from embryos. Examples are mosses, ferns, conifers and flowering plants.

Major Groups of Plants

Plants are divided into two major groups:

- Nonvascular plants or bryophytes lack conducting tissues (xylem and phloem). Examples include liverworts, hornworts, and mosses.
- Vascular plants have conducting tissues. Vascular plants are of two types i.e., seedless plants (e.g., ferns) and seed plants (e.g., conifers and flowering plants).

Moss

Liverwort

Hornwort

Nonvascular plants

Sago palm

Pine

Cedrus

Ginkgo biloba

Seedless vasculaplants

Capsicum

Mustard

Seed plants

Figure 1.8: major groups of Kingdom Plantae

Table: Distinguishing Characteristics of the kingdoms of three domains						
Domain	**Bacteria**	**Archaea**	**Eukarya**			
Kingdom	**Monera**		**Protista**	**Fungi**	**Plantae**	**Animalia**
Cell Type	Prokaryotic	Prokaryotic	Eukaryotic	Eukaryotic	Eukaryotic	Eukaryotic
Nuclear Envelope	Absent	Absent	Present	Present	Present	Present
Presence of Cell Wall	In all	In all	In some	In All	In all	Absent
Composition of Cell Wall	Peptidoglycan	Various chemicals	Various chemicals	Chitin	Cellulose and other polysaccharides	No Cell wall
Mode of Nutrition	Autotroph or heterotroph	Autotroph or heterotroph	Photosynthetic or heterotroph, or combination	Absorptive heterotroph	Photosynthetic autotrophs	Ingestive heterotroph
Multi - cellularity	Absent	Absent	Absent in most forms	Present in most forms	Present in all forms	Present in all forms

4. Kingdom Animalia

This kingdom of eukaryotes includes animals which are eukaryotic, multicellular and heterotrophic. They develop from embryos. They ingest food and digest it within their bodies.

1.4- CLASSIFICATION OF KINGDOM ANIMALIA

The kingdom Animalia is broadly divided into the following phyla.

1- Phylum Porifera

This phylum contains sponges. Most of them are marine while some live in freshwaters. *Leucosolenia* and *Euplectella* (Venus' flower basket) are marine sponges. *Spongilla* is a common freshwater sponge.

A commercial sponge is prepared by drying, beating, and washing a sponge until all cells are removed.

Sponges do not have tissue level organization. Most sponges are asymmetrical but some have radially symmetry. They do not have nervous system. There are numerous pores in body wall called ostia. Through ostia, water enters the body. The larger pore through which water leaves the body is called osculum. The outer layer of body is made of thin, flat cells called pinacocytes. The second layer is jelly-like and is called mesohyle. It contains amoeboid cells. The third layer, which lines the spongocoel, is made of choanocytes or collar cells. They have skeleton in the form of minute needles of calcium carbonate or silica. Most sponges reproduce asexually by budding or regeneration. Some sponges form resistant capsules, called gemmules. When parent sponge dies, it releases its gemmules. In favourable environment, amoeboid cells come out of the gemmules and form a new sponge.

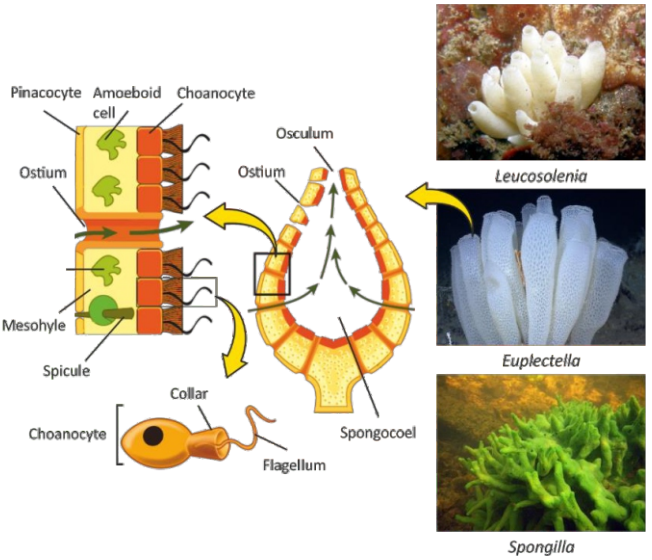


Figure 1.9: Representative sponges and general structure

2- Phylum Cnidaria

Almost all cnidarians are marine, although a few are found in freshwater e.g., *hydra* and jellyfish. Most cnidarians are colonial e.g., *obelia*, corals, sea fans etc. Most of them are sessile e.g., *hydra*, coral, *obelia* etc. Some cnidarians are motile e.g., jellyfish.

They are radially symmetrical animals and are diploblastic. It means that the adult body contains two tissue layers i.e., the epidermis and the gastrodermis, derived from ectoderm and endoderm respectively. Between the epidermis and gastrodermis, a jelly-like mesoglea is present. It contains amoeboid cells that have originated either from ectoderm or endoderm. They possess special cells, called cnidocytes. A cnidocyte contains a special organelle, called nematocyst. Nematocysts defend the body and captures prey. Cnidarians have a blind-ending cavity, called gastrovascular cavity or enteron. It opens outside by a single opening, the mouth. Mouth also acts as anus for the removal of undigested material. Mouth is surrounded by a series of projections, called tentacles. This types of digestive system in which there is a single opening for the entry of food and removal of undigested matter, is called **sac- like** digestive system.

Corals are colonial cnidarians. They produce hard exoskeleton of Calcium carbonate. The skeleton makes coral islands and coral reefs.

Coral reef

The nervous system is in the form of a network of neurons in the body wall. There is no central nervous system (brain and spinal cord). They do not have respiratory,

excretory and transport systems. There are two body forms in cnidarians i.e., polyps and medusae. **Polyps** are cylindrical and are attached to a substrate at the aboral end. They reproduce asexually. **Medusae** are umbrella-like and are free-swimming. They reproduce sexually.

Figure 1.10: Representative cnidarians

3- Phylum Platyhelminthes

They are called "flatworms". They are unsegmented and body is soft and dorsoventrally compressed. Most of them are free-living e.g., planaria. Some are endoparasites of humans and other animals e.g., liver fluke, tapeworm, and blood-fluke.

They are triploblastic i.e., the tissues of the body are derived from three embryonic layers; ectoderm, mesoderm and endoderm. They are acoelomates. A loose connective tissue called parenchyma fills space between the body wall and body organs. They have bilateral symmetry with distinct left and right sides as well as dorsal and ventral sides. They do not have respiratory and circulatory (transport) systems. They have a network of tubular protonephridia. These tubules have numerous branches. Each branch ends in a bulb-like cell called flame cell. The cilia of flame cells beat to suck surrounding fluid into the tubules. The tubules filter the waste materials from fluid and release them out of body wall through a small opening called a nephridiopore. They have a network of neurons. There are cerebral ganglia in the anterior end (head). These ganglia are attached to longitudinal nerve cords that are interconnected across the body by transverse branches. Most free-living flatworms have two simple eyespots at their anterior end. Flatworms reproduce asexually by "fission" in which the animal constricts in the middle and then divides into two pieces. Each piece then regenerates the missing part. The sexually-reproducing flatworms are hermaphrodites (bisexual).

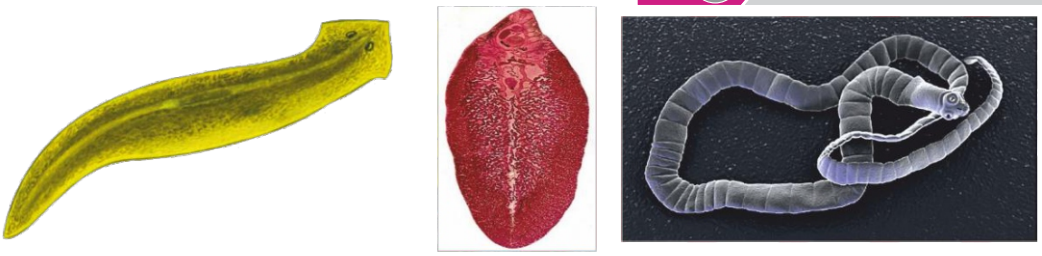


Figure 1.11 : Representative flatworms

4- Phylum Nematoda

The pseudocoelomates are classified in seven phyla. These phyla are grouped as a unit called Aschelminths. Phylum Nematoda is the representative phylum of this group.

They are roundworms with elongated worm-like (round) body with pointed ends. Some roundworms are free-living (in water and soil) e.g., *Caenorhabditis elegans.* Many are parasites e.g., *ascaris,* hookworm, pinworm, and whipworm.

They are triploblastic, bilateral symmetrical, and possess unsegmented body. They are pseudocoelomates because they possess a false body cavity called pseudocoelom filled with fluid. They possess tube-like digestive system. It consists of an alimentary canal with two openings; mouth at anterior end and anus at posterior end. The parasitic roundworms have simplified digestive systems. Their excretory system consists of protonephridia and two excretory canals, which unite at the anterior end to form a single canal. The single canal then opens outside through a nephridiopore on the ventral surface. They possess a network of neurons in body. There is a nerve ring around the pharynx, which is attached to four longitudinal nerve cords. They have raised hair-like sense organ called sensory papillae, present on lips. They do not have defined respiratory and circulating systems. They are unisexual i.e.; male nematodes have testes and female nematodes have ovaries.

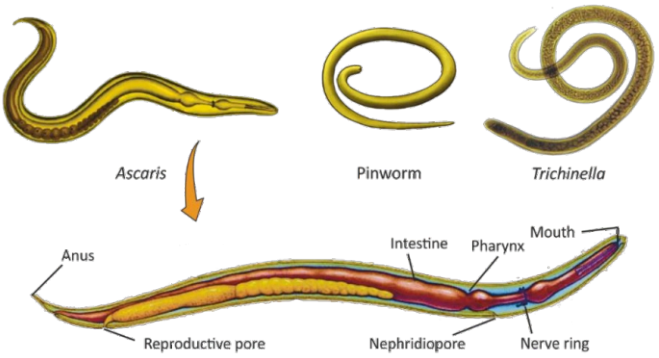


Figure 1.12: Representative roundworms and general structure

5- Phylum Mollusca

Molluscs have soft un-segmented bodies. They are widely distributed in natural habitats. Some of them are exclusively aquatic e.g., mussels, octopus and oyster. The others live in moist places e.g., land snail.

In open-type system, the blood does not retain the vessel. Rather, it directly bathes cells in tissue spaces (sinuses).

Molluscs are triploblastic and have bilateral symmetry. They possess true coelom. Among coelomates, they are included in the group called protostomes. Their body can be divided into three parts i.e., head, visceral mass (contains organs of digestion, excretion and reproduction), and foot (attached with visceral mass). They have an epithelial envelope around the visceral mass, called as mantle. The space between mantle and visceral mass is called as mantle cavity. In most molluscs, the outer surface of mantle secretes a calcareous shell. All molluscs (except bivalvia) have is a rasping tongue-like organ, called radula. All of them (except cephalopods) have open type blood circulatory system. Their heart consists of a single ventricle and two auricles. They possess tube-like digestive system in which the gut has two openings, i.e., mouth and anus. Their excretory system consists of paired tubular structures called nephridia. Wastes are gathered from sinuses and discharged into coelom around the heart. The nephridia open in this coelom. They have tiny cilia around their openings, which move the fluid from coelom into the nephridia. Nephridia discharge waste materials in mantle cavity, from where they are expelled out. In molluscs, gills work for the exchange of gases. They have three pairs of interconnected ganglia present in the head, visceral mass and foot. The ganglia are interconnected by means of nerve cord. They move with the help of muscular foot. Some molluscs are sessile. Most molluscs are unisexual.

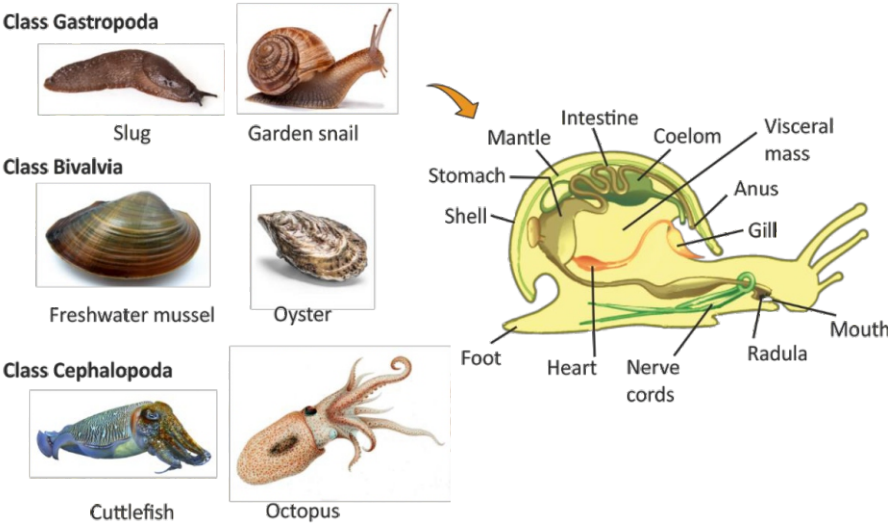


Figure 1.13: Representative molluscs and general structure

6- Phylum Annelida

Annelids are commonly called segmented worms. They are found in marine water (e.g., nereis), freshwater (e.g., leech), and in damp soil (e.g., earthworm). Some annelids are ectoparasites e.g., leeches.

Their body is divided transversely into a number of similar parts called segments. Internally, the segments are separated from each other by cross walls called septa. Each segment is provided with its own circulatory, excretory and neural elements. This type of segmentation in body is called metameric segmentation. Annelids are bilaterally symmetrical and triploblastic. They are protostome coelomates. Annelids have special parts called setae. Setae are chitinous bristles in the ventral wall of each segment. Setae are absent in leeches. Their body wall is surrounded by a moist, acellular cuticle secreted by epidermis. They possess tube-like digestive system. The digestive tube is divided into distinct parts, each performing a specific function. The parasitic annelids have simplified digestive system.

The segments are indicated externally by constrictions of the body surface in the form of little rings ("Annelid" means "little ring").

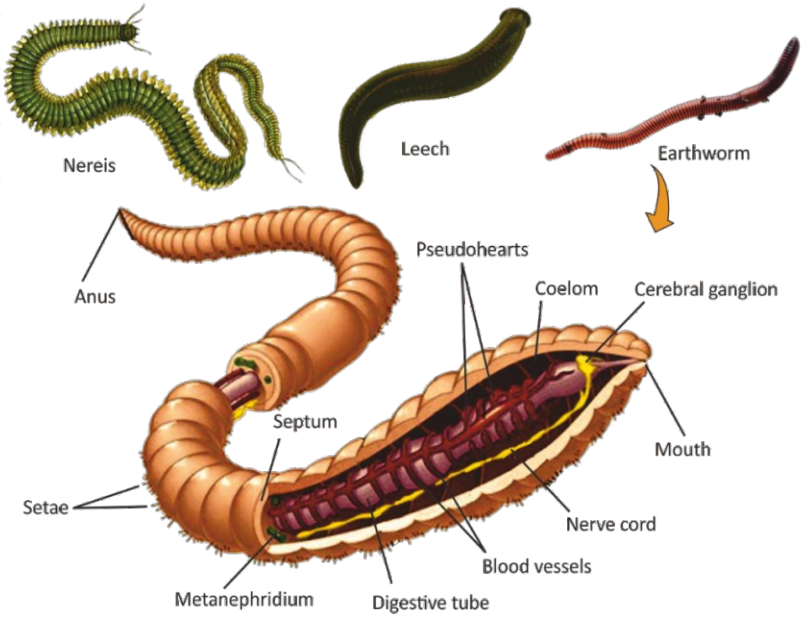


Figure 1.14: Representative annelids and general structure

Their excretory system consists of ciliated, funnel-shaped metanephridia. Each segment has one pair of metanephridia. They possess a closed-type circulatory system. Blood always flows in blood vessels. They have specialized pulsating blood vessels (pseudohearts). Blood of most annelids has respiratory pigment, haemoglobin, dissolved in blood plasma. Gaseous exchange occurs through the skin. There is a

cerebral ganglion or brain in the anterior segment. A double, longitudinal ventral nerve cord arises from brain and gives nerves in each segment. Ganglia are also present in each segment. They have tactile receptors, chemoreceptors, balance receptors, and photoreceptors. Some annelids also well-developed eyes with lenses. Most annelids are hermaphrodite (e.g., earthworm, leech) and some are unisexual (e.g., nereis).

7- Phylum Arthropoda

Diverse groups such as insects, crustaceans, spiders, scorpions, and centipedes are included in this phylum. They are found in every type of habitat. Many of terrestrial members can also fly.

Arthropods are the most successful of all invertebrates. About 900,000 species – two thirds of all the named species on Earth arthropods.

They are triploblastic, bilateral symmetrical, protostome coelomates. The coelom is reduced and is present only around reproductive and excretory systems. They have jointed appendages which are modified for specialized functions e.g., running, crawling swimming, capturing prey, respiration, reproduction etc. In different arthropods, the jointed appendages around the mouth, are modified in different ways and form mouth parts. The body is segmented. Some segments are fused to form specialized body regions called tagmata. These include head, thorax and abdomen. They have exoskeleton or cuticle, which is secreted by the epidermis of body wall. It is made chiefly of chitin. In young arthropods, exoskeleton is shed from time to time. After shedding the exoskeleton, the animal grows at a fast rate and then re-secretes new exoskeleton. This process is called ecdysis or molting.

They possess open-type circulatory system. Most of the time, blood flows in hemocoel, which is derived from an embryonic cavity called blastocoel. Their blood is colourless as it is without haemoglobin and is known as haemolymph. Most arthropods possess a respiratory system that consists of air tubes called trachea. Main tracheal tubes open out through openings called spiracles. Aquatic arthropods respire through gills. Arthropods have tube-like digestive system. The alimentary canal is divided into different parts. Their excretory system comprises of Malpighian tubules. These are narrow tubules projected from the alimentary canal, attached at the junction of midgut and hindgut. The nitrogenous wastes are excreted in the form of solid uric acid crystals. They have well-developed central nervous system with three fused pairs of cerebral ganglia (brain) in head. There is a double ventral nerve cord which has ventral ganglia in each segment. Smaller nerves arise from ventral ganglia in each segment. They have well developed compound eyes and antennae. They can swim, crawl or fly depending on their habitat.

They are unisexual.

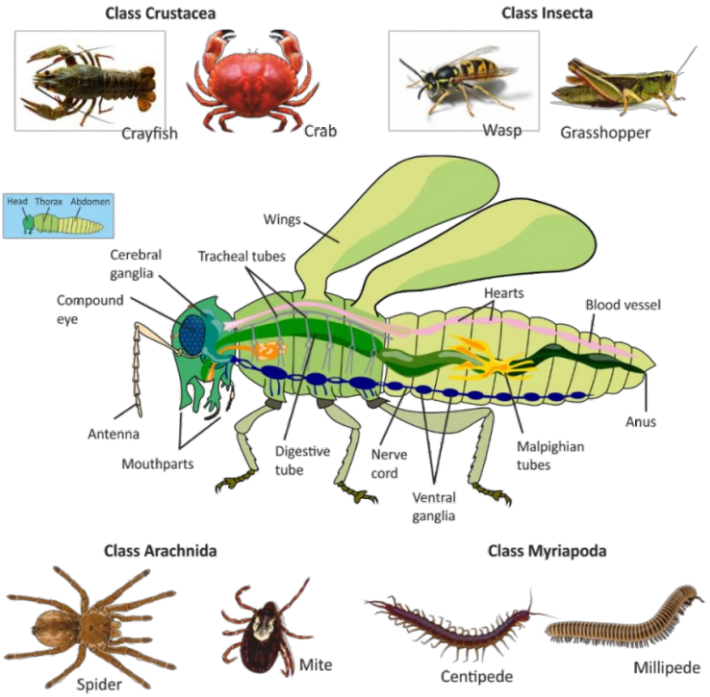


Figure 1.15: Representative arthropods and general structure

Important arthropods include insects (e.g., mosquito, butterfly, moth, wasp, beetles, grasshopper), crabs, lobsters, prawn, shrimps, crayfishes, spider, tick, mite, scorpion, centipedes and millipedes.

8- Phylum Echinodermata

They are exclusively marine animals. Some are flattened like biscuit (e.g., cake urchin), some are star-shaped with short arms (e.g., sea star or starfish), some are globular (e.g., sea urchin), some are star-shaped with long arms (e.g., brittle star), and some are elongated (e.g., sea cucumber).

They are triploblastic and deuterostomes coelomates. Their larvae are bilateral symmetrical but the adults show radial symmetry. In their radial symmetry, the body parts are arranged in five, or multiple of five, around an oral-aboral axis. They possess a calcareous endoskeleton in the form of plates called ossicles. These plates are derived from mesoderm but come out of skin also and make spines on the skin. They have water-vascular system consisting of tubes and spaces present in the coelom. A ring canal surrounds the mouth. It opens outside through a sieve-like plate, called madreporite. Five (or a multiple of five) radial canals branch from the ring canal. Many lateral canals emerge from each radial canal and each lateral canal ends at a tube foot. Tube feet are the extensions of water vascular system. The tube feet extend and attach with some substrate. When water is drawn back from the sucked tube feet, they

contracts and body is pulled. Echinoderms possess tube-like digestive system. The mouth leads to oesophagus, stomach, intestine and rectum. The rectum opens out through anus.

There are no specialized organs for respiration and excretion. They possess a poorly developed nervous system made of a nerve net, a nerve ring, and five (or multiple of five) radial nerves. Most sensory receptors are distributed over the surface of the body and tube feet. Asexual reproduction involves division of the body, followed by the regeneration of each half. Echinoderms are unisexual.

Many echinoderms are able to regenerate the lost parts, and some, especially sea stars and brittle stars, drop various parts when they are under attack and then regenerate the lost parts.

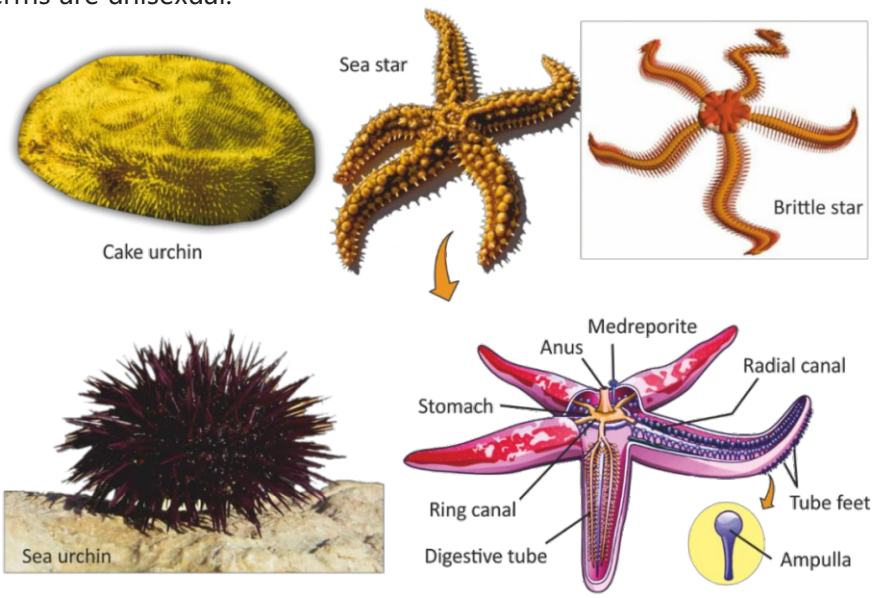


Figure 1.16: Representative echinoderms and general structure

10- Phylum Chordata

Chordates are bilateral symmetrical, triploblastic, deuterostome coelomates. The following four characteristics are unique to chordates, present at some stage in development.

1. Notochord: All chordates develop notochord during embryonic life. It is a rod-like semi rigid body of vacuolated cells. It extends throughout the length of body between gut and dorsal nerve cord. The lower chordates retain this notochord throughout life. While, in vertebrates it is partly or entirely replaced by vertebral column, during development.

2. Pharyngeal slits: These are a series of openings in the lateral walls of pharynx. All chordates develop paired gill slits in embryonic stage. In some chordates (e.g.,

Amphioxus and fishes), these develop into gills. In some (e.g., most amphibians), these are functional for some period in their life history. In others (e.g., reptiles, birds and mammals), these are modified for various purposes.

3. Tubular nerve cord: In all chordates, a tubular nerve cord runs through the longitudinal axis of the body, just dorsal to the notochord. It expands anteriorly as a brain.

4. Post anal tail: All chordates develop a tail, posteriorly beyond the anal opening. Some chordates retain it throughout life while others degenerate it during embryonic life.

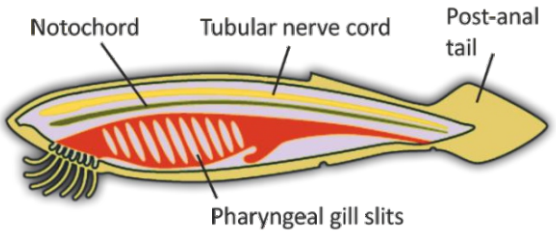


Figure 1.17: Diagnostic characters of chordates

Phylum chordata includes two major groups i.e., invertebrate chordates and vertebrates.

- **Subphylum Urochordata** includes the invertebrates chordates in which notochord and nerve cord are present only in their free-swimming larvae. Sea squirts are the examples of urochordates.
- **Subphylum Cephalochordata** includes the invertebrate chordates in which notochord persists throughout life. Amphioxus is a common cephalochordate.

Figure 1.18: Sea squirts

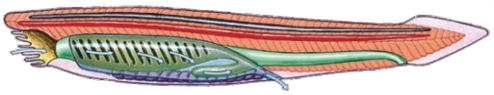


Figure 1.19: Amphioxus

- **Vertebrates:** They have a vertebral column and cranium. Vertebrates are divided into seven classes which are placed into two groups.

1.5- CLASSIFICATION OF VERTEBRATES

Vertebrates are divided into two groups.

1. **Group Pisces:** It includes 3 classes i.e., Cyclostomata, Chondrichthyes, and Osteichthyes. They do not have limbs.

2. **Group Tetrapoda:** It includes 4 classes i.e., Amphibia, Reptilia, Aves, and Mammalia. They have four limbs.

1. Class Cyclostomata

These are jawless fishes. Lampreys and hagfish are common examples. Their bodies are eel-like and not covered with scales. They possess cartilaginous skeleton. Like other fishes, they have a single-circuit heart with one atrium and one ventricle. Fertilization is external.

Figure 1.20: Jawless fishes

2. Class Chondrichthyes

The group includes sharks, skates, rays, and ratfishes. They have skeleton of cartilage. Their body is covered by placoid (tooth-like) scales, called denticles. They have jaws and biting mouthparts. The pectoral and pelvic fins are paired. There are two dorsal fins. They possess single-circuit heart with one atrium and one ventricle. There is a pair of small openings, called spiracle, behind eyes. These are used for breathing. They do not have swim bladder. Fertilization is internal.

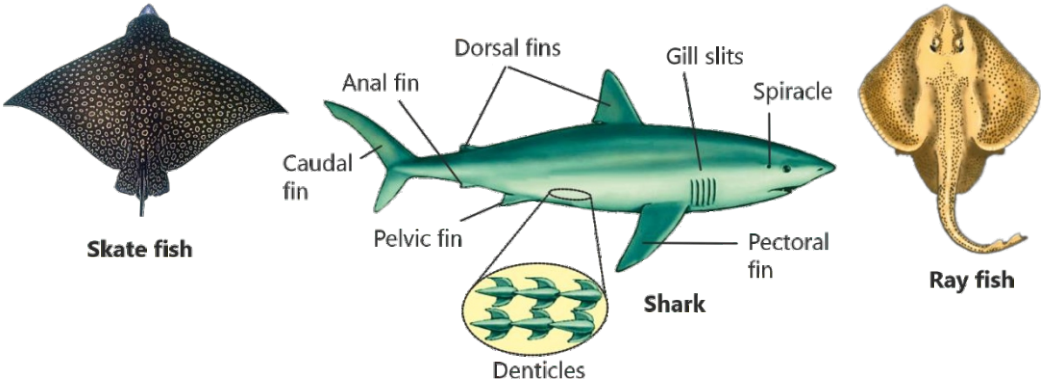


Figure 1.21: Cartilaginous fishes

3. Class Osteichthyes

The have bony endoskeleton, streamlined body, dermal bony scales, and terminal mouth with jaws (with or without teeth). Notochord is replaced by vertebral column, but some bony fishes may retain it in reduced form. They also have a swim bladder that helps in buoyancy. They possess both median (dorsal, caudal and ventral) and paired (pelvic and pectoral) fins. They contain four pairs of gills. A protective bony flap, operculum, protects the gills. They have well developed nervous system in which there are ten pairs of cranial nerves. Fertilization is mostly external. The freshwater bony

fishes include rohu, trout, Katla, catfish etc. The marine bony fishes include seahorse, flying fish and angler fish etc.

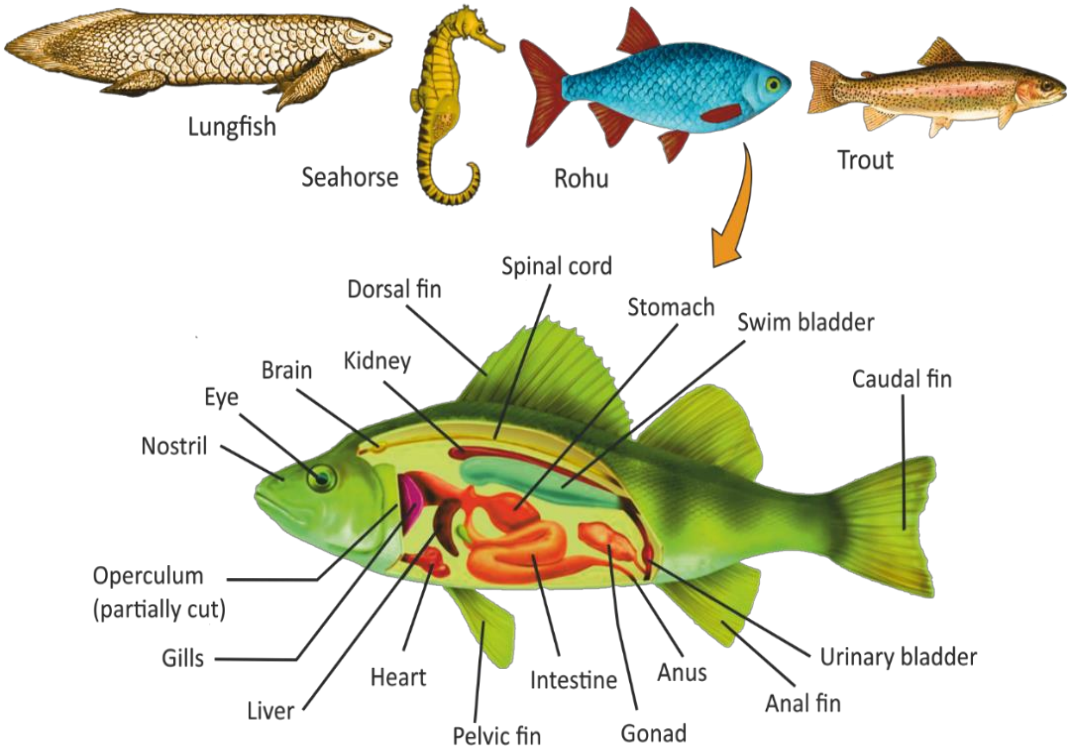


Figure 1.22: Representative bony fishes and general structure

4. Class Amphibia

It is the first class of tetrapods. They have bony endoskeleton. Unlike fishes, amphibians have a neck. The first vertebra (cervical vertebra) moves against the back of skull and allows the skull to nod vertically. Their skin is smooth (without scales) and moist. It helps in gas exchange, temperature regulation, and absorption and storage of water. Their heart is **double-circuit**. It is three-chambered, with two atria and one ventricle. They respire by gills in the larval stage and by lungs and skin in the adult stage. They depend on external heat source and so are **ectotherms**. They cannot regulate their body temperature and cannot maintain it constant. So, they are **poikilothermic** animals and hibernate in winter. Salamander, newts, and mud puppies are tailed amphibians. Frogs and toads are tail-less amphibians, and caecilians are leg-less amphibians. Amphibians are unisexual. Fertilization is usually external.

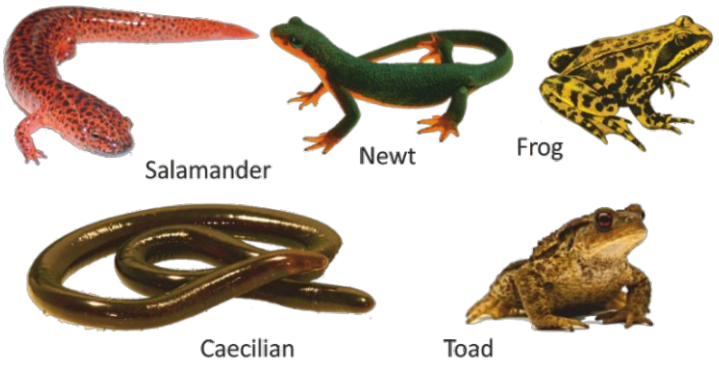


Figure 1.23: Representative amphibians

5. Class Reptilia

Reptiles are the first animal group that possess amniotic eggs. **Amniotic** eggs make protective extra-embryonic membranes i.e., amnion, allantois, and chorion. These membranes protect the embryo from drying out, nourish it and enable it to develop on land. The amniotic eggs also contain a large amount of yolk, the primary food supply for the embryo. Such eggs have abundant albumin, which provides additional nutrients and water. The amniotic eggs are also covered with leathery calcareous shell which is

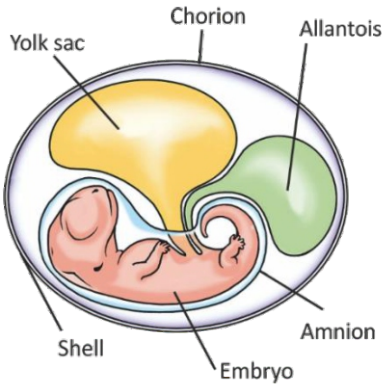


Figure 1.24: Amniotic egg

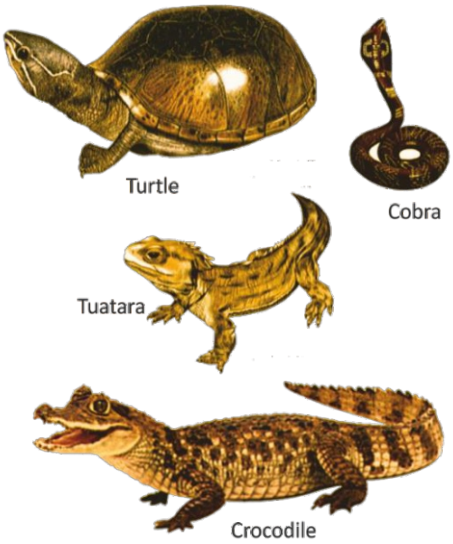


Figure 1.25: Representative reptiles

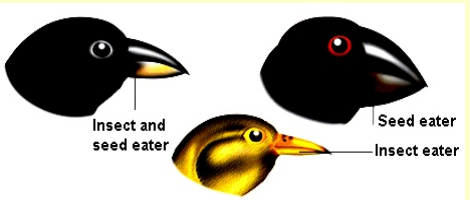
partly permeable to gases but not to water.

Reptiles have dry scaly skin. The bony endoskeleton of reptiles is harder than amphibians. The skull is longer than amphibians. In reptiles, first two cervical vertebrae (atlas and axis) allow more movements of head. In their heart, ventricle is incompletely partitioned, into left and right ventricles.

Reptiles, like amphibians, are **ectothermic** and use external heat source for thermoregulation. They cannot keep their body temperature at constant, and are **poikilotherms**. Fertilization in internal. They are oviparous (egg-laying). The present-day reptiles are lizards, snakes, tuatara and crocodiles.

6. Class Aves

Birds have a covering of feathers on the body. Feathers form the flight surfaces that provide lift and aid in steering. Feathers also prevent heat and water loss. Birds are **endotherms**. It means that they can obtain heat from cellular processes. A source of internal heat allows them to maintain a nearly constant core temperature. The animals who can maintain their core temperature are known as **homeotherms**.



Bills and tongues are modified for a variety of feeding habits and food sources.

The body of birds is streamlined and spindle shaped. The forelimbs are modified into wings. Their bones are light due to large air spaces. A lighter sheath called bill replaces the teeth. The sternum (chest bone) bears a large, bone called keel for the attachment of flight muscles.

In many birds a diverticulum of the oesophagus, called **crop**, is a storage structure that allows birds to quickly ingest large quantities of food. A region of stomach, called **gizzard**, has muscular walls to crush food. Their heart is four-chambered, with complete separation of atria and ventricles. Birds have much developed nervous system. Vision and hearing are important senses for most birds.

Their external nares open in pharynx through nasal passage ways. The pharynx leads to trachea and then bronchi. The organ of voice, called **syrinx**, is situated at the lower end of trachea. The bronchi lead to a complex system of **air sacs** that occupy much of the body and even extend to some of the bones. The air sacs connect to lungs, which are made of small air tubes called **parabronchi**.

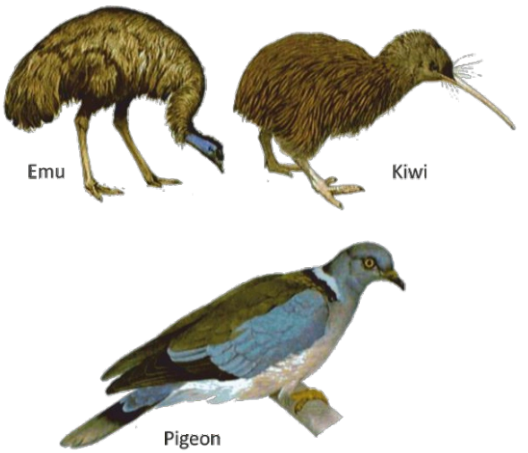


Figure 1.26: Representative birds

Like reptiles and mammals, birds have **amniotic** eggs with large amounts of yolk and albumin. Such eggs are also covered with leathery shell. In birds, fertilization is internal and development is external i.e., they are **oviparous**. Some birds have

secondarily lost the power of flight and are called **running birds** e.g., ostrich, kiwi, rhea, cassowary, and emu. The flying birds include pigeon, parrot, crow, eagle, robin etc.

7. Class Mammalia

Mammalia includes the group of vertebrates which are nourished by milk from the mammary glands of mother, and have hair on their body. Mammals have skin glands, developed from epidermis. Sebaceous (oil) glands secrete oily secretion. Sudoriferous (sweat) glands release watery secretions used in evaporative cooling. Mammary glands are functional in female mammals. Most mammals have two sets of teeth during their lives i.e., milk teeth and permanent teeth. External ear or pinna is present. The middle ear has a chain of three bones i.e., incus, malleus and stapes. Mammals are endothermic and homoeothermic animals. They possess four-chambered heart. They have a muscular diaphragm that separates the coelom into thoracic and abdominal cavities. They have well developed voice apparatus in the form of larynx (with vocal cords) and epiglottis. In mammals, fertilization is internal. There are three groups of mammals:

Most mammals (placental mammals) give birth to young ones i.e., they are **viviparous**. Some mammals lay eggs and so are **oviparous**. While some (marsupials).

1. In egg-laying mammals lay eggs in which whole development of their embryo proceeds. These mammals are found in Australia e.g., Duckbill platypus and echidna (spiny anteater).
2. Some mammals (marsupials) have a pouch (marsupium) on the abdomen of female. These mammals give birth to immature young ones which complete their development in mothers' pouch. They are called **ovoviviparous**. Opossum, kangaroo and Tasmanian wolf are the examples of such mammals.

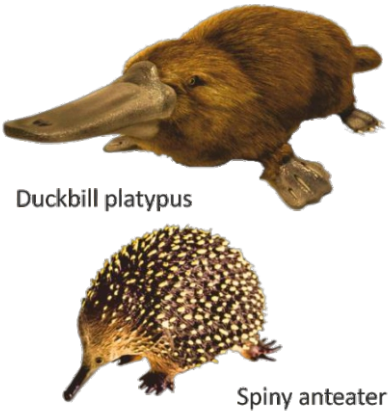


Figure 1.27: Representative egg-laying mammals

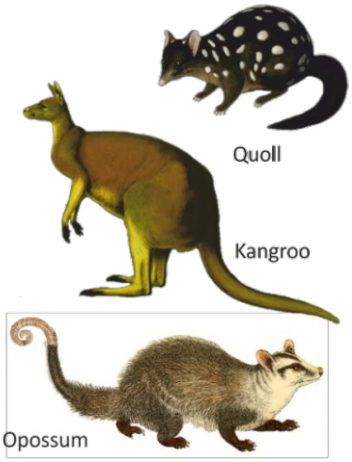


Figure 1.28: Representative pouched mammals

3. Placental mammals are the most advanced mammals. During development, a structure called placenta, is formed between mother's uterus wall and foetus body. The foetus is nourished and wastes from foetus are removed through this placenta. Dolphin, rat, monkey, bat, elephant and human are some examples of placental mammals.

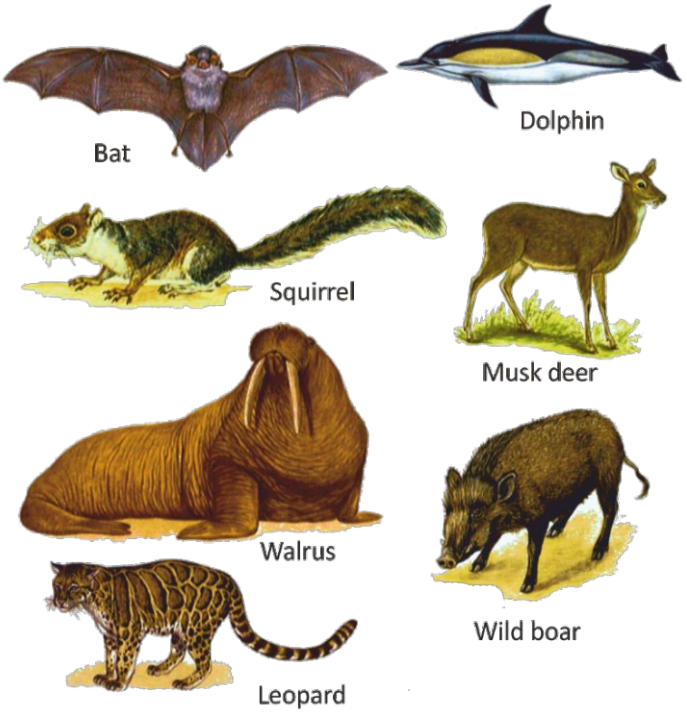


Figure 1.29: Representative eutherians

1.6- CLASSIFICATION OF VIRUSES

Viruses are not considered organisms because they are acellular i.e.; not made of cells. They lack any of the characteristics of the three domains of life and are not classified in any domain and kingdom.

Prions and viroids are also acellular. They are also not considered living organisms. Prions are composed of protein only and Viroids are composed of circular RNA only. Both these particles cause infectious diseases in certain plants.

A virus consists of nucleic acid (DNA or RNA) surrounded by a protein coat. They cannot run any metabolism and depend upon the host cell (including plants, animals, and bacteria) to replicate and synthesize their proteins.

Viruses are classified based on several characteristics, including their genetic material, replication strategy, morphology, and the hosts they infect. The classification of viruses follows guidelines established by the International Committee on Taxonomy of Viruses (ICTV).

Classification on the basis of Host Range

1. Animal Viruses: Infect animals, including humans. Examples: Influenza virus, Rabies virus.
2. Plant Viruses: Infect plants. Examples: Tobacco mosaic virus, Potato virus X.
3. Bacteriophages: Infect bacteria. Examples: T4 phage, Lambda phage.
4. Archaea Viruses: Infect archaea. Examples: Sulfolobus spindle-shaped virus.

Classification on the basis of Morphology

1. Helical Viruses: These have a capsid with a helical structure surrounding the nucleic acid. Examples: Tobacco mosaic virus, Rabies virus.
2. Icosahedral Viruses: These have a capsid with a symmetrical icosahedral shape. Examples: Adenoviruses, Herpesviruses.
3. Complex Viruses: These have a complex structure, often with a combination of icosahedral and helical features, and sometimes additional structures like tails. Examples: Bacteriophages (viruses that infect bacteria).
4. Enveloped Viruses: These have an outer lipid envelope derived from the host cell membrane, surrounding their capsid. Examples: Influenza virus, HIV.
5. Non-enveloped (Naked) Viruses: These lack an outer lipid envelope and consist only of a capsid enclosing the nucleic acid. Examples: Poliovirus, Adenovirus.

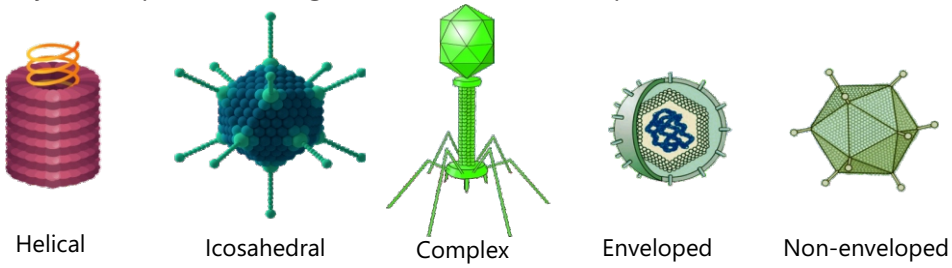


Figure 1.30: Basic shapes of viruses

Classification on the basis of Genetic Material

1. DNA Viruses: Viruses with DNA as their genetic material. This DNA can be single-stranded (ssDNA) or double-stranded (dsDNA). Examples include:
   - dsDNA viruses: Adenoviruses (cause respiratory infections), Herpesviruses (cause herpes, chickenpox).
   - ssDNA viruses: Parvoviruses (cause gastroenteritis).
2. RNA Viruses: Viruses with RNA as their genetic material. This RNA can be single-stranded (ssRNA) or double-stranded (dsRNA). Examples include:
   - ssRNA viruses: Coronaviruses (cause COVID-19), Influenza viruses (cause flu).
   - dsRNA viruses: Rotaviruses (cause gastroenteritis).

Classification on the basis of Replication Strategy

1. Positive-Sense RNA Viruses: The RNA genome is directly translated into proteins by the host cell's ribosomes. Examples include Poliovirus, Hepatitis C virus.

2. Negative-Sense RNA Viruses: The RNA genome is transcribed into mRNA by a viral RNA polymerase before translation. Examples include Rabies virus, Ebola virus.
3. Reverse Transcribing Viruses: These viruses replicate through a DNA intermediate using the enzyme reverse transcriptase. They can have RNA or DNA genomes. Examples include:
   - RNA genome: Retroviruses like HIV (cause AIDS).
   - DNA genome: Hepadnaviruses like Hepatitis B virus.

1.7- BIODIVERSITY

Biodiversity, a term derived from "biological diversity," refers to the variety of life forms present in different ecosystems, encompassing the diversity of species, genes, and ecosystems. It represents the richness and variability of living organisms and their interactions with each other and their environments.

Ecosystem:
An ecosystem is a dynamic and interactive system composed of living organisms and their physical environment. It includes all the biotic factors as well as the abiotic factors.

Niche:
A niche refers to the role or function of an organism or species within an ecosystem. It includes its habitat, its interactions with other organisms (predation, competition, and symbiosis), and its role in energy flow within the ecosystem.

Biodiversity Assessment Levels

The assessment of biodiversity involves multiple levels, each providing unique insights into the complexity of life.

Species Level: At the species level, biodiversity is assessed by identifying and counting the different species present within a given area. Species diversity includes not only the number of species but also their relative abundance and distribution.

Genetic Level: At the genetic level, biodiversity refers to the variety of genetic information contained within all individual organisms of a species. This genetic diversity is crucial for the adaptability and survival of species, enabling them to cope with environmental changes and challenges.

Ecosystem Level: At this level, biodiversity assessment includes the range of habitats, from forests and wetlands to grasslands and deserts. It involves understanding how different ecosystems function and how they contribute to overall ecological health.

Importance of Random Sampling in Determining Biodiversity

Random sampling is a fundamental technique in ecological studies for assessing biodiversity within a specific area. This method is crucial for several reasons:

1. **Minimizes Bias:** It ensures that every part of the study area has an equal chance of being sampled, which provides a more accurate representation of the overall biodiversity.

2. **Provides Reliable Estimates:** Random sampling allows for the collection of data that can be statistically analyzed to estimate species richness, abundance, and distribution.
3. **Facilitates Comparisons:** It enables comparisons between different areas or habitats by providing standardized methods of data collection.
4. **Enhances Representativeness** By covering different parts of the study area, random sampling ensures that the sample represents the diversity of the entire area.
5. **Supports Conservation Efforts:** Accurate biodiversity assessments through random sampling are essential for identifying areas of high conservation value and for monitoring changes in biodiversity over time.

Methods to Assess Biodiversity

Various methods are employed for assessing the distribution and abundance of organisms in an area:

Methods to Assess Distribution

1. Quadrat Sampling

It involves dividing the study area into a grid and sampling within randomly selected squares (quadrats). This method is particularly useful for studying plant populations or sessile organisms. For example, in a forest, a researcher might lay out quadrats of a fixed size and record the presence or absence of each plant species within these quadrats.

2. Transect Sampling

It involves laying out a line or strip (transect) across the study area and recording species at regular intervals along this line. This method is effective for studying the distribution of species across environments. For example, in a coastal zone, a transect can be laid from the high tide line to the low tide line, to record the types and abundance of intertidal organisms.

3. Aerial Surveys

Aerial surveys use aircraft or drones to observe and record the distribution of organisms over large areas. For example, it can be used to track the distribution of bird species across a large wetland area or to monitor large mammal populations in savannas.

Quadrat Sampling Transect Sampling Aerial Surveys

Figure 1.31: Methods to assess distribution of organisms

Methods to Assess Abundance

1. Point Counts: Point counts involve observing and recording the number of individuals of a species from a fixed point over a specified period. This method is commonly used for birds and other mobile animals.

2. Mark-Recapture: It involves capturing, marking, and releasing individuals of a species, then recapturing them later to estimate population size and density. This method is useful for animals that are difficult to count directly.

3. Quadrat Counts: In this method, researchers use quadrats to count the number of individuals of a species within each quadrat and then infer these counts to estimate overall abundance.

4. Capture-Recapture Methods: These models account for variables such as varying capture probabilities and movement between areas.

5. Remote Sensing: Remote sensing uses satellite or drone imagery to assess the abundance and distribution of species, particularly for large-scale or inaccessible areas.

1.8- SPECIES AND SPECIATION

Species

The term "species" is a fundamental concept in biology. A species is generally defined as a group of individuals that can interbreed and produce fertile offspring under natural conditions. Members of the same species share common characteristics and genetic makeup, which distinguishes them from individuals of other species.

Identification of species by using physical traits and similarities can sometimes be problematic due to the existence of cryptic species - organisms that appear similar but are genetically distinct. To address this, German-American biologist, **Ernst Mayr**, emphasized reproductive isolation as the key criterion. According to this concept, species are groups of interbreeding natural populations. Members of different species do not typically mate or produce viable, fertile offspring.

Speciation

Speciation is the evolutionary process by which new species arise from a common ancestor. It involves the accumulation of genetic changes that lead to reproductive isolation between populations. There are several mechanisms of speciation, for example:

1. Allopatric Speciation

It occurs when a population is geographically separated into two or more isolated groups. These groups experience different environments and evolve independently. Over time, the accumulated differences can become significant enough to prevent interbreeding, even if the geographical barrier is removed. An example is the speciation observed in Darwin's finches on the Galápagos Islands, where different populations adapted to diverse environments.

2. Peripatric Speciation

It involves a small, isolated population at the edge of a larger population. The small population undergoes rapid evolutionary changes, leading to divergence from the original population. An example can be seen in island species that evolve from a small founding population.

3. Parapatric Speciation

This occurs when populations are adjacent to each other but occupy different environments along a gradient. Gene flow between the populations is limited, and they evolve adaptations to their specific environments. Over time, this can lead to reproductive isolation. An example is the grass species *"Anthoxanthum odoratum"*, which exhibits different adaptations to varying soil conditions across a gradient, leading to reproductive isolation in different soil types.

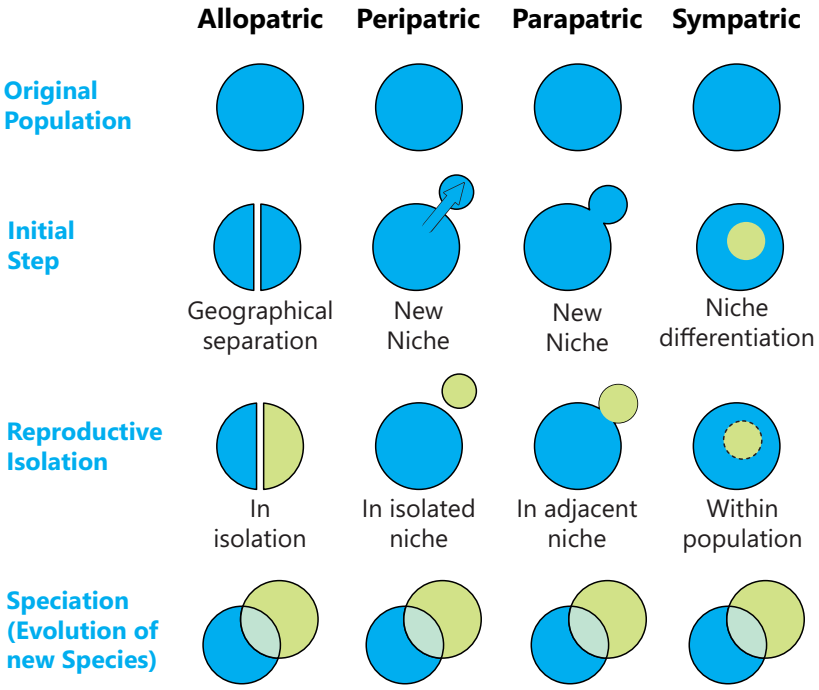


Figure 1.32: Modes of speciation

4. Sympatric Speciation

In this form, new species arise within the same geographical area without physical barriers. Sympatric speciation often occurs through mechanisms such as polyploidy (where an organism has multiple sets of chromosomes) or niche differentiation (where different subpopulations exploit different resources). For instance, certain plants can undergo polyploidy, leading to immediate reproductive isolation and the formation of new species.

EXERCISE

SECTION 1:MULTIPLE CHOICE QUESTIONS

1. Which domain of life is characterized by organisms that often inhabit extreme environments and have cell membranes with ether-linked lipids?
   (a) Bacteria (b) Archaea (c) Eukarya (d) Protista
2. What is a key difference between the domains Bacteria and Archaea?
   (a) Bacteria have membrane-bound organelles, while Archaea do not.
   (b) Bacterial cell walls have peptidoglycan, while Archaeal cell walls do not have it.
   (c) Archaea are only found in extreme environments, while Bacteria are not.
   (d) Bacteria are all unicellular, while Archaea include multicellular organisms.
3. Which of the following kingdoms includes organisms that are mostly unicellular, eukaryotic, and can be autotrophic or heterotrophic?
   (a) Fungi (b) Animalia (c) Plantae (d) Protoctista
4. In which kingdom are organisms predominantly multicellular, autotrophic, and have cell walls made of cellulose?
   (a) Animalia (b) Fungi (c) Plantae (d) Protoctista
5. Which of the following criteria is commonly used to classify viruses?
   (a) Their ability to cause specific diseases
   (b) The type of nucleic acid they contain
   (c) The colour of the virus particles
   (d) Their mode of transmission
6. Which virus group includes viruses such as Coronaviruses and influenza viruses?
   (a) Double-stranded DNA viruses (b) Single-stranded DNA viruses
   (c) Double-stranded RNA viruses (d) Single-stranded RNA viruses
7. At which level of biodiversity assessment do we evaluate the variety of different species within a particular habitat or ecosystem?
   (a) Genetic diversity (b) Ecosystem diversity
   (c) Species diversity (d) Functional diversity
8. Which method is best suited for assessing the distribution of species across a gradient of environmental conditions within a single geographical area?
   (a) Quadrat Sampling (b) Point Counts
   (c) Transect Sampling (d) Remote Sensing
9. Which of the following statements is true regarding the concept of a species?
   (a) A species is always defined by its physical characteristics alone.
   (b) Different species can interbreed and produce fertile offspring.
   (c) Members of the same species are reproductively isolated from members of other species.
   (d) The concept of a species can be defined solely based on genetic similarity.

10. What type of speciation occurs when populations are geographically separated by a physical barrier?
    (a) Sympatric Speciation
    (b) Parapatric Speciation
    (c) Allopatric Speciation
    (d) Peripatric Speciation

SECTION 2:SHORT QUESTIONS

1. What are the three domains of life and how do they differ in terms of cellular structure?
2. Describe one key feature that differentiates Archaea from Bacteria.
3. Which kingdom is characterized by organisms with chitin in their cell walls and that are mostly decomposers?
4. What type of speciation occurs when populations are geographically separated?
5. What is the role of genetic drift in the process of speciation?
6. What is the primary method used to assess species distribution along an environmental gradient?
7. Which level of biodiversity assessment involves evaluating the variety of ecosystems in a region?

SECTION 3: LONG QUESTIONS

1. Compare and contrast the domains Archaea and Bacteria and discuss how these differences reflect their evolutionary histories.
2. Explain the concept of a species according to the biological species concept. How does this definition help in understanding species boundaries and the process of speciation? Provide examples to illustrate your points.
3. Discuss the mechanisms of allopatric and sympatric speciation.
4. Describe the main characteristics of the kingdoms Protoctista, Fungi, Plantae, and Animalia. Provide examples for each kingdom.
5. Outline the major classification systems for viruses based on their structural features and replication methods. Discuss the significance of these classifications in virology.
6. Explain the different levels at which biodiversity can be assessed. How do these levels contribute to our understanding of biological diversity and conservation efforts?
7. Discuss the importance of random sampling methods in ecological studies.
8. Describe the concept of an ecosystem and niche.

INQUISITIVE QUESTIONS

1. How are viruses classified based on their nucleic acid content and replication method?
2. What may be the drawback in the definition of species according to the biological species concept?
3. How does biodiversity help maintain balance in an ecosystem?

Chapter 2

BACTERIA AND VIRUSES

STUDENTS'LEARNING OUTCOMES

After studying this chapter, the students will be able to:

- Draw an annotated diagram of a generalized bacterial cell.
- Describe detailed structure and chemical composition of bacterial cell wall and other coverings.
- Justify the endospore formation in bacteria to withstand unfavourable conditions.
- Explain motility in bacteria.
- Describe with diagram structure of bacterial flagellum.
- Describe bacteria as recyclers of nature.
- Outline the ecological and economic importance of bacteria.
- Explain the use of bacteria in research and technology.
- Define the term normal flora.
- Describe the benefits of the bacterial flora of humans.
- Describe the structure of a model bacteriophage, and HIV.

Recalling:
Robert H. Whittaker proposed the five-kingdoms of life i.e., Monera, Protista, Fungi, Plantae, and Animalia. The first one includes prokaryotes and the other four include eukaryotes.

You know that over the years many schemes have been proposed for classifying organisms into kingdoms. You have studied in chapter 1, the five-kingdom classification system, proposed by **Robert H. Whittaker**, is recommended in biology. This system classified the organisms in a comprehensive way that reflects evolutionary history of organisms. According to this classification system, all prokaryotes are included in a separate kingdom i.e., the kingdom Monera.

In the last decade, molecular studies have highlighted serious flaws in the five-kingdom classification system. You have also studied in chapter 1, most biologists favour replacing it with a new system, called **three-domain system** It is more aligned with the data gained from molecular studies.

You know that bacteria are the prokaryotes classified in the domain of their own, i.e., the domain Bacteria. In this chapter we will study detailed structure of bacterial cell. We will also study the importance of bacteria.

2.1- STRUCTURE OF BACTERIA

Bacteria are a diverse group and all of them have unicellular prokaryotic organization, which lack membrane bounded organelles, including a well-defined nucleus. They have the simplest cellular organization.

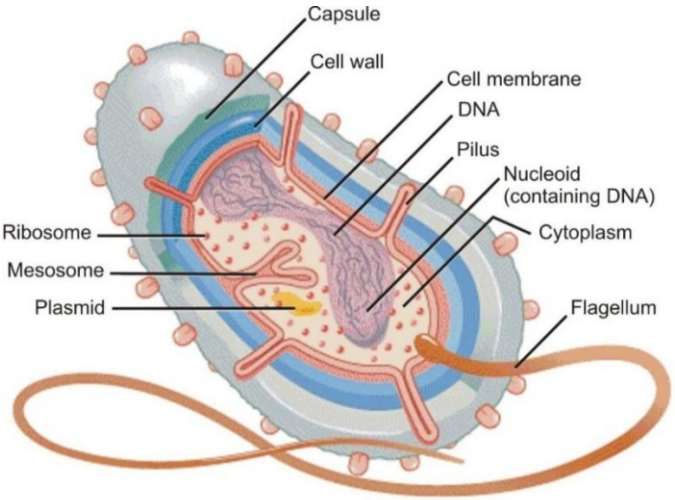


Figure 2.1: Structure of a generalized bacterium

Cell Wall

It is a rigid wall around the plasma membrane of bacterial cell. The major component of bacterial cell wall is a unique macromolecule, called **peptidoglycan** or **murein**. It is composed of long glycan (polysaccharide) chain, cross-linked with short peptide fragments (Figure 2.2). Its amount differs in different bacteria. Cell wall also contains lipids, which are linked to peptidoglycan.

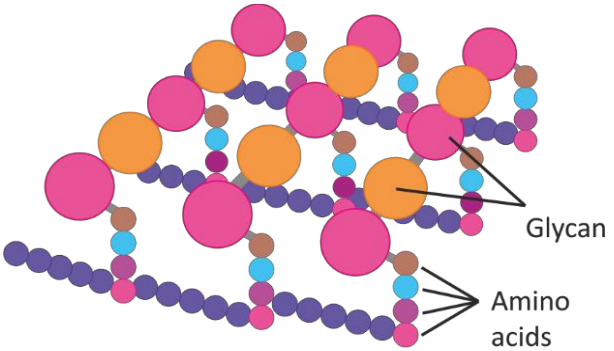


Figure 2.2: The molecular model of peptidoglycan

Sir Hans Christian Gram devised the technique of Gram's staining. Gram-positive bacteria stain purple because they retain violet dye. Gram-negative bacteria do not retain violet dye and so they appear in original colour.

The composition of cell wall is quite different in Gram-positive and Gram-negative bacteria. The cell wall of Gram-positive bacteria contains thick layer of peptidoglycan and has less lipid content. While the cell wall of Gram-negative bacteria has a thin layer of peptidoglycan.

The cell wall of Gram-negative bacteria has an outer membrane made of lipopolysaccharides and lipoproteins. The outer membrane makes Gram-negative bacteria resistant to many antibiotics. It contains a protein called porin, which acts like a pore for specific molecules. The cell wall of Gram-negative bacteria has more

periplasmic space (space between peptidoglycan layer and cell membrane) than Gram-positive.

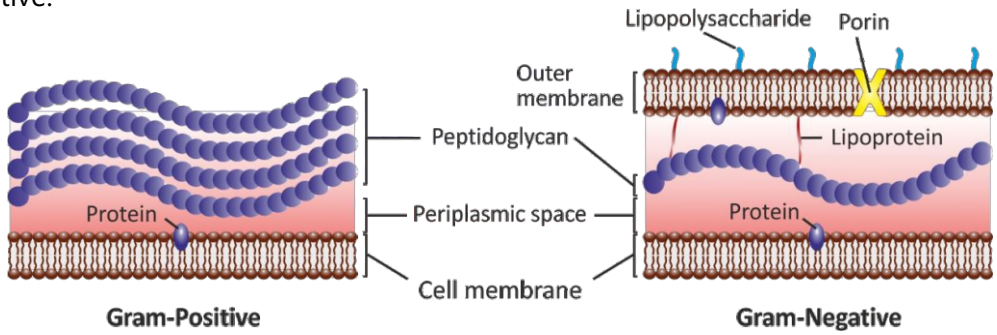


Figure 2.3: Cell wall composition of Gram-positive and Gram-negative bacteria

Some bacteria produce **capsule** outside their cell walls. It is a gelatinous layer and gives sticky characters to bacterial colonies.

Cell Membrane

Cell membrane or plasma membrane is present just beneath cell wall. It lies at the outermost in bacteria that lack cell wall (e.g., *Mycoplasmas* and *Sarcoplasmas*). The cell membrane of bacteria does not have sterols (e.g., cholesterol) in its chemical makeup. At some points, cell membrane invaginates and forms vesicles, tubules or lamellae in cytoplasm. These structures are known as **mesosomes** These are involved in DNA replication and cell division and also serve as respiratory centres.

Cytoplasm and Genetic Material

Cytoplasm contains dissolved substances and large structures such as nucleoid, ribosomes, and mesosomes. It lacks cytoskeleton and membrane-bounded organelles. Many ribosomes are freely dispersed in cytoplasmic matrix and some are loosely attached to plasma membrane. Bacterial ribosomes are smaller than eukaryotic ribosomes. Each ribosome sediments at 70S (larger subunit at 50S and smaller subunit at 30S). Near the centre of cytoplasm, there is an irregular-shaped dense area i.e., **nucleoid**. It contains DNA. A bacterium possesses a single, circular, double stranded DNA. Bacterial DNA does not have attached histones. It is sometimes called the chromosome of bacterium.

Some bacteria have circular, double-stranded extra chromosomal DNA molecules, called **plasmids**. They are self-replicating and can replicate before or after division. They contain genes that enable bacteria for resistance against unfavourable conditions (e.g., antibiotics).

Plasmids also serve as important vectors, in genetic engineering. They are used to carry selected genes to bacteria for cloning or for the synthesis of specific proteins.

2.2- ENDOSPORE FORMATION IN BACTERIA

Many bacteria can survive extended periods of harsh conditions by forming specialized "resting" cells, called **endospores** (Figure 2.4). Endospores are thick-walled and metabolically inactive (dormant). The process by which bacteria make endospores, is called **sporulation**. It happens in the following way:

When a bacterium faces unfavourable conditions, it replicates its DNA. Cell membrane makes a septum to isolate the new DNA and a small portion of cytoplasm. Cell membrane again grows around the new DNA, cytoplasm, and septum. In this way, the new DNA is surrounded by two membranes. The DNA of vegetative cell disintegrates and whole cell begins to dehydrate. A new peptidoglycan layer forms between the membranes around separated DNA and cytoplasm. A spore coat also forms around it. The structure matures into endospore. The vegetative cell breaks and endospore is released. Endospore remains dormant unless favourable conditions return. Under favourable conditions, endospore germinates to give rise to a new vegetative cell.

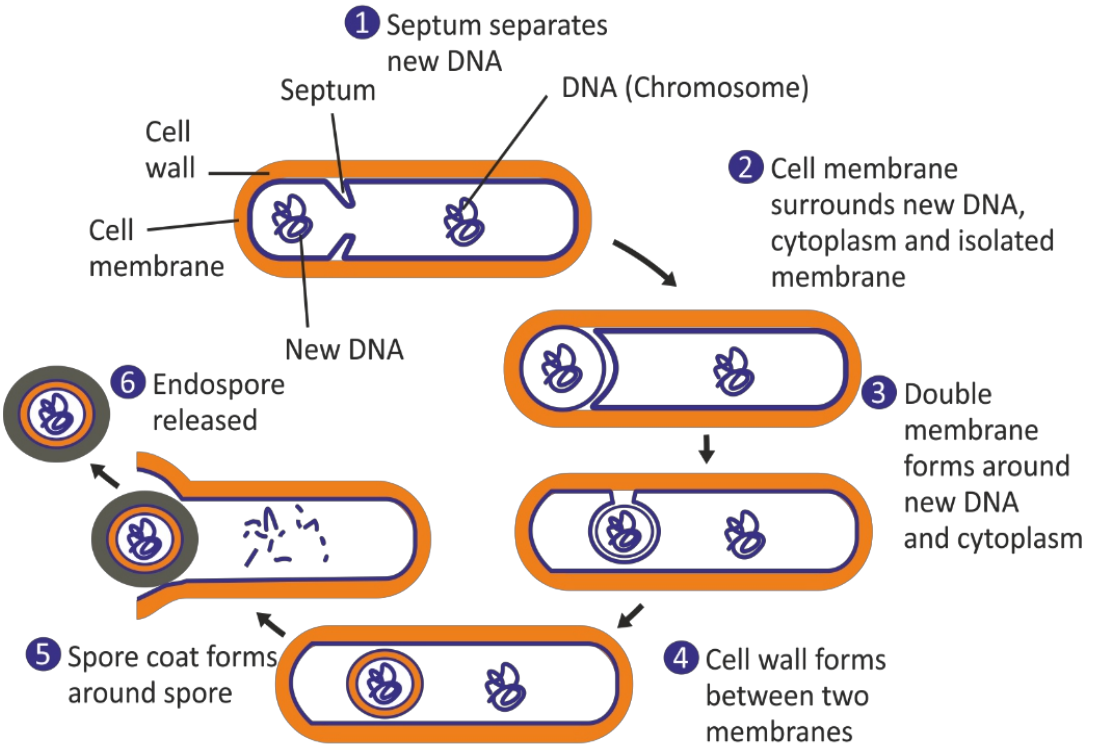


Figure 2.4: Process of endospore formation (sporulation) in bacteria

2.3- MOTILITY IN BACTERIA

Bacteria use different motility patterns to navigate and explore natural habitats.

Flagellar movements: Most bacilli and spirilla bacteria move by means of flagella. They swim by using their flagella. When a bacterial population moves together by means of flagella, the movement is called **swarming**. Flagellar movement allows bacteria to travel in liquid media. Counter clockwise rotation of flagellum pushes the cell forward with the flagellum trailing behind.

Twitching or crawling: It is used to move over surfaces. It is mediated by pili, which bind to surrounding solid surface and retract. Thus, bacterial cell is pulled forward.

Gliding: It is similar to twitching. In gliding, bacteria secrete slimy substance, which help them for smooth gliding over solid surfaces.

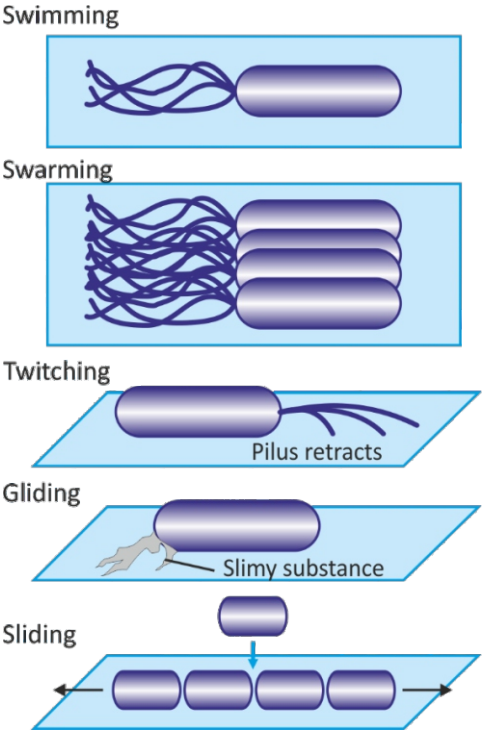


Figure 2.5: Motility in bacteria

Sliding: It is due to the expansion created by the pushing force of dividing cells.

Brownian movement: Some bacteria (e.g., *Streptococcus*) that do not have flagella or pili, move due to the random and uncontrolled movements of the particles present in fluid.

Movement by axial filament: Some bacteria (e.g., spirochaetes), have a modified flagellum. It is known as axial filament. It is anchored at one end and runs length-wise in periplasmic space (between cell membrane and outer membrane). It consists of two sets of flagella-like fibrils anchored at the two poles of cell. It helps spirochaetes for flexing, swimming, creeping and spinning movements.

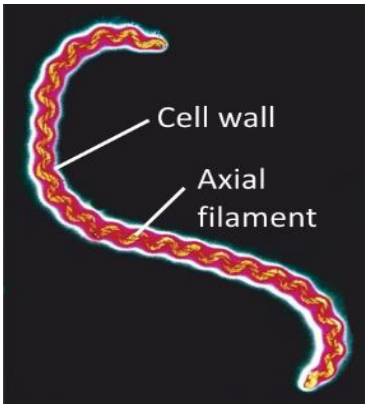


Figure 2.6: Axial filament in a spirochaete

2.5- FLAGELLA

Many kinds of bacteria have flagella, which enable them to move. The secondary function of flagella is to detect and respond to chemical signals. The bacteria which do not possess flagella are called atrichous. The bacteria with single polar flagellum are called monotrichous. The bacteria with a tuft of flagella at one pole are called lophotrichous. The bacteria with flagella at each of two poles are called amphitrichous. The bacteria with flagella surrounding the whole cell are called peritrichous (Figure 2.7).

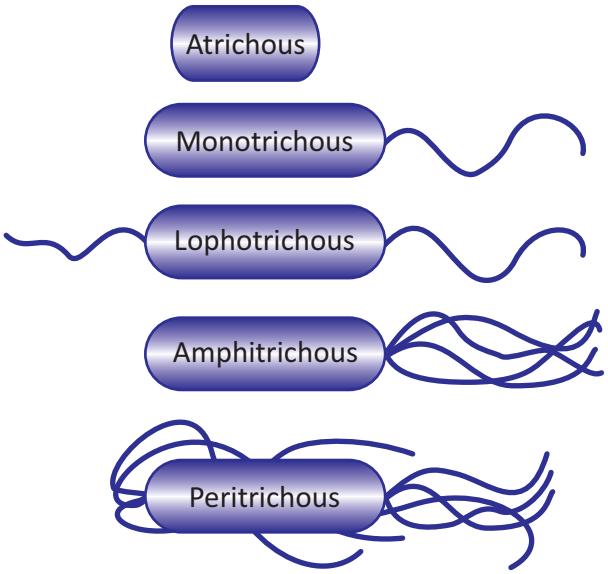


Figure 2.7: The different arrangements of bacterial flagella

Structure

The flagellum of bacteria is entirely different in structure from the flagellum of eukaryotes. They are not built on 9+2 pattern of microtubules, but are composed of flagellin protein. The bacterial flagellum consists of a basal body, a hook and a filament. The basal body is present just beneath cell membrane. It consists of rotating rings (one pair in Gram-positive bacteria and two pairs in Gram-negative bacteria). The rings anchor the flagellum in cell membrane and cell wall. The hook is a curved structure that connects basal body with the filament.

Some bacteria have pili (singular; pilus). These are non-helical, filamentous appendages and are smaller and thinner than flagella. Pili are used for attachment of bacteria to various surfaces. They are also involved in the mating process (conjugation) between cells.

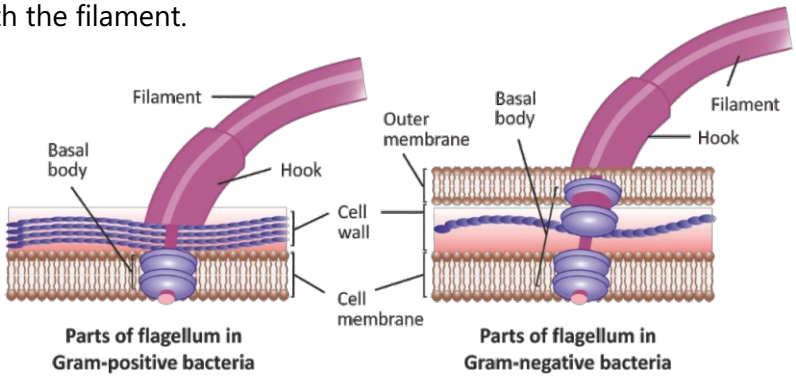


Figure 2.8: The structure of bacterial flagella

2.6- BACTERIA;ECOLOGY AND DIVERSITY

The fossil record shows that prokaryotes i.e., archaea and bacteria were abundant 3.5 billion years ago. They evolved and remained all alone on Earth for the next 2 billion years. Today, prokaryotes (archaea and bacteria) are found wherever there is life. Bacteria are found in water, air, soil, food and in the bodies of animals and plants. They outnumber all eukaryotes. They can survive in extreme habitats.

Diversity in Bacteria and their Ecology

Margulis and **Schwartz** proposed a useful classification system for all prokaryotes. They classified them into 16 phyla. The following discussion deals with the important groups of the domain bacteria (Figure 2.9).

Perhaps most interesting of all is the recent discovery that the bulk of our modern petroleum deposits were formed by masses of decayed cyanobacteria.

1- Omnibacteria: These are rigid, rod-shaped, heterotrophic, Gram-negative bacteria. Many important pathogens are included in this group. Most of these bacteria have flagella. They do not produce spores. They are usually aerobic. *Escherichia coli* is an example of such bacteria. This group also includes vibrios.

2. Cyanobacteria: These are photosynthetic bacteria. They played most important role in the history of the Earth for increasing free oxygen in atmosphere. They contain chlorophyll-a and accessory pigments like carotenoids, and blue and red phycobilins. Many cyanobacteria fix atmospheric nitrogen in their special cells called **heterocysts** They are common in soil in the form of mats. Cyanobacteria-containing lichens are found on rock surfaces. The mats on the sediments in the sea are dominated by cyanobacteria.

Colourful blooms may occur in polluted water as a result of the rampant growth of cyanobacteria. The colours of such blooms result from the photosynthetic pigments of cyanobacteria.

3. Mycoplasmas and **Spiroplasmas** These groups differ from all other bacteria in that they lack cell walls. As they lack cell walls, they are resistant to penicillin and other antibiotics that work by inhibiting cell wall growth. Some mycoplasmas cause diseases in mammals e.g., certain types of pneumonia in humans. Spiroplasmas cause significant plant diseases e.g., the lethal yellowing disease of coconuts.

4. Spirochaetes These are long spirilla with Gram-negative cell walls. They may have 2 to more than 100 flagella. *Treponema* are important spirochaetes. They cause syphilis (a fatal sexually transmitted disease).

5. Pseudomonads These are straight or curved Gram-negative rods with one or many flagella at one end. They are found in soil and water. They can easily break down organic compounds. Some of them are autotrophic but many are plant pathogens. Some of them play role in denitrification. *Pseudomonas aeruginosa* occurs in soil, water and raw

vegetables. Although it is usually harmless, it can form serious infections in weak people.

6. Actinomycetes These have filamentous growth forms. They produce spores that are resistant to unfavourable conditions. Some actinomycetes are nitrogen fixers and are found in the root nodules of many flowering plants. Some actinomycetes are responsible for dental plaque, in which the enamel of teeth is destroyed. A member of this group i.e., *Mycobacterium leprae* causes leprosy. Another member i.e., *Mycobacterium tuberculosis*is the cause of tuberculosis. Many antibiotics e.g., tetracycline, chloramphenicol, erythromycin, and neomycin were derived originally from actinomycetes.

7. Nitrogen-fixing aerobic bacteria: This group includes economically important bacteria. They are Gram-negative and most are flagellated. *Azotobacter*is a member of this group. It is found in soil and water and converts atmospheric nitrogen into nitrates.

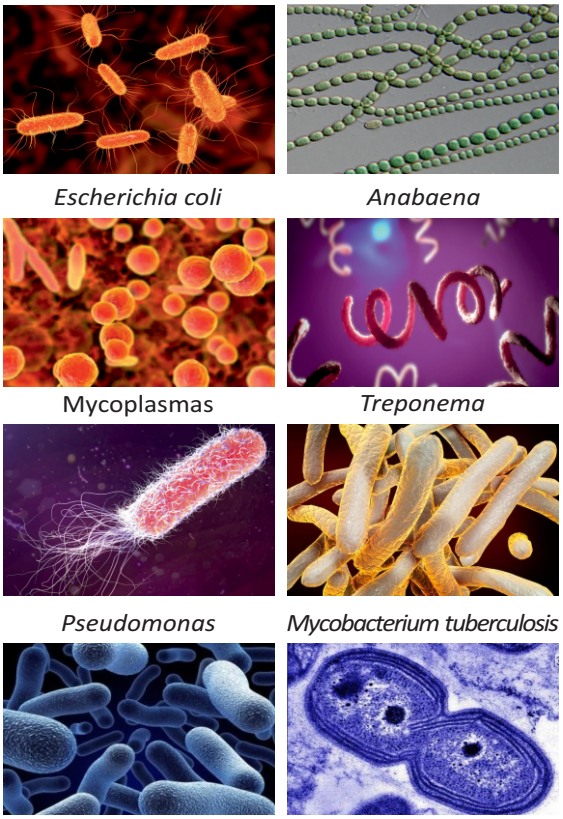


Figure 2.9: Major groups of bacteria

About 150 new antibiotics from actinomycetes are being discovered each year.

8. Chemosynthetic bacteria: These bacteria derive energy from the oxidation of inorganic compounds of nitrogen, sulphur and iron. They use this energy for the synthesis of their food. *Nitrosomonas* and *Nitrobacter* are included in this group. They oxidize nitrogen compounds (NH_3) to gain energy. The NH_3 is in turn converted to nitrite and nitrate. Thus, they play vital role in nitrogen cycle.

Table: Characteristics of some Groups of Bacteria

Name of Group	Form	Motility	Nutrition	Ecological role
Omnibacteria	R	N, F	H	Pathogens and decomposers
Cyanobacteria	R, C, M	G, N	P	Carbon and nitrogen fixers
Mycoplasmas and Spiroplasmas	No wall	N	H	Pathogens
Spirochaetes	S	F	H	Decomposers and pathogens

Pseudomonads	R	F	H, C	Decomposers and plant pathogens
Actinomycetes	M, R	N	H	Pathogens and nitrogen fixers
N-fixing aerobes	R	N, F	H	Free-living and mutualistic nitrogen fixers
Chemosynthetic	R, C	N, F	C	Oxidize nitrogen and sulphur compounds, play role in nitrogen cycle

Form: R, rods (bacilli); C, cocci; S, spirilla; M, regular chains or aggregations
Motility: F, flagellated; N, nonmotile; G, gliding
Nutrition: H, heterotrophic; C, chemosynthetic; P, photosynthetic

2.7- IMPORTANCE OF BACTERIA

Bacteria are very important organisms not only for environment but also for all other organisms. They have beneficial as well as harmful effects on life on Earth.

Beneficial Bacteria

Among the great diversity of bacteria, many bacteria are beneficial ecologically as well as economically.

Recyclers of nature

Bacteria are involved in almost all biogeochemical cycles in which different essential elements move to and fro between organisms and environment. Nitrifying bacteria (*Nitrosomonas, Nitrobacter* and *Azotobacter*) and denitrifying bacteria (*Pseudomonas*) play significant role in the completion of nitrogen cycle. Decomposer bacteria decompose dead organic matter and play key role in carbon-hydrogen-oxygen cycle. The activities of photosynthetic bacteria e.g., cyanobacteria play role in the increase of free oxygen in Earth's atmosphere.

Makers of useful products

Many bacteria e.g., *Lactobacillus* in combination with yeasts and molds, have been used for thousands of years in the preparation of fermented foods such as cheese, pickles, soy sauce, vinegar, wine and yogurt. In pharmaceutical and agrochemical industry, bacteria are most important in the production of important chemicals. Some bacteria are used for the production of antibiotics. Commercial preparation of animals' skin for making leather goods, involves the use of bacteria.

Environmental cleaners

Many bacteria can degrade organic compounds very easily. Such bacteria have been used for the removal or degradation of pollutants (bioremediation) from environment. For example, bacteria are used to decompose city sewage into harmless products. Some bacteria can digest the hydrocarbons present in petroleum. These bacteria are used to clean up oil spills. Bacteria are also used for the bioremediation of industrial toxic wastes.

Biopesticides

Bacteria are used in the place of pesticides in biological pest control. This commonly involves Bacillus thuringiensis, a Gram-positive, soil dwelling bacterium.

These biopesticides are environmentally friendly and have little or no effect on humans, wildlife, pollinators and most other beneficial insects.

Research and technology tools

Bacteria can grow quickly and scientists can manipulate with them very easily. Due to these reasons, bacteria are used in the fields of molecular biology, genetics and biochemistry. Scientists make mutations in bacterial DNA and examine the changes in characteristics. In this way, they determine the function of genes and enzymes in bacteria. This knowledge is then applied to study the same genes and enzymes in more complex organisms. Scientists also insert human genes in bacteria and produce therapeutic proteins e.g., insulin, growth hormones, or antibodies.

2.8- NORMAL FLORA

In a healthy animal, the internal tissues, e.g., blood, brain, muscle, etc., are normally free of microorganisms. On the other hand, the surface tissues, e.g., skin and mucous membranes, are constantly in contact with environment and are colonized by certain microbial species. The mixture of organisms regularly found at any anatomical site is referred to as the normal flora.

The normal flora of humans consists of bacteria, a few fungi and protists, and some methanogenic archaea. Bacteria are the most numerous and obvious microbial components of normal flora.

Benefits of Bacterial Flora of Humans

The associations between humans and their normal flora are mutualistic. In human body, normal flora gets nutrients, a stable environment and constant temperature, protection, and transport. Similarly, body also gets many benefits from normal bacteria; for example;

1. Synthesis of vitamins: Bacteria in alimentary canal produce vitamins. They excrete vitamins which are in excess of their needs. From alimentary canal, these vitamins are absorbed and distributed in body. For example, enteric bacteria secrete Vitamin K and Vitamin B12, and lactic acid bacteria produce certain B-vitamins.

2. Prevent colonization by pathogens: The bacteria of normal flora compete with pathogens for attachment sites and nutrients. So, pathogens have less chance of entering body tissues.

3. Inhibit or kill pathogens: The intestinal bacteria produce a variety of substances, which inhibit or kill pathogen bacteria.

4. Stimulates the production of cross-reactive antibodies: Since the normal flora behaves as antigens, they induce immunological response. Low levels of antibodies produced against the normal flora are known to cross-react with certain pathogens, and thereby prevent infection or invasion.

2.9- VIRUS

You are familiar with the five kingdoms of living organisms. You also know that there are some creatures that do not possess cellular organization yet show some characteristics of livings. Viruses are the representatives of such organisms.

Structure of Virus

Viruses are extremely small infectious agents and can only be seen under electron microscope. They range in size from 20 nm (parvovirus) to 250 nm (pox viruses). They are 10 to 1000 times smaller than most bacteria. That is why, they can pass through the pores of filter paper.

The central core of a virus is its genome. It is made up of nucleic acid (either DNA or RNA). The core is surrounded by a protein coat, called **capsid** It gives definite shape to virus. Capsid is made up of protein subunits called as **capsomeres** The number and kind of capsomeres is characteristic of a particular virus. Central core and capsid are collectively called as **nucleocapsid**

Herpes virus (causes cold sores, chickenpox etc.) contains 162 capsomeres in its capsid.
Adenovirus (causes common cold) contains 252 capsomeres in its capsid.

In some animal viruses only, nucleocapsid is covered by another membrane called **envelope**. It is a lipid-rich membrane and is derived from host cell. Non enveloped viruses are known as naked-viruses. There is a great diversity in the general appearance of viruses (Figure 2.10). The animal and plant viruses may be polyhedron (having many sides) or helical. The bacterial viruses (bacteriophages) may be cubical, icosahedral (having 20 faces), helical, or complex (polyhedral head and rod-shaped tail).

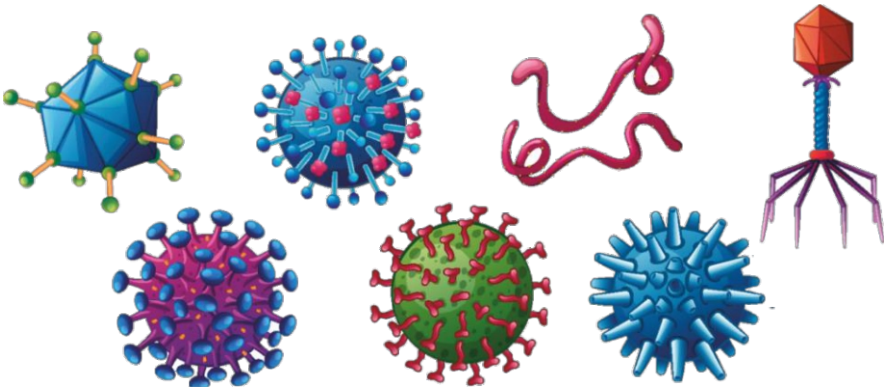


Figure 2.10: Diversity in viruses' shapes

Structure of Bacteriophage

Bacteriophages are used as carriers in genetic engineering. The gene of interest is inserted into the DNA of bacteriophage, which carries it to the

target bacterial cell. When virus incorporates its DNA into bacterial chromosome, the gene of interest also becomes a part of bacterial DNA. Such transgenic bacteria (transgenic: whose genome has DNA of some other organism) can be grown to get copies of the gene of interest and to get the required protein.

Bacteriophages are a diverse group of viruses that attack bacteria. They are among the most complex viruses. The best known phages of *Escherichia coli* are T-phages. There are many varieties of T-phages. A T4 phage consists of a head and a tail (Figure 2.11). The head is an elongated pyramidal (with two triangles having a common base), hexagonal (six sided), prism-shaped structure. Its capsid is made of proteins while core contains a long double stranded DNA. A straight tail is attached with head. The tail is also made of inner core and outer sheath, both of which are made of different proteins. A neck attaches sheath with head and an end plate is present on the other side of sheath. Six tail fibres are attached with end plate. They help the phage to attach with bacterial wall. These structures are also made of proteins.

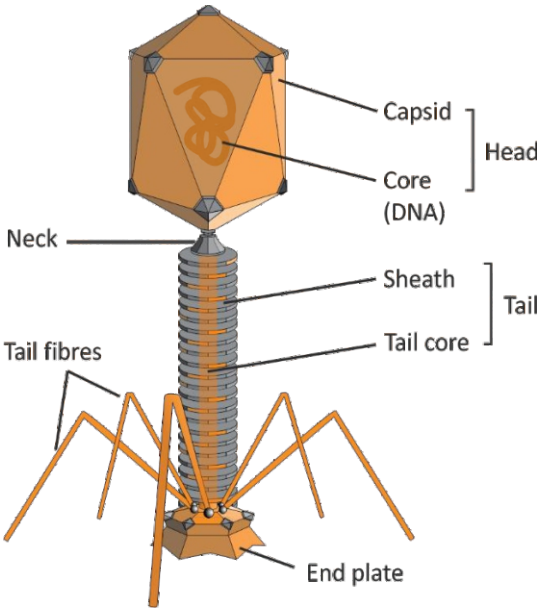


Figure 2.11 : Structure of a bacteriophage (T4 phage)

Structure of HIV

Human Immunodeficiency Virus (HIV) belongs to the group called **retroviruses** It is a special group of animal viruses. Retroviruses contain RNA and their capsids. These structures are surrounded by lipid rich envelops. The envelope also comprising glycoproteins spikes, which help the virus identify and bind to its target. They are spherical in form and are about 100 nm in diameter. The most distinguishing character of retroviruses is the presence of a specific enzyme, **reverse transcriptase** This enzyme

catalyses the process of reverse transcription in which a single stranded RNA is reversely transcribed into a strand of DNA. The enzyme then uses DNA strand to complete a double helix of DNA.

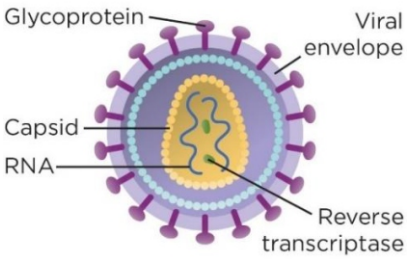


Figure 2.12: Structure of HIV

Experts have concluded that HIV originated in the jungles of Africa among wild chimps. Evidence suggests that a form of this virus entered human species and became HIV by way of monkey bites or ingesting monkey meat and brains.

HIV is responsible for the disease **AIDS (acquired immunodeficiency syndrome)**. AIDS weakens the immune system of patient. The disease is fatal because no one can survive without immune system to defend against other viral and bacterial infections. The disease was first reported in 1981 and the patients were found homosexual. Later on, AIDS was discovered in non-homosexual patients too who had received blood or blood products from other AIDS patients.

In 1984, it was discovered that the agent causing AIDS was a virus. In 1986, the AIDS causing virus was given the name Human Immunodeficiency Virus (HIV). It is a host specific virus. It can multiply in monkeys but do not cause AIDS in them.

EXERCISE

SECTION 1: MULTIPLE CHOICE QUESTIONS

1. Which of the following component is not found in all kinds of bacteria?
   (a) Ribosomes (b) Cell membrane
   (c) Nucleoid (d) Capsule
2. The bacterial chromosome is typically:
   (a) Linear, double-stranded DNA (b) Circular, single-stranded RNA
   (c) Circular, double-stranded DNA (d) Linear, single-stranded DNA
3. In bacterial cells, respiration occurs at:
   (a) Mitochondria (b) Cell membrane
   (c) Ribosomes (d) Endoplasmic reticulum
4. Which group of bacteria is known as a good source of antibiotics?
   (a) Omnibacteria (b) Spirochaetes
   (c) Pseudomonads (d) Actinomycetes
5. What is the primary function of flagella in bacterial cells?
   (a) DNA replication (b) Cell division

(c) Motility (d) Protein synthesis

6. Which type of motility in bacteria is mediated by pili?
   (a) Brownian movement (b) Gliding motility
   (c) Twitching motility (d) Swarming motility
7. Which of the following bacterial structures is responsible for detecting and responding to chemicals?
   (a) Capsule (b) Pili
   (b) Flagella (d) Ribosomes
8. Which one of the following are not Nitrifying bacteria?
   (a) Nitrosomonas (b) Nitrobacter
   (c) Azotobacter (d) Pseudomonas
9. The enzyme responsible for converting HIV RNA into DNA is:
   (a) RNA polymerase (b) Reverse transcriptase
   (c) DNA helicase (d) Integrase
10. The HIV capsid contains:
   (a) Single-stranded DNA and reverse transcriptase
   (b) Single-stranded RNA and reverse transcriptase
   (c) Double-stranded DNA and integrase
   (d) Double-stranded RNA and RNA polymerase

SECTION2: SHORT QUESTIONS

1. Write about the structural components of a bacterial cell wall and their arrangement.
2. Write the composition of the peptidoglycan layer in bacterial cell walls.
3. What are mesosomes? What are their functions?
4. How can plasmids be used in genetic engineering?
5. Define sporulation.
6. What is the function of the bacterial capsule?
7. Write the role of pili in bacterial cells. How do they differ from flagella?
8. What are plasmids, and how do they contribute to enabling bacteria to resistance against unfavourable conditions?
9. Write about the role of endospores in bacterial survival.
10. What is the significance of lipopolysaccharides and lipoproteins in Gram-negative bacteria?
11. How do spirochetes achieve motility?
12. Differentiate between twitching and gliding movements in bacterial motility.
13. How do bacteria without flagella achieve motility?

14. What is the difference between swimming motility and swarming motility in bacteria?

SECTION 3: LONG QUESTIONS

1. Compare and contrast the cell wall of Gram-positive and Gram-negative bacteria.
2. Explain different methods of movement in bacteria.
3. Explain the structure of bacterium flagellum.
4. State the formation of endospore in bacteria.
5. Briefly describe the ecological and economic importance of bacteria.
6. Explain the use of bacteria in research and technology.
7. Define the term normal flora. State the benefits which we get from normal bacterial flora.
8. Explain the structure of a model bacteriophage and HIV.

INQUISITIVE QUESTIONS

1. Why do bacteria have ribosomes even though they do not have membrane-bound organelles?
2. If bacteria do not have mitochondria, how do they generate energy for survival?
3. Why do certain bacteria exhibit twitching motility using pili instead of flagella?
4. Give reasons in favour of the statement "Prevention is better than cure" and present your arguments in the class.
5. Correlate the social and cultural values of a country with the prevalence of AIDS.

Chapter 3

CELLS AND SUBCELLULAR ORGANELLES

STUDENTS'LEARNING OUTCOMES

After studying this chapter, the students will be able to:

- Describe that cells are the basic unit of life with respect to seven properties of life (movement, respiration, homeostasis, growth, reproduction, excretion, nutrition).
- State cell theory (including how to validate it and exceptions to it).
- Compare and contrast the workings of a light microscope and electron microscope with focus on resolution and magnification and live vs dead samples.
- Identify the ultrastructure of animal and plant cells.
- Describe the structure and functions of cell wall, cell membrane and subcellular organelles (endoplasmic reticulum, ribosomes Golgi apparatus, vesicles, lysosomes, peroxisome, vacuoles, mitochondria, plastids, centrioles, nucleus).
- Differentiate between prokaryotic and eukaryotic cells with diagrams.
- Explain the structure of the cell membrane and the techniques that can be used to study it.
- Define cell signalling.
- Discuss the pathway of a signal from outside the cell to the inside. (protein signal and steroid signal).
- Explain the 4 membrane transport mechanisms with diagrams (simple diffusion, facilitated diffusion, osmosis, active transport).
- Describe endocytosis and exocytosis with diagrams.
- Compare and contrast simple and facilitated diffusion.
- Define stem cells and advantages of using stem cells
- Categorize different types of stem cells.
- Evaluate the advantages and disadvantages of using induced Pluripotent Stem Cells.

In this chapter "Cell and Subcellular Organelles," we will do a detailed study of cells, the fundamental units that compose all living things. Building on your previous knowledge from Grade IX, we will explore the cell theory and examine the structures of both animal and plant cells. You'll also discover the vital processes of cell signalling, and the revolutionary potential of stem cells. Additionally, we will investigate the mechanisms of membrane transport that are crucial for cellular function.

3.1- CELLS – THE BASIC UNIT OF LIFE

Cells are the basic unit of life, making up every living organism. In unicellular organisms like amoebas and bacteria, a single cell carries out all the functions necessary for life. Multicellular organisms, such as plants and animals, are composed of numerous specialized cells that work together to sustain life.

You know that all living organisms show the seven basic properties of life i.e., movement, respiration, homeostasis, growth, reproduction, excretion, and nutrition.

These properties actually define living organisms. Cells perform all the fundamental activities that characterize living organisms.

1. **Movement:** Cells can move. For example, sperm cells move with their flagella. White blood cells travel through the bloodstream to fight infections. Inside cells, organelles move to carry out vital functions.
2. **Nutrition:** Cells obtain nutrients from their environment to produce energy, build cellular structures, and drive biochemical reactions.
3. **Respiration:** Cells generate energy through respiration. This process breaks glucose to release ATP, the energy currency that powers cellular activities.
4. **Excretion:** Cells remove waste products through diffusion and active transport, preventing toxic buildup.
5. **Homeostasis:** Cells maintain a stable internal environment by regulating the movement of substances across their membranes.
6. **Growth:** Cells grow by taking in nutrients and converting them into cellular components.
7. **Reproduction:** Cells reproduce through mitosis and meiosis. Mitosis produces identical daughter cells for growth and repair, while meiosis creates gametes for sexual reproduction.

3.2- CELL THEORY

At the beginning of 17th century, many scientists began the use of microscopes to study very small objects. In 1665, English scientist **Robert Hooke** examined a thin slice of cork of oak tree under microscope. He observed that the cork was made of "many little boxes". Hooke also examined the pieces of stem and root of oak tree under microscope. He found that these were also made of similar little boxes. He concluded that the parts of plants were made of compartments. Hooke named these compartments as **"cellulae"**.

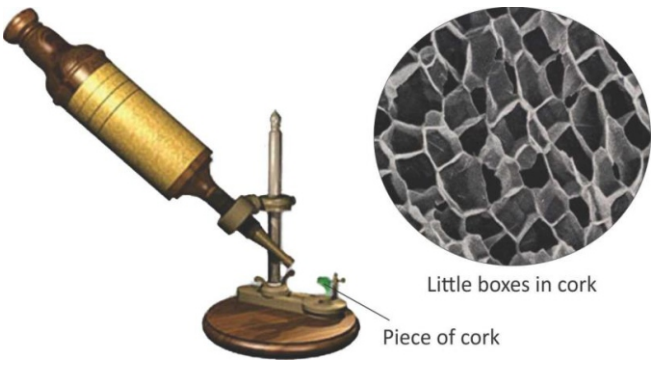


Figure 3.1: Robert Hooke's microscopeand observation

In 1673, a Dutch scientist **Anton van Leeuwenhoek** made a better microscope and observed living cells in pond water. He called these cells as **animalcules**

In 1809, the French biologist **Jean Baptiste de-Lamarck** also observed cells when he examined the parts of animals and plants under microscope. Later on, in 1831 the British botanist **Robert Brown** discovered nucleus in the cell.

After these studies, biologists began to organize information about cells. In 1838, the German botanist **Matthias Schleiden** observed many parts of plants under microscope. He concluded that all plants were composed of cells. The next year, the German zoologist **Theodor Schwann** concluded the same for animals. In 1885, the German physician **Rudolf Virchow** (1821–1902) observed that all cells come from other cells. In 1862, **Louis Pasteur** provided the experimental proof of this idea. These observations were combined to form a basic theory about cells. It is called cell theory. It has three essential points.

1. All living organisms are composed of one or more cells.
2. Cells are the basic units of structure and function in an organism.
3. Cells come only from the division of pre-existing cells.

Validation of Cell Theory

Cell theory can be validated through several observations and experiments. For example:

1. By using light microscopes and electron microscopes, scientists visualize cell structures and find tangible evidence that cells are indeed the structural units of all living organisms.
2. Through techniques like live-cell imaging and genetic studies, scientists can track how cells replicate and give rise to new cells. These techniques validate the principle that all cells originate from pre-existing cells.
3. Techniques like DNA sequencing reveal that cells share common genetic material and metabolic pathways, reinforcing the notion that the cell is the fundamental unit of life.
4. Experiments, such as cell culture studies and tissue engineering, validate cell theory by demonstrating cellular growth, differentiation, and reproduction.

Exceptions to Cell Theory

While cell theory is widely accepted, there are notable exceptions. For example:

1. Viruses challenge cell theory because they are not made of cells and cannot carry out life processes independently. They require a host cell to replicate and are considered by many scientists to be at the border of living and non-living entities. Similarly, prions and viroids show properties of living organism but are not composed of cells. They are made of only DNA, RNA or proteins.

2. Eukaryotic organelles mitochondria and chloroplasts have their own DNA and can replicate independently of the cell's nucleus. This suggests they may have originated from free-living prokaryotic cells.
3. Some organisms, such as certain fungi and algae, have structures where multiple nuclei coexist within a shared cytoplasmic mass. These structures blur the boundaries of individual cells as defined by traditional cell theory.
4. Muscle cells (myocytes) in vertebrates can fuse to form multinucleated fibres, challenging the concept of a single cell as the basic unit in complex tissues.

3.3- MICROSCOPY

The discovery of cells and then the further studies of the internal structure of cells were dependent upon the use of microscope. Microscopy is the technique of using microscopes to observe and study objects that are too small to be seen with the naked eye. Microscopes use lenses and light or electron beams to magnify and illuminate specimens.

Magnification and Resolution

These are two key characteristics of microscopes.

Magnification: This refers to a microscope's ability to enlarge the image of an object. Different lenses within a microscope offer varying levels of magnification. It is denoted by the symbol 'X', indicating how many times larger the image appears compared to the actual size. For example, a 10X lens can enlarge a 1 µm object to 10 µm. Total magnification in a microscope is determined by multiplying the magnification of all lenses.

Resolution: This refers to a microscope's ability to distinguish between two points that are close together on an object. The greater the resolution, the finer the detail that can be observed. The naked human eye has a resolution of about 0.1 mm. In contrast, a light microscope can resolve details down to approximately 250 nm (nanometres).

Light Microscopy

In light microscope, light is used to make the image of object. Light passes through object and then through two glass lenses. One lens produces an enlarged image of the object and the second lens magnifies the image more. After passing through object and lenses, the light forms enlarged clear image of object in viewer's eye.

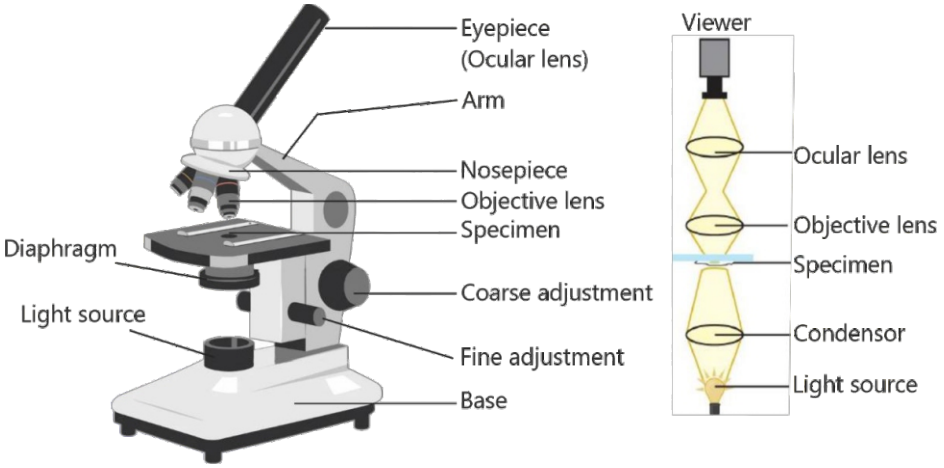


Figure 3.2: (a) Major parts of light microscope; (b) Working Principle of Light Microscope

The magnification of a light microscope is 1500X. It means it can magnify objects about 1500 times. Its resolving power is 0.2 micrometre (μm) and 1μm = 1/1000 mm. In other words, the light microscope cannot distinguish objects smaller than 0.2 μm.

Light microscopes are advantageous for viewing living organisms, but since individual cells are generally transparent, their components are not distinguishable unless they are coloured with special stains (coloured chemicals). Staining, however, usually kills the cells.

Electron Microscopy

In electron microscope, a beam of electrons passes through the object. Magnetic lenses focus the electron beam on a screen or photographic film and make much enlarged image. Its resolving power is much greater than light microscope. It can clearly show objects as small as 0.2 nanometre (nm) and 1 nm = 1/1000,000 mm. However, electron microscope cannot be used for viewing living material because of the methods needed to prepare the specimens. Biologists use two types of electron microscopes.

Transmission Electron Microscope (TEM) is used to view the internal structure of cell. TEM transmits a beam of electrons through a very thin specimen. It can magnify objects up to 250,000 times. **Scanning Electron Microscope (SEM)** is used to study the details of surfaces of cells or any other objects. The surfaces are coated with metal. When electron beam hits the metal, it is reflected and makes enlarged image. SEMs can magnify objects up to 100,000 times.

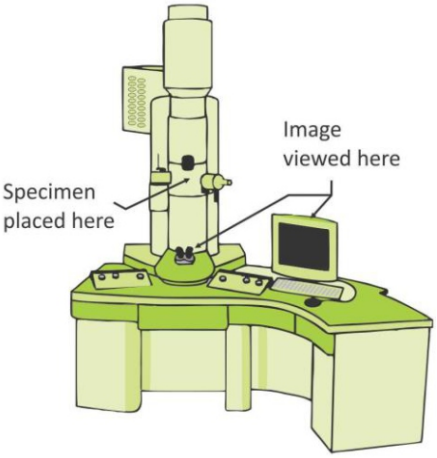


Figure 3.3: Electron microscope

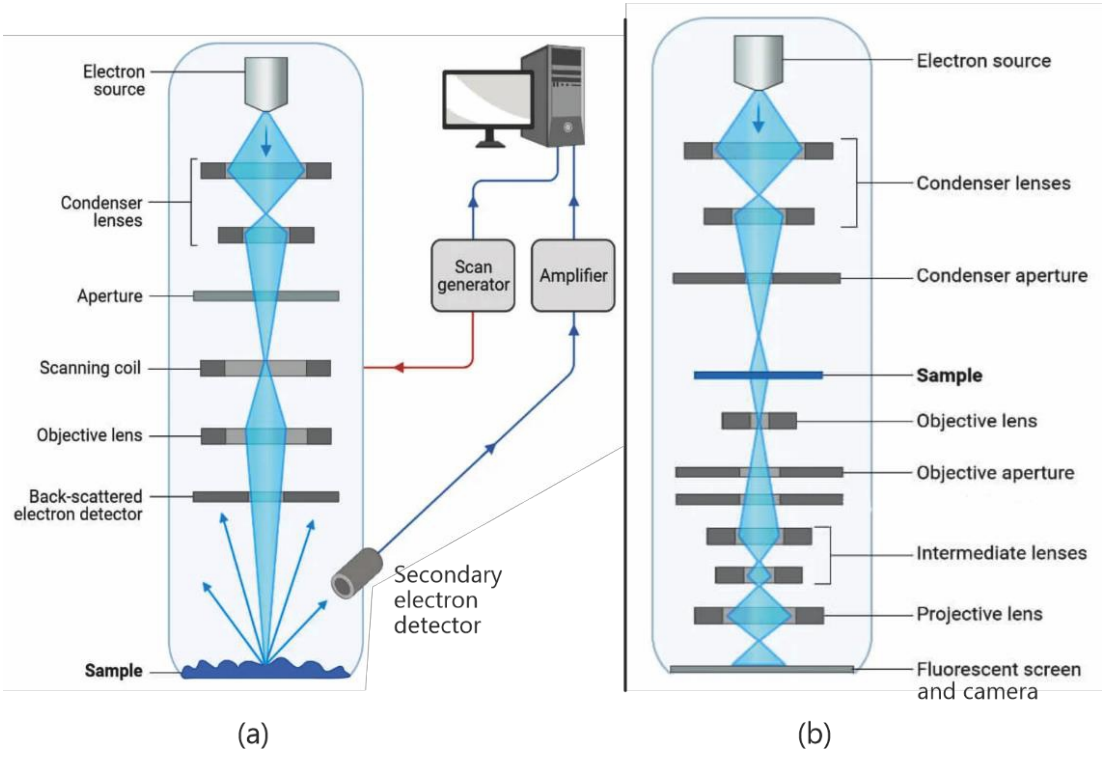


Figure 3.4: Working principle of; (a) Scanning electron microscope; (b) Transmission electron microscope

Difference Between Electron Microscope and Light Microscope	
Light Microscope	**Electron Microscope**
Uses light (approx. 400-700 nm) as an illuminating source	Uses electron beams (approx. 1 nm) as an illuminating source
Lower magnification (usually 500X to 1500X) than an electron microscope	Higher magnification (direct magnification is 16000X and photographic magnification is 1000000X)
Low resolution (may be 0.2 µm)	High resolution (may be 0.2 nm)
Both live and dead specimens can be seen	Only dead and the dried specimen can be seen
Specimen preparation takes about a few minutes or an hour	Specimen preparation takes several days
The image is seen through the ocular lens. No screen needed	The image is received on a zinc sulphate fluorescent screen

3.4- Structure of Cell

You know that there are two basic types of cells i.e., prokaryotic and eukaryotic. All bacteria are prokaryotes. Yeast and Euglena are examples of unicellular eukaryotes. Plants and animals are examples of multicellular eukaryotes. Eukaryotic cells are more complex than the prokaryotic cells. In the following paragraphs we will study the structures present in cells and their functions.

Cell Wall

Cell wall is a more or less solid layer surrounding a cell. It is found in bacteria, fungi, plants, and algae. When a cell wall is removed using cell wall degrading enzymes, the remaining components of the cell are called a **protoplast**.

The **primary wall** is the actual cell wall of cell. It is composed of polysaccharides i.e. cellulose, hemicellulose and pectin. The cellulose microfibrils are aligned at all angles and are held together by

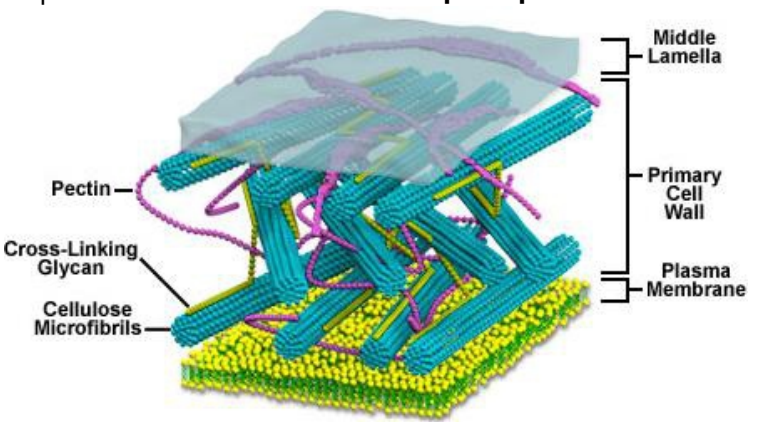


Figure 3.5: The composition of primary cell wall

hydrogen bonds. Many proteins are also present in primary walls. The **middle lamella** is a gelatinous layer that separates and holds the primary walls of the neighbouring cells. It is laid first, formed from the cell plate during cytokinesis, and the primary cell wall is then expanded inside the middle lamella. It contains magnesium and calcium pectates (salts of pectic acid). In some plant cells, after maturation, a **secondary wall** is made between protoplast and primary wall. Secondary cell walls contain lignin, cellulose and hemicellulose. Due to the presence of lignin, secondary wall is more rigid than the primary wall.

Plasmodesmata (singular, plasmodesma): These are small channels that directly connect the cytoplasm of neighbouring plant cells to each other. Plasmodesmata penetrate both the primary and secondary cell walls. They allow certain molecules to pass directly from one cell to another. So, they are important in cellular communication.

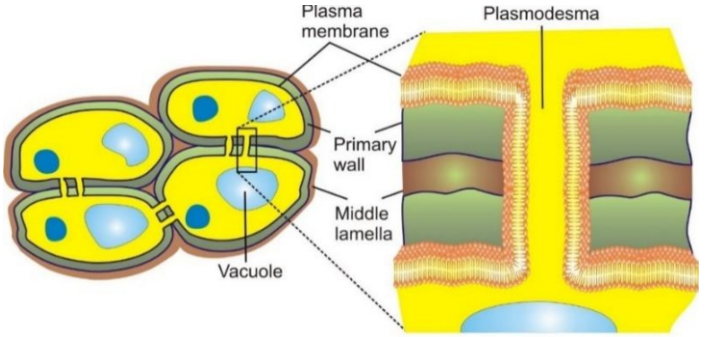
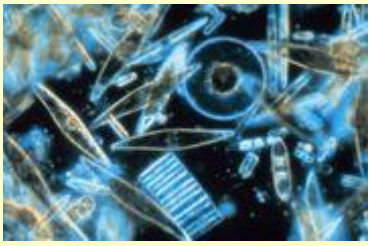


Figure 3.6: The cell walls of two neighbouring cells showing a plasmodesma

Plasmodesmata have caused debate among scientists regarding cell theory. Some scientists suggest that the cells of higher plants are not really cells since they are not physically separated or independent from one another.

The group of algae called diatoms synthesize their cell walls from silicic acid. The acid is polymerized inside cells, then the wall is extruded to protect the cell. The synthesis of Silica cell walls requires less energy. That is why there are higher growth rates in diatoms.



Plasmodesmata are formed during cell division when parts of the endoplasmic reticulum of the parent cell get trapped in the new cell wall.

Cell walls have a number of functions: They provide rigidity to the cell for structural and mechanical support; maintain cell shape and the direction of cell growth and ultimately the architecture of the plant. The cell wall also prevents expansion when water enters the cell. Cell walls protect against pathogens and the environment and are a store of carbohydrates for the plant.

The cell wall of algae contains cellulose and a variety of glycoproteins.
The cell wall of fungi is composed of chitin, the same carbohydrate that gives strength to the exoskeletons of insects.
The cell wall of prokaryotes (bacteria and cyanobacteria) is composed of peptidoglycan, that is a single large polymer of amino acids and sugar.
The cell wall of archaebacteria is composed of different polysaccharides and proteins, with no peptidoglycan.

Plasma Membrane

All prokaryotic and eukaryotic cells have a plasma membrane that encloses their contents and serves as a semi-porous barrier to the outside environment.

Structure of plasma membrane

The fluid mosaic model is a widely accepted concept that describes the dynamic nature of plasma membrane. It was proposed by two American biologists S.J. Singer and Garth Nicolson in 1972. According to the fluid mosaic model, the basic foundation of plasma membrane is a **lipid bilayer**. This bilayer is made of phospholipids. A collection of proteins float within the lipid bilayer.

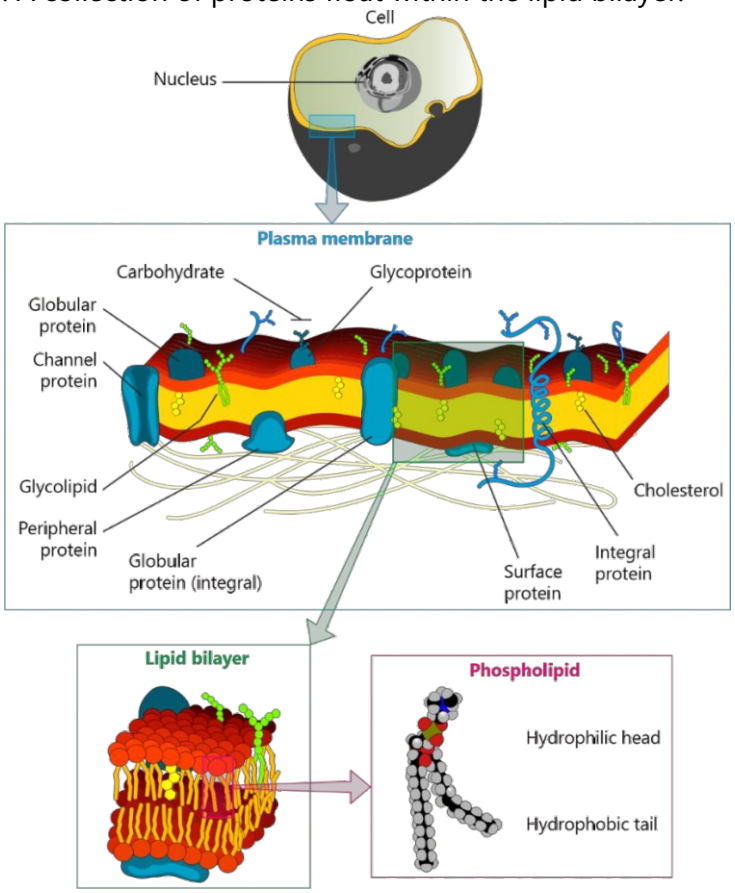


Figure 3.7: Structural components of plasma membrane

The phospholipids have a phosphate group at one end of each molecule. Phospholipids are characteristically **hydrophilic** ("water-loving") at their phosphate ends and **hydrophobic** ("water-fearing") along their tail regions containing C-H chains. In the lipid bilayer of plasma membrane, the hydrophobic lipid tails are oriented inwards and the hydrophilic phosphate groups are aligned outwards, either toward the cytoplasm of the cell or the extracellular environment.

The interior of lipid bilayer sheet is hydrophobic. It repels water-soluble molecules that attempt to pass through it. If a cell was fully encased in pure lipid bilayer, it would be completely impermeable to water-soluble molecules e.g., sugars, polar amino acids etc. That is why, in addition to phospholipids molecules, the membranes also contain proteins that provide passageways across the membrane.

In eukaryotes, plasma membranes have cholesterol molecules, wedged into the phospholipid bilayer. They keep the fluidity of membrane at low temperatures. Many proteins float within the phospholipid bilayer of plasma membrane. Some other proteins simply adhere to the surfaces of the bilayer. The positioning of proteins is related to the organization of cytoskeleton. Plasma membrane proteins function in several different ways.

- Many proteins play role in the selective transport of certain substances across the phospholipid bilayer, either acting as channels or active transport molecules.
- Some proteins help in attachment of plasma membrane to cytoskeleton and external fibres.
- Some proteins, on the exterior surface, attach with sugars and make identification marks.
- Other proteins function as receptors, which bind messenger molecules (e.g. hormones) and transmit signals to the interior of cell.
- Some proteins also exhibit enzymatic activity, catalysing various reactions related to the plasma membrane.

The ability to distinguish among different cells is crucial to life. In allows cells in an embryo to sort themselves into tissues and organs. It also helps cells of the immune system to recognize and reject foreign cells, e.g., infectious bacteria.

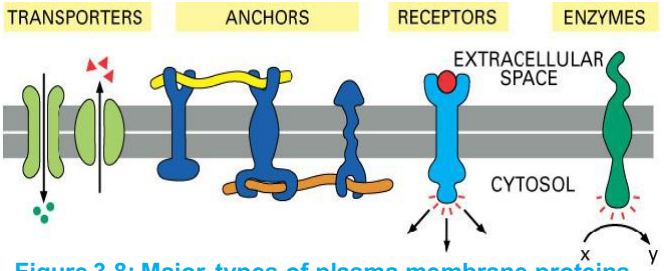


Figure 3.8: Major types of plasma membrane proteins

Membrane	Percent by weight		
	Protein	Lipid	Carbohydrate
Human red blood cell	49	43	8
Mitochondria (outer membrane)	52	48	0
Mitochondria (inner membrane)	76	24	0
Bacteria	75	25	0

The outside surface of plasma membrane has chains of sugars bonded to proteins and lipids. A protein with attached sugar is called a **glycoprotein**, whereas a lipid with attached sugar is called a **glycolipid**. The glycoproteins and glycolipids vary from species to species, from individual to individual in the same species, and even from one cell type to another in the same individual. The glycolipids and glycoproteins (collectively called glycocalyx) function as cell identification marks that are recognized by other cells.

Functions of plasma membrane

Plasma membranes serve as semi-porous barriers to the outside environment. The membrane acts as a boundary, holding the cell constituents together. The plasma membrane is permeable to specific molecules, however, and allows nutrients and other essential elements to enter the cell and waste materials to leave the cell. Small molecules, such as oxygen, carbon dioxide, and water, are able to pass freely across the membrane, but the passage of larger molecules, such as amino acids and sugars, is carefully regulated. Eukaryotic cells also have membranes around some of their interior organelles. Like the exterior plasma membrane, these membranes also regulate the flow of materials into and out of organelles.

Techniques to study the structure of plasma membrane

1. Transmission Electron Microscopy can reveal detailed structures of the lipid bilayer and associated proteins.
2. Scanning Electron Microscopy is useful for examining the surface topology of cells and membranes.
3. Confocal Microscopy uses laser scanning and fluorescence to create sharp, detailed images of the cell membrane.
4. Total Internal Reflection Fluorescence Microscopy is used for high-resolution images of the membrane and its interactions with the cytoskeleton and other cellular components.
5. Atomic Force Microscopy provides topographical images of cell membrane at high resolution.
6. X-ray Crystallography is used to determine the atomic structure of membrane proteins.

7. Lipidomics involves the comprehensive analysis of lipids in the cell membrane using techniques like mass spectrometry.
8. Fluorescence Recovery After Photobleaching is used to study the mobility and dynamics of membrane proteins and lipids. It involves bleaching a fluorescently labelled region of the membrane with a laser and observing the recovery of fluorescence as unbleached molecules move into the area.

Cytoplasm and Organelles

You know that a cell consists of three major components i.e., plasma membrane, cytoplasm and nucleus. The cytoplasm is a semi-viscous and semi-transparent substance. In eukaryotic cells, it is present between the plasma membrane and nuclear envelope. In prokaryotic cells, it covers all the space beneath plasma membrane. It consists of an aqueous ground substance, known as **cytosol**, which contains a variety of organelles and other inclusions. Cytosol contains water in which many organic (proteins, carbohydrates, lipids) and inorganic salts are completely or partially dissolved. The cytoplasm of the cell provides space for the proper functioning of the organelles and also acts as the site for various biochemical (metabolic) reactions for example Glycolysis (breakdown of glucose during aerobic respiration).

The cytoplasm contains discrete structures which are specific for various cellular functions and are called **cell organelles** The organelles are generally enclosed by membrane except few such as ribosome. The following paragraphs describe the structures and functions of important organelles.

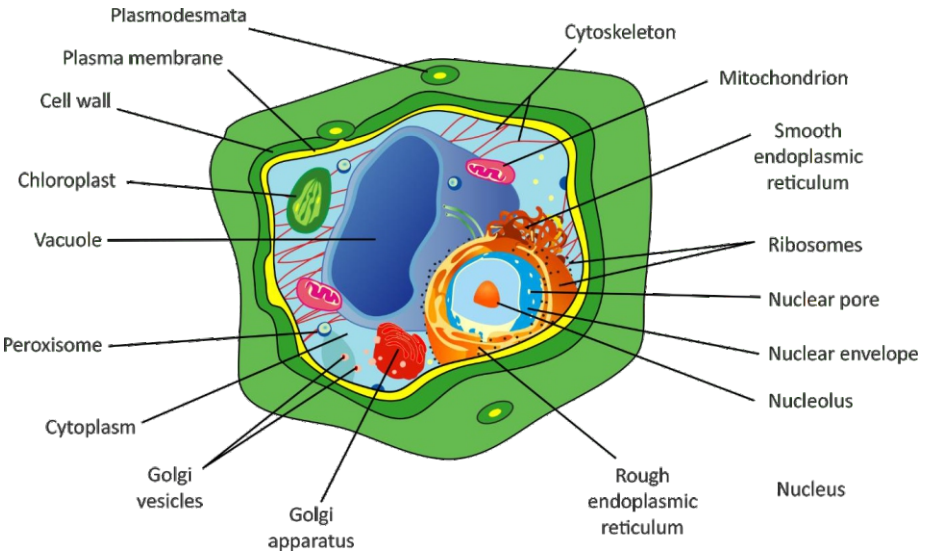


Figure 3.9: The Ultra-structure of a Plant cell

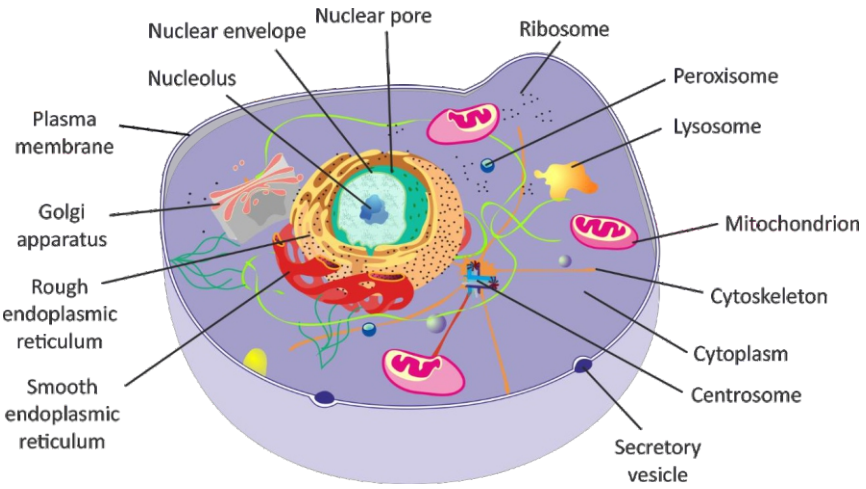


Figure 3.10: The Ultra-structure of an Animal cell

1- Nucleus

A prominent nucleus is present in all eukaryotic cells (at centre in animal cells while pushed to side in plant cells). The spherical nucleus typically occupies about 10 percent of a eukaryotic cell's volume. It serves as information processing and administrative centre of the cell. It performs two major functions: it stores the cell's hereditary material (DNA) and coordinates the cell's activities e.g., growth, protein synthesis and cell division.

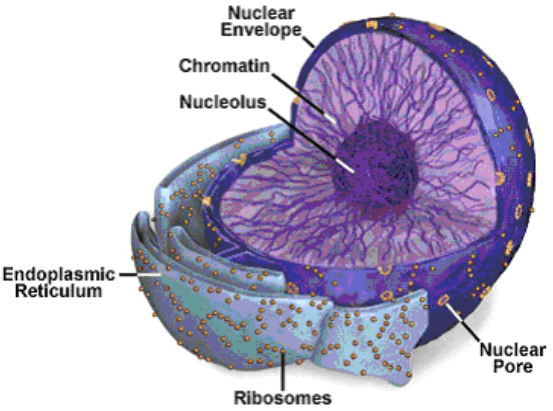


Figure 3.11 : The structure of nucleus

Building blocks of DNA and RNA and ATPs are allowed to enter into the nucleus. Ribosomal subunits which are built in nucleoli are the examples of materials that are allowed to leave the nucleus and enter the cytoplasm.

The semifluid matrix found inside the nucleus is called **nucleoplasm** Within the nucleoplasm, most of the nuclear material consists of chromatin that organizes to form chromosomes during cell division. The nucleus also contains one or more nucleoli, which synthesize ribosomes.

The Nuclear Envelope and Nuclear Pores

The nuclear envelope is a double-layered membrane that encloses the contents of the nucleus during most of the cell's lifecycle. The space between the

double layers is called the perinuclear space and is connected with the rough endoplasmic reticulum. During cell division, the nuclear envelope disintegrates, but reforms in the daughter cells. On the inner side of nuclear envelope, there is a protein lining, called **nuclear lamina**. It binds to chromatin to give it structural support.

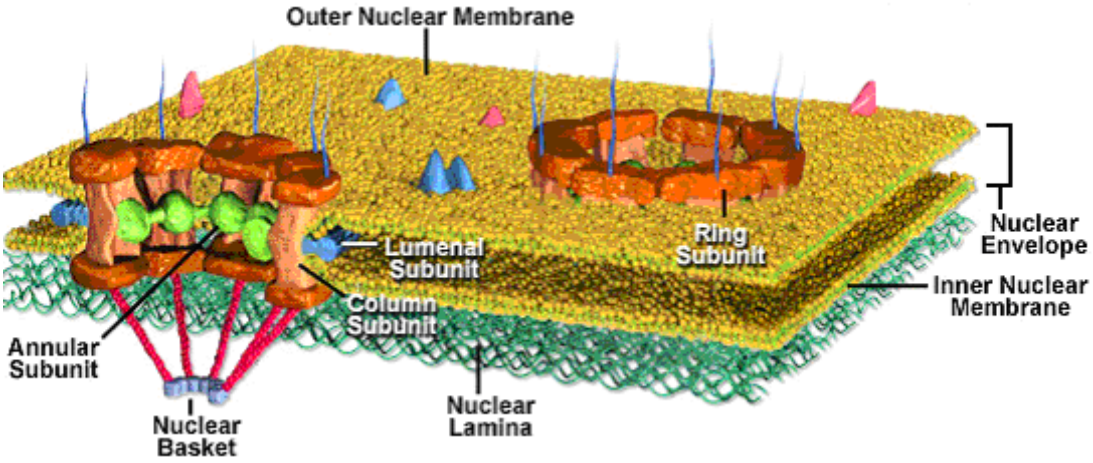


Figure 3.12: The structure of nuclear envelope and nuclearpore complex

The nuclear envelope has tiny holes known as **nuclear pores** These pores regulate the passage of molecules between nucleus and cytoplasm. Nuclear pores are permeable to small molecules. Some larger proteins, e.g., histones, are also allowed to enter into nucleus. A nuclear pore is made of an elaborate structure called the nuclear pore complex. It is composed of several subunits. These are; **annular subunit** (surrounding the inside of the pore), **column subunit** (making the wall of the complex), **ring subunit** (attached to the outer side of the column subunit), and **lumenal subunit** (anchoring the pore complex into the nuclear envelope). Tiny fibrils usually extend form the complex and make a basket-like structure on the nuclear side of the complex.

In cells that produce large amounts of protein, and thus require significant numbers of ribosomes, the size of the nucleolus is considerable.
At the onset of mitosis, the single nucleolus present in cell disappears, and after division new nucleolus is formed from the NORs.

Nucleolus

The nucleolus is a prominent darkly stained structure in the nucleoplasm. There may be one or two nucleoli in a nucleus. Nucleoli manufacture the subunits that combine to form ribosomes. Nucleoli are formed at certain sites in chromosome, called Nucleolus Organizer Regions (NORs). The DNA found at NORs encodes the ribosomal RNA (rRNA).

The nucleolus consists of granular and fibrillar components, and DNA. The granules consist of ribosomal subunits that have already been formed. The fibrils are composed of the raw materials of ribosome subunits i.e., rRNA molecules and associated proteins.

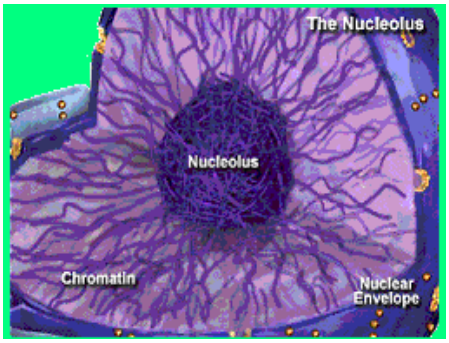


Figure 3.13: The nucleolus within a nucleus

Chromatin and Chromosomes

Nucleus contains string-like fibres, collectively called chromatin. It is composed of DNA and proteins. The structure of chromatin reveals that it is made of a series of bead-like structures, called nucleosomes. In a nucleosome, DNA strand wraps around groups of small proteins called histones.

Inside the nucleus of every human cell, there is a 6 feet long DNA. It is subdivided into 46 individual molecules (each 1.5 inches long), one for each chromosome.

During interphase (when the cell is carrying out its normal functions), the chromatin is dispersed throughout the nucleus in the form of a tangle of fibres. When the cell begins to divide, all chromatin strands are compressed into specialized structures, the chromosomes. A chromosome is made of arms, called chromatids, and a central point, called centromere.

There are two types of chromatin. **Euchromatin** is the genetically active chromatin involved in transcribing RNA to produce proteins. The other kind of chromatin is termed **heterochromatin**. Its DNA is genetically inactive.

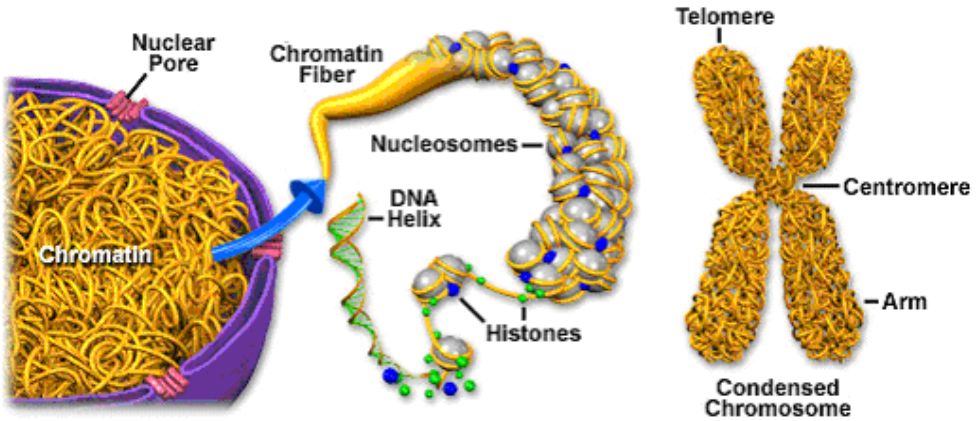


Figure 3.14: Condensation of chromatin to form a chromosome

The number of chromosomes within the nuclei of an organism's cells is species-specific. Human diploid cells (those that are not gametes) have 46 chromosomes. The chromosome number may be as low as 2, as in some ants and

roundworms, or more may be than a thousand, as in the Indian fern (*Ophioglossum reticulatum*), which has 1,260 chromosomes. It means that the number of chromosomes in a species does not correlate to the complexity of the organism.

2- Endoplasmic Reticulum(ER)

It is a network of flattened sacs and branching tubules that extends throughout the cytoplasm in plant and animal cells. These sacs and tubules are called cisternae (singular *cisterna*).

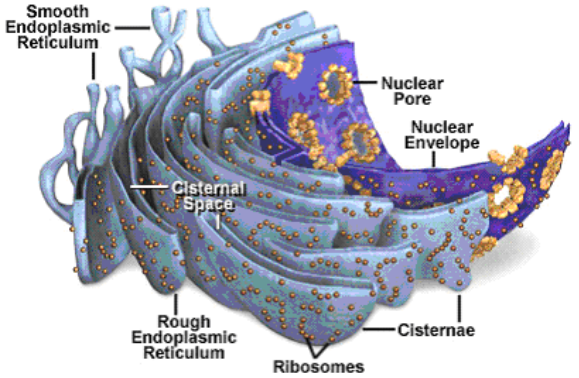


Figure 3.15: Endoplasmic reticulum

Due to their physical membranous connection, the lumen of the endoplasmic reticulum and the space between the layers of the nuclear envelope comprise a single compartment. This close association enables the endoplasmic reticulum and the nucleus to share information in a very efficient manner.

All cisternae are interconnected so that the ER has only one large and highly convoluted lumen, called cisternal space. It takes up more than 10 percent of the total volume of a cell. The cisternae are also connected to the double-layered nuclear envelope. So, the ER provides a pipeline between nucleus and cytoplasm. The ER manufactures, processes, and transports a wide variety of biochemical compounds for use inside and outside of the cell. There are two kinds of endoplasmic reticulum: rough and smooth.

The surface of **rough endoplasmic reticulum** (RER) is covered with ribosomes, giving it a bumpy appearance when viewed through the microscope. This type of endoplasmic reticulum is involved mainly in the production and processing of proteins. During processing of proteins, RER adds other chemicals (e.g. sugars) to proteins. Then RER transports the processed proteins to areas of the cell where they are needed, or sends them to Golgi apparatus for further processing and modification.

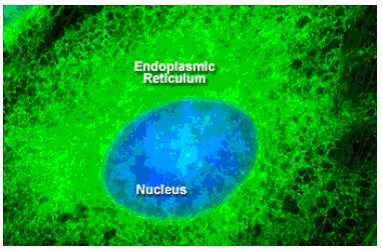


Figure 3.17: A fluorescence image of an endothelial cell showing ER (green)

Smooth endoplasmic reticulum is much more extensive in the cells which do lot of lipid and carbohydrate metabolism (brain and muscle) or detoxification (liver).

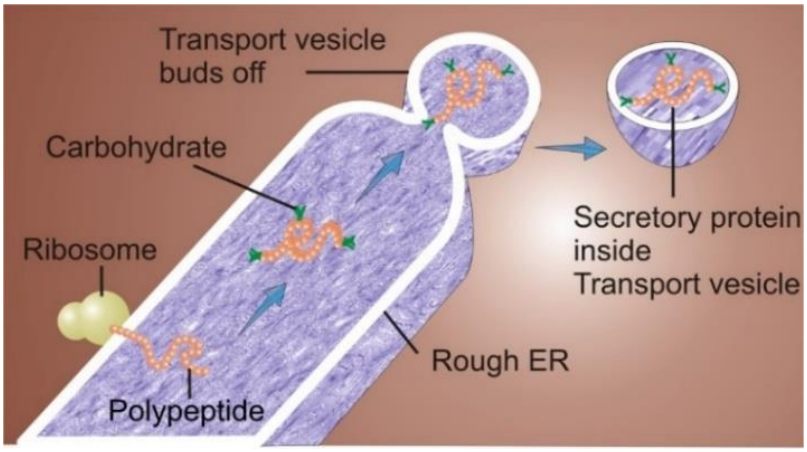


Figure 3.16: The functioning of rough endoplasmic reticulum

The surface of **smooth endoplasmic reticulum** (SER) lacks ribosomes. So, it appears more even under the microscope. In most cells, it is much less extensive than the rough endoplasmic reticulum. Smooth endoplasmic reticulum is chiefly involved in the production of lipids, building blocks for carbohydrate metabolism, and the detoxification of drugs and poisons. Smooth endoplasmic reticulum also plays a role in various cellular activities by storing calcium and doing calcium metabolism. In muscle cells, smooth endoplasmic reticulum releases calcium to trigger muscle contractions.

3- Ribosomes

All living cells contain ribosomes that are tiny granular structures composed of approximately 60 percent ribosomal RNA (rRNA) and 40 percent protein. Ribosomes are not bound by a membrane and are much smaller than other organelles. In eukaryotic cells, ribosomes are mainly found attached to rough endoplasmic reticulum and some are scattered freely. In prokaryotic cells, all ribosomes are freely scattered in cytoplasm. Ribosomes serve as the protein production machinery for the cell. They are most abundant in cells that are active in protein synthesis, such as pancreas and brain cells. A typical cell contains several thousand ribosomes but some cell types may have a few million ribosomes.

Eukaryote ribosomes are produced and assembled in the nucleolus. Ribosomal proteins enter the nucleolus and combine with rRNA strands to create the two ribosomal subunits (one small and one large). The ribosome subunits leave the nucleus through the nuclear pores. In the cytoplasm, both subunits combine for the purpose of protein synthesis. When protein synthesis is not being done, the two subunits get separated.

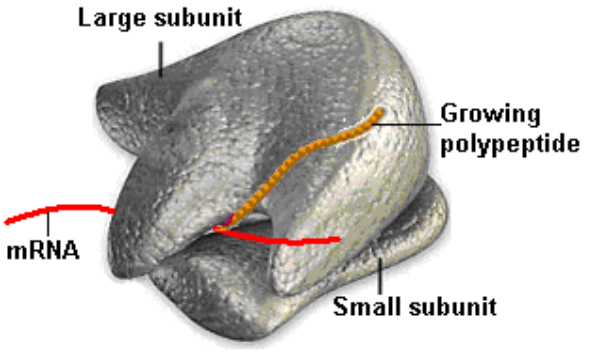


Figure 3.18: Ribosometranslating the mRNA

In addition to the most familiar cellular locations of ribosomes, they can also be found inside mitochondria and the chloroplasts of plants. These ribosomes notably differ in size and makeup than the ribosomes found in cytoplasm, and are more like those present in prokaryotes.

Protein synthesis requires the assistance of two other kinds of RNA molecules in addition to rRNA. Messenger RNA (mRNA) provides the instructions, which it has taken from the DNA. Transfer RNA (tRNA) brings amino acids to the ribosome. Once the chain of amino acids has been synthesized, the ribosome releases it.

The proteins that are synthesized by free ribosomes are for the cell's own internal use. While the proteins produced by the ribosomes bound to RER are transported outside of the cell.

The subunits of a ribosome are described by their **Svedberg (S) values**, which are based upon their rate of sedimentation in a centrifuge. The complete ribosome in a eukaryotic cell has a Svedberg value of 80S. The smaller subunit has value of 40S while the larger subunit has 60S. Prokaryotic cells, on the other hand, contain 70S ribosomes, each of which consists of a 30S and a 50S subunit.

The Svedberg values are not additive i.e. the values of the two subunits of a ribosome do not add up to the Svedberg value of the complete ribosome. This is because the rate of sedimentation of a molecule depends upon its size and shape, rather than simply its molecular weight.

4- Mitochondria

Mitochondria (sing., *mitochondrion*) are rod-shaped organelles that are considered the power generators of the cell. A mitochondrion is bounded by two membranes. There is a narrow intermembrane space between the two membranes. Beneath the inner membrane, there is a larger internal matrix. The outer membrane is smooth and acts like a sieve, filtering out molecules

Scientists hypothesize about the origin of mitochondria. According to them, millions of years ago small, free-living prokaryotes were engulfed, but not consumed, by larger prokaryotes. The two organisms developed a symbiotic relationship over time, the larger organism providing the smaller with ample nutrients and the smaller organism providing ATP molecules to the larger one.

that are too big. The inner membrane is highly convoluted and forms many infoldings called cristae which increase the surface area.

The inner surface of the cristae has knob-like extensions into the matrix, known as F-1 particles. These particles are actually the enzymes called ATP-synthase. Other complexes are also found in inner mitochondrial membrane, which serve as electron carriers in electron transport chain. Mitochondria are different from most other organelles. A mitochondrion has its own circular DNA (similar to the DNA of prokaryotes), all kinds of RNA and 70S ribosomes. A mitochondrion can replicate independently of the cell.

Mitochondria are the sites of cellular respiration. They generate adenosine triphosphate (ATP) from oxygen and nutrients. ATP is the chemical energy "currency" of the cell that powers the cell's metabolic activities. Enzymes in the matrix catalyse some of the steps of cellular respiration like Krebs cycle. Other proteins that function electron transport chain are found on the inner membrane.

The number of mitochondria present in a cell depends upon the metabolic requirements of that cell, and may range from one to thousands. Mitochondria are found in nearly all eukaryotes, including plants, animals, fungi, and protists, and are large enough to be observed with a light microscope.

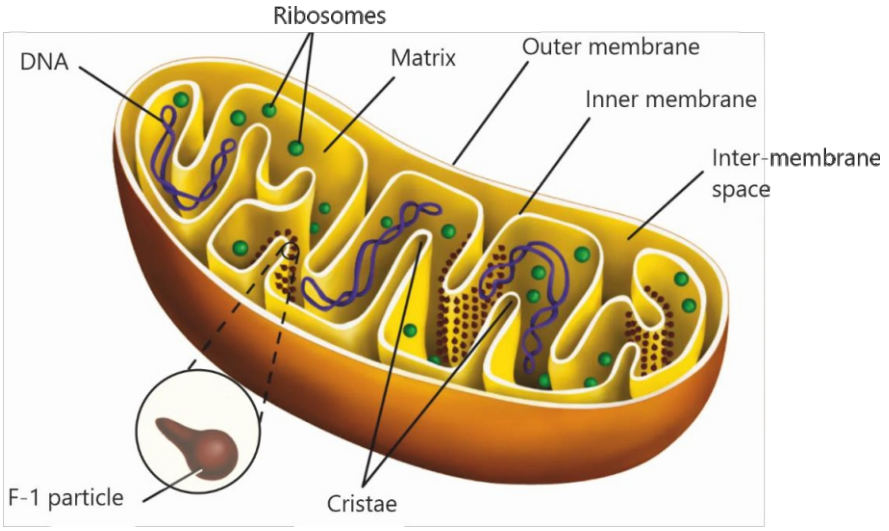


Figure 3.19: Structure of a mitochondrion

5- Chloroplasts

One of the most important characteristics of plants is their ability to conduct photosynthesis

Recalling:
Cells of plants and many protists have three types of plastids i.e., chloroplasts, chromoplasts and leucoplasts. The colourless leucoplasts are involved in the storage and yellow-to-red coloured chromoplasts give colours to plant parts.

i.e., to make their own food by converting light energy into chemical energy. This process occurs in almost all plant species and is carried out in specialized organelles known as chloroplasts. All of the green structures in plants, including stems and un-ripened fruit, contain chloroplasts, but the majority of photosynthetic activity in most plants occurs in the leaves. On the average, the chloroplast density on the surface of a leaf is about one-half million per square millimetre. Chloroplasts contain the pigments chlorophyll "a" and chlorophyll "b", which are able to absorb the light energy needed for photosynthesis to occur.

The ellipsoid-shaped chloroplast is enclosed by two membranes and the area between the two membranes is called the intermembrane space. A semi-fluid called stroma is present inside the inner membrane. It contains dissolved enzymes and comprises most of the chloroplast's volume. The outer membrane is much more permeable than the inner layer.

The inner membranes lie in close association with one another and fuse along their peripheries. In this way, two adjacent membranes form a disk-shaped compartment called **thylakoid**. Many thylakoids form stacks called **grana** (singular *granum*). The **lamellae** are the non-green compartments that connect two grana. Each granum may contain a few to several thylakoids, and a chloroplast may contain a hundred or more grana. Like the mitochondrion, the chloroplast is different from most other organelles because it has its own DNA and reproduces independently of the cell in which it is found.

Mitochondria are similar to chloroplasts. Both organelles convert energy for the cell. Mitochondria perform aerobic respiration. They generate chemical energy in the form of ATP by metabolizing sugars, fats and other chemical fuels with the assistance of oxygen. Chloroplasts perform photosynthesis. They convert energy from the sun into the biosynthesis of organic nutrients using carbon dioxide and water. Like mitochondria, chloroplasts also contain their own DNA and are able to grow and reproduce independently of the cell.

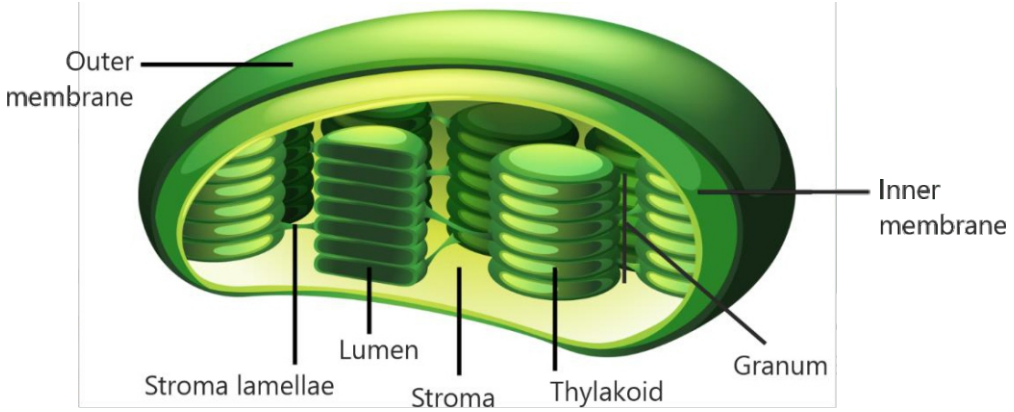


Figure 3.20: Structure of chloroplast

Light is absorbed by chlorophyll molecules embedded in the thylakoid disks. When these chlorophyll molecules absorb light, they emit electrons and thus ATPs are formed. Using these ATPs, in the stroma, low-energy carbon dioxide is transformed into a high-energy compound like glucose.

6- Golgi Apparatus

Recalling:
Golgi apparatus was discovered by Camillo Golgi.

Golgi apparatus consists of five to eight cup-shaped, membrane-covered sacs called cisternae that are stacked over each other. It is found in the cells of plant, animal and unicellular eukaryotes. In some unicellular flagellates, the Golgi apparatus may consist of 60 cisternae. Similarly, the number of Golgi apparatuses in a cell varies according to its function. Animal cells generally contain between ten and twenty Golgi stacks in their Golgi apparatus. This complex is usually located close to the nucleus.

Each Golgi stack has two distinct faces. The 'cis' face is found near the endoplasmic reticulum. The 'trans' face is positioned near the plasma membrane.

The Golgi apparatus is the distribution and shipping department for the cell's chemical products. It modifies proteins and lipids that have been built in the endoplasmic reticulum and prepares them for export outside the cell or for transport to other locations in the cell.

Camillo Golgi was investigating the nervous system by using a new staining technique (known as Golgi staining). He observed a structure inside cells and named it as reticular apparatus. He publicly announced his discovery in 1898 and the structure was named after him as the Golgi apparatus. Many scientists did not believe that what Golgi observed was a real organelle and instead argued that the apparent body was a visual distortion caused by staining. The invention of the electron microscope in the twentieth century finally confirmed that the Golgi apparatus is a cellular organelle.

Small vesicles that contain proteins, carbohydrates, phospholipids and other molecules, bud off from the ER. These vesicles move through the cytoplasm until they reach the 'cis' face of Golgi apparatus. The vesicles fuse with Golgi apparatus and release their molecules into it. Here, the compounds are further processed. Enzymes present in the Golgi lumen convert them into glycoproteins and glycolipids.

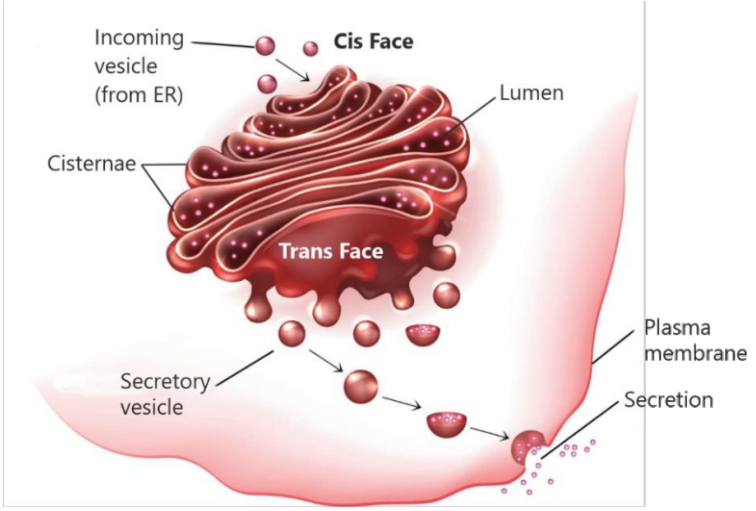


Figure 3.21: Structure of Golgi apparatus and its functioning

The product is extruded from the 'trans' face of the Golgi apparatus in a vesicle and directed to its final destination inside or outside the cell. The exported products are known as secretions. Other products are returned to the endoplasmic reticulum or may undergo maturation to become lysosomes. In addition, the Golgi apparatus in plant cells produces pectin and other polysaccharides specifically needed for plant structure and metabolism.

7- Lysosomes

Recalling:
Lysosomes were discovered by a Belgian scientist Christian René de Duve. They contain strong digestive enzymes.

Lysosomes are spherical organelles bounded by a single membrane. They serve as digestive compartments of the cell. Lysosomes are found in most eukaryotic cells. In animals, they are most numerous in disease-fighting cells, such as white blood cells. This is because white blood cells must digest materials like bacteria, viruses, and other foreign intruders.

The cell is safe from the enzymes of lysosomes. These enzymes require acidic environment (of pH of about 4.8). The lysosomal matrix is acidic but cytosol is a neutral environment. So, even if a lysosome is ruptured, its digestive enzymes become inactive and the cell remains uninjured.

They are also involved in breaking the cellular materials that have exceeded their lifetime or are no longer useful. In this regard, the lysosomes perform **autophagy**. They break down cellular waste products, fats, carbohydrates, proteins, and other macromolecules into simple compounds, which are then transferred back into the cytoplasm for making new materials.

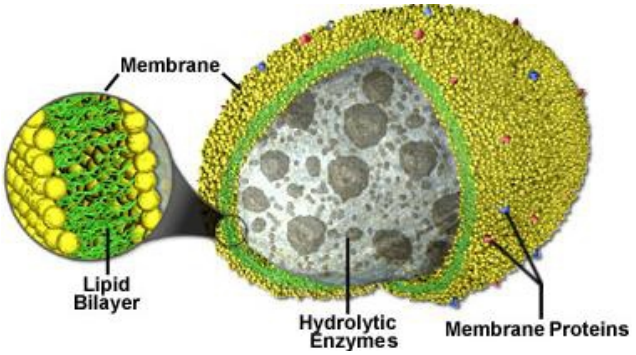


Figure 3.22: Structure of lysosome

Lysosomes have about 40 different hydrolytic enzymes, all of which are manufactured in the endoplasmic reticulum and modified in the Golgi apparatus. The membrane covering of the lysosome protects the rest of the cell from the harsh digestive enzymes contained in the lysosomes, which would otherwise cause significant damage.

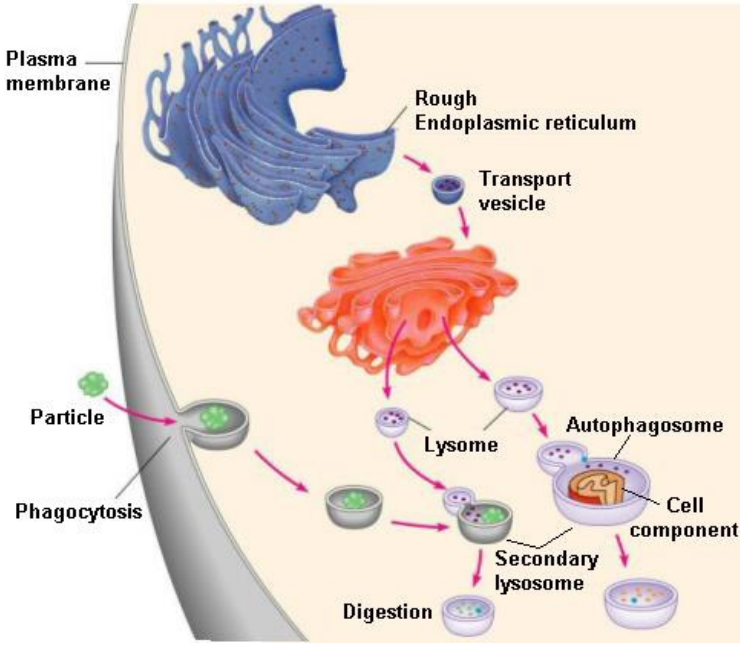


Figure 3.23: Role of lysosome in the breakdown of the phagocytosed particle and cellular component

In the mid-18th century, Belgian scientist Christian René de Duve was investigating carbohydrate metabolism in liver cells. He observed that when cells are damaged in the centrifuge, they release acid phosphatase. He suggested that this digestive enzyme was encased in some membrane bounded organelle within the cell, which he named as lysosome.

In **lysosomal storage diseases**, the patient lacks one of the hydrolytic enzymes of lysosome. The abnormal lysosome fills with

Many cells in your brain die during development. This directed suicide is accomplished by the rupture of the lysosomes within the cells that are being eliminated.

indigestible substances, which interfere with cellular functions. For example, in Pompe's disease the lysosome lacks a glycogen-digesting enzyme. So, harmful amounts of glycogen accumulate in liver cells. In Tay-Sachs disease an essential lipid-digesting enzyme is missing. Accumulation of these lipids in the nerve cells of brain damages the nervous system, causes mental retardation, and death in early childhood.

Lysosomes also function in the elimination of whole cell. Selective cell death is a mechanism used by multicellular organisms in their development. For example, when a tadpole develops into a frog, the cells of the tail are destroyed by the enzymes of lysosomes.

8- Peroxisomes

Peroxisomes are single membrane bounded organelles in all eukaryotic cells. These were discovered by Christian de Duve, who also discovered lysosomes.

Peroxisomes contain a variety of enzymes. Many of these enzymes are oxidative that carry out oxidation i.e. the removal of electrons and hydrogens. These enzymes primarily function to rid the cell of toxic substances. Some peroxisomes, such as those in liver cells, detoxify alcohol and other harmful compounds by carrying out their oxidation.

Some peroxisomes contain catalase enzymes, which break down hydrogen peroxide (a common by-product of cellular metabolism) into water and oxygen.

$$\underset{\text{Hydrogen peroxide}}{2H_2O_2} \xrightarrow{\text{Catalase}} \underset{\text{Water}}{2H_2O} + \underset{\text{Oxygen}}{O_2}$$

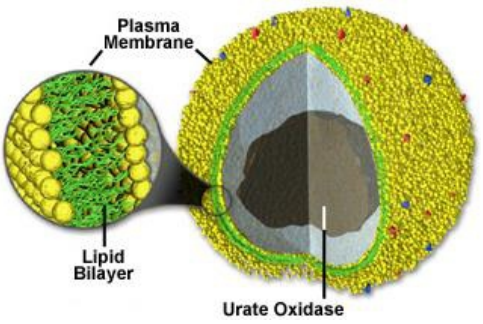


Figure 3.24: Structure of peroxisome

Defects in peroxisomes cause a number of metabolic disorders. The most serious of these disorders is Zellweger syndrome, which is characterized by absence or reduced number of peroxisomes in the cells. It is congenital disorder (present at birth) and has no cure or effective treatment and usually causes death within the first year of life.

9- Glyoxysomes

Glyoxysomes are similar to peroxisomes but are found only in plant cells. These organelles contain enzymes that convert lipids into carbohydrates. They are most abundant in the cells of lipid-rich seeds (e.g. castor beans and soyabeans). During germination, these organelles convert stored lipids into carbohydrates that provide energy for seed germination.

10- Vacuoles

Recalling:
Vacuoles are fluid filled single-membrane bounded organelles. Cells have many small vacuoles in their cytoplasm. However, when a plant cell matures its small vacuoles fuse to form a single large vacuole.

These are membrane-bounded sacs. Vacuoles function in several ways. For example, in mature plant cells, a single large vacuole provides structural support, as well as serves functions in storage, waste disposal, protection, and growth. Vacuoles in animal cells, however, are much smaller, and are more commonly used to temporarily store materials or to transport substances.

Many plant cells have a large, single central vacuole. This large vacuole slowly develops by fusion of smaller vacuoles. It takes up most of the space in the cell (80 percent or more). The vacuole in plant cells is enclosed by a membrane called tonoplast. The material inside the vacuole is called cell sap. The cell sap differs markedly from the surrounding cytoplasm.

Several materials commonly stored in plant vacuoles have been found to be useful for humans, such as opium, rubber, and garlic flavouring.

The central vacuole in plant cells plays an important structural role for the plant. This role of the vacuole is related to its ability to control turgor pressure. Turgor pressure makes the rigidity of the cell.

Under optimum conditions, a plant receives adequate amounts of water and the central vacuoles of its cells swell as the liquid collects within them. It creates a high turgor pressure, which helps maintain the structural integrity of the plant, along with the support from the cell wall. Vacuoles also often store the pigments that give certain flowers their colours, which aid them in the attraction of bees and other pollinators. Vacuoles also release molecules that are poisonous to various insects and animals, thus discouraging them from consuming the plant.

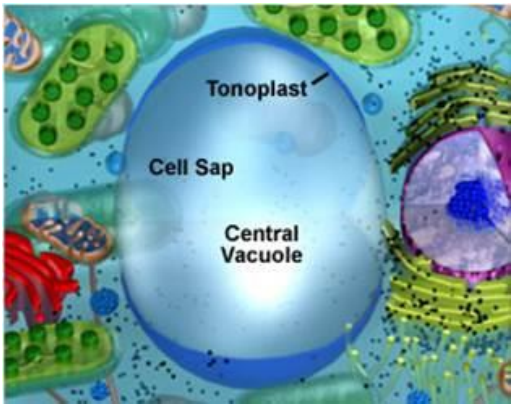


Figure 3.25: Structure of vacuole in plant cell

11 - Centrioles

Recalling:
Centrioles are hollow and cylindrical organelles. A centriole is made of nine triplets of microtubules.

In the cells of animals and most protists, centrioles are organelles

associated with the assembly and organization of the fibres of cytoskeleton i.e., microtubules (including spindle fibres).

In eukaryotic cells centrioles occur in pairs. The two centrioles are located at right angles to one another near the nuclear envelope. In ciliated or flagellated cells centrioles are involved in the formation of cilia and flagella. Each cilium and flagellum is anchored by a centriole, known as **basal body**.

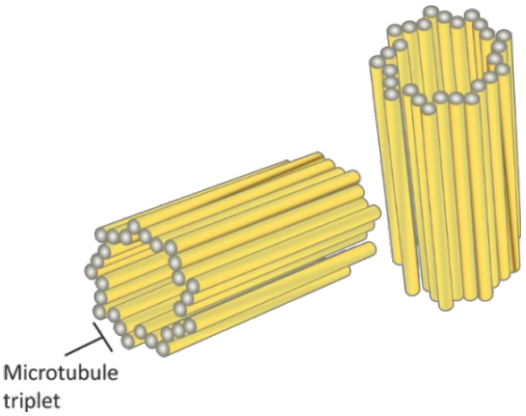


Figure 3.26: Two centrioles

The cells of plants and fungi lack centrioles and basal bodies, and their microtubules and spindle fibres are organized from the structures of cytoplasm.

12- Cytoskeleton

It is a network of protein fibres present in cytoplasm. It includes the following types of fibres:

1. **Microfilaments:** These are present in all eukaryotic cells. Microfilaments are solid rods made of a globular protein, called **actin**. Microfilaments disassemble and re-assemble and help the cells to change shape and move. Microfilaments also enable a dividing cell to pinch off into two cells. In association with myosin, microfilaments help in cellular contraction.
2. **Microtubules:** These straight, hollow cylinders are composed of subunits. Each subunit is made of two different **tubulin** proteins known as *alpha*-tubulin and *beta*-tubulin. Microtubules give structure and shape to a cell. They also serve as highways for the transport of organelles. Moreover, microtubules are the major components of cilia and flagella, and participate in the formation of spindle fibres during cell division.
3. **Intermediate filaments:** These are found only in some higher animal groups. They are made of different proteins but the most common type of protein subunit is **vimentin**. Some cells may have intermediate filaments made of other proteins. For example, skin cells contain a protein **keratin**. Intermediate filaments maintain cell shape and rigidity, and serve to anchor several organelles, including the nucleus.

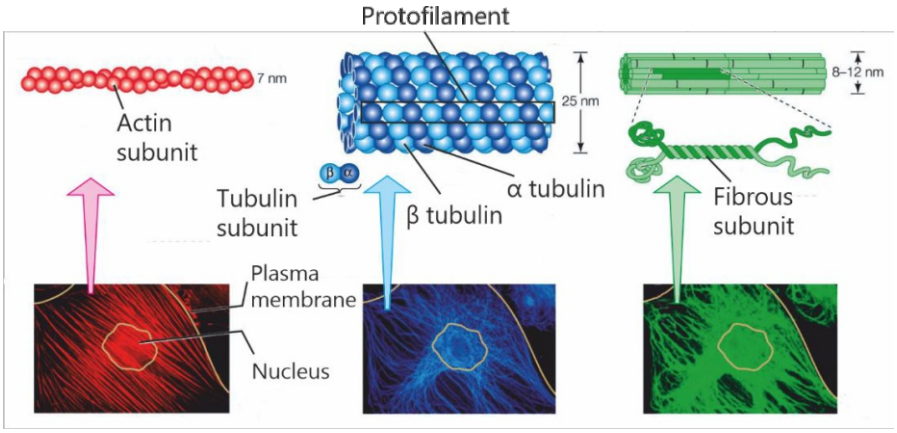


Figure 3.27: Components of cytoskeleton

13- Cilia and Flagella

Cilium (plural *cilia*) and flagellum (plural *flagella*) are the locomotor appendages that protrude from certain cells. They are thin, tail-like projections extending from the cell body. Cilia are short in length and are usually numerous in number; while flagella are longer but less numerous in number. Cilia are rare in plants. Many protozoans (ciliates) possess cilia. Larger eukaryotes such as mammals have cilia on some cells' surfaces. For example, in humans, cilia are found in the lining of the trachea where they sweep mucus and dirt out of breathing tubes.

The core of eukaryotic cilia and flagella is called **axoneme**. It contains two central microtubules that are surrounded by an outer ring of nine doublet microtubules. Dynein molecules are located around the circumference of the axoneme. These dynein molecules bridge the gaps between adjacent microtubule doublets.

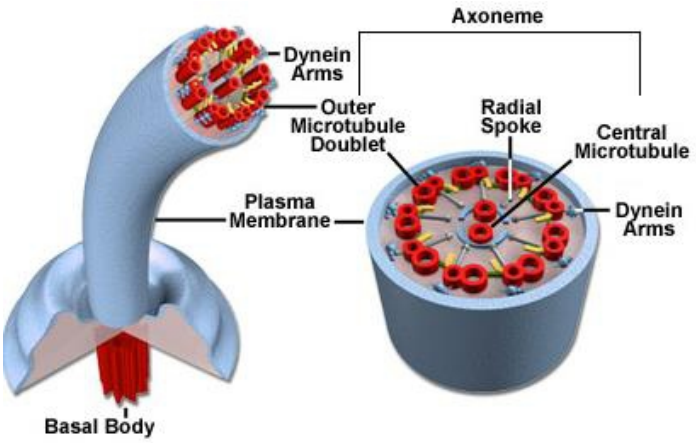


Figure 3.28: Structure of eukaryotic cilium and flagellum

Biologists refer to this organization as a "9 + 2" structure. A plasma membrane surrounds the entire axoneme. At the base of the cilium its organising centre, called basal body, is present. Basal body has the same basic structure of the outer ring of

axoneme, but each of the nine sets of outer filaments is composed of three microtubules, rather than a doublet of microtubules. The basal body is actually the centriole. Prokaryotic flagella have a completely different structure built from the protein flagellin.

3.5- PROKARYOTIC AND EUKARYOTIC CELLS

Bacteria and archaea are made of prokaryotic cells whereas all other forms are composed of eukaryotic cells. Both prokaryotic and eukaryotic cells have DNA as their genetic material; both have plasma membranes as their coverings; and both have ribosomes for protein synthesis. You have gone through the details of the cell organelles.

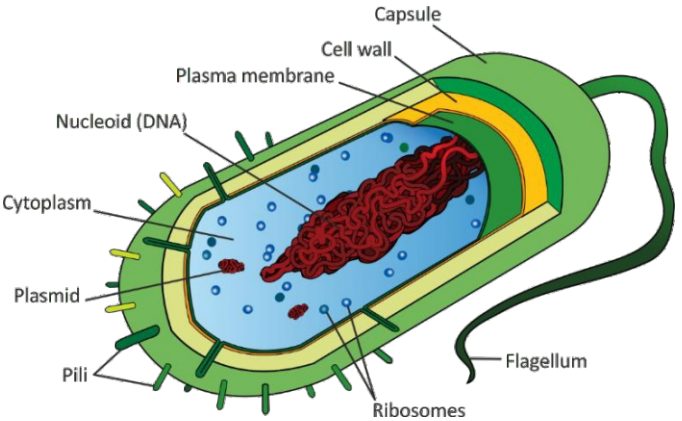


Figure 3.29: Structure of a generalized prokaryotic cell

Prokaryotic cells are much simpler than eukaryotic ones. Most prokaryotic cells range from 2 to 8 µm in length i.e., about one-tenth of the size of a typical eukaryotic cell. A prokaryotic cell lacks a nucleus. The much less extensive DNA of prokaryotic cell is present in the more-or-less central region known as **nucleoid** (*nucleus-like*).

A prokaryotic cell also lacks other membrane-bounded organelles like endoplasmic reticulum, mitochondria, chloroplasts, Golgi apparatus, lysosomes, peroxisomes etc. The entire cytoplasm of a prokaryotic cell is one unit with no internal support structures. Ribosomes are present in prokaryotic cell but these are smaller in size than those of eukaryotic cells.

The Svedberg values (sedimentation rates) of the smaller and larger subunits of ribosomes of prokaryotic cells are 30S and 50S respectively. The sedimentation rate of a complete ribosome is 70S. Surrounding the plasma membrane of most prokaryotic cells is a cell wall but it does not contain cellulose. It composed of peptidoglycan that is a single large polymer of amino acids and sugar. In bacteria the cell wall may also be surrounded by a capsule and may also have extensions for attachment known as pili (singular *pillus*). Prokaryotic flagella are made of repeating units of the protein flagellin and they do not contain microtubule triplets. Mitosis and meiosis are missing in prokaryotic cell and it divides by direct division (binary fission).

Difference between Eukaryotic and Prokaryotic cells		
Characteristics	**Eukaryotic Cell**	**Prokaryotic Cell**
Distinct Nucleus	Present	Absent
Number of chromosomes	More than one	One--but not true chromosome: Plasmids
Cell Type	Usually multicellular	Usually unicellular (some cyanobacteria may be multicellular)
Example	Protozoans, Algae, Fungi, Animals, Plants	Bacteria and Archaea
Lysosomes and peroxisomes	Present	Absent
Microtubules	Present	Absent or rare
Endoplasmic reticulum	Present	Absent
Mitochondria	Present	Absent
Cytoskeleton	Present	May be absent
Vacuoles	Present	Present
Ribosomes	Larger	Smaller
Golgi apparatus	Present	Absent
Chloroplasts	Present (in plants)	Absent; chlorophyll scattered in the cytoplasm
Cell Division	Mitosis or meiosis	Mitosis and meiosis are missing; cell divides by direct division (binary fission)
Flagella	Membrane bounded; contains two central microtubules surrounded by an outer ring of nine doublet microtubules	Not membrane bounded; made of repeating units of flagellin; do not contain microtubule triplets
Cell wall	Only in plant cells and fungi (chemically simpler)	Composed of peptidoglycan (a single large polymer of amino acids and sugar)
Cell size	10-100 um	1-10 um

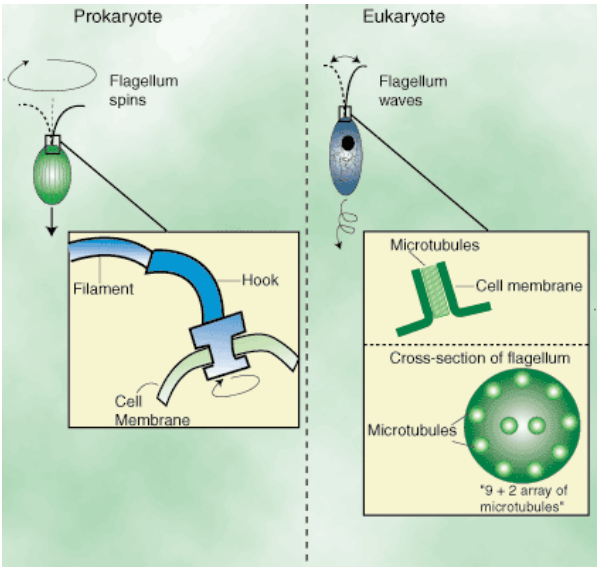


Figure 3.30: Difference between the structures of prokaryotic and eukaryotic flagella

3.6- CELL SIGNALLING

Cell signalling is the ability of cells to respond to stimuli from their environment producing cellular responses. It involves the transmission of signals between cells through a series of molecular events, often leading to a cellular response.

Steps of Cell Signalling

1- Signal Reception

Cell signalling begins when a signal molecule (ligand) binds to a receptor on the membrane of a target cell. These receptors are typically proteins embedded in the cell membrane but can also be located inside the cell. Each receptor is specific to a particular ligand.

2- Signal Transduction

Once the receptor binds to the ligand, it undergoes a conformational change that activates an intracellular signalling pathway. This often involves a series of interactions and modifications, creating a signalling cascade that amplifies the signal. Small molecules like cAMP (cyclic AMP), calcium ions, and inositol triphosphate (IP3) can act as second messengers, transmitting the signal from the receptor to target molecules inside the cell.

3- Cellular Response

The signal transduction pathway often leads to changes in gene expression, turning specific genes on or off. This can result in various cellular responses, such as cell growth, division, differentiation, or apoptosis (programmed cell death). Signalling can also lead to changes in cellular metabolism, enzyme activity, or the opening and closing of ion channels.

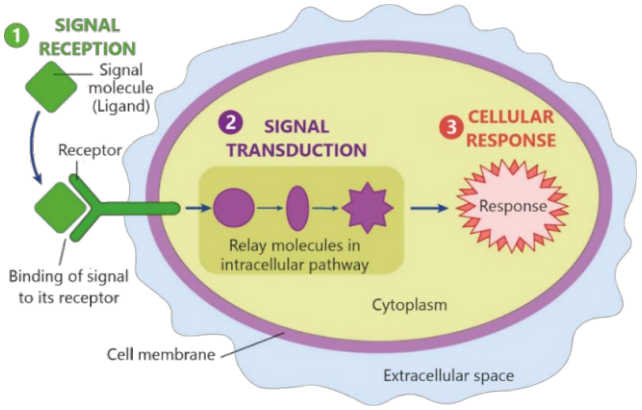


Figure 3.31: Steps of cell signalling

Pathways of Cell Signals from Outside to Inside

Cell signalling pathways involve the transmission of signals from the cell's exterior to its interior, resulting in a specific cellular response. There are two main types of signalling pathways based.

Protein/Peptide Signalling

Protein or peptide signalling molecules are water-soluble. So, they cannot pass through plasma membrane. When such ligand approaches the cell surface, it binds to its specific receptor on plasma membrane. This binding causes a conformational change in the receptor protein and activates it. The activated receptor triggers a series of reactions within the cell. These reactions generate second messenger like cyclic AMP (cAMP) which starts changes e.g., changes in gene expression. The pathway can lead to changes in metabolism, cell growth, division, or apoptosis.

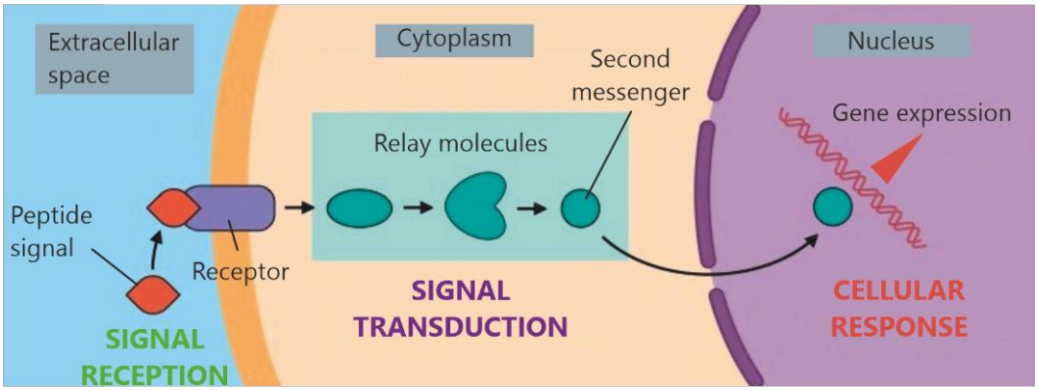


Figure 3.32: Protein/peptide signalling pathway

Steroid Signalling

Steroid hormones, being lipophilic, can diffuse through the plasma membrane of the target cell. Once inside, they bind to specific intracellular receptors located in the cytoplasm or nucleus. This binding results in the formation of active receptor-hormone complex which moves into the nucleus if it was not already there. Inside nucleus, the receptor-hormone complex binds to specific DNA sequences in target genes. This binding regulates the transcription of these genes, leading to increased or decreased production of specific proteins.

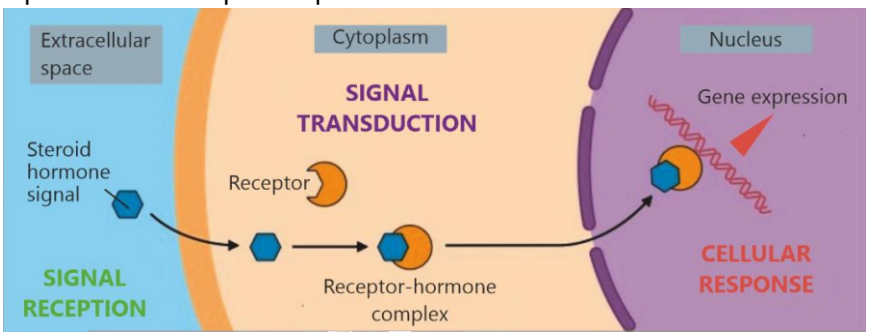


Figure 3.33: Steroid signalling pathway

3.7- MEMBRANE TRANSPORT MECHANISMS

While exchanging matter with cells' environment, plasma membranes maintain equilibrium inside the cell as well as outside.

You know that the movement of substances in and out of cells is crucial for cellular functions. These movements are done for nutrient uptake, waste elimination, gas exchange, and signal transduction. Cells rely on the plasma membrane for regulating the movement of substances in and out of the cell. Membrane transport mechanisms are essential processes that enable the cell to maintain homeostasis, acquire nutrients, remove waste products, and communicate with its environment.

These mechanisms include two mechanisms i.e., passive transport (which requires no energy input) and active transport (which utilizes energy).

Passive Transport

The movement of molecules across plasma membrane without any expenditure of energy is called passive transport. The following are the types of passive transport.

Diffusion

Diffusion is the net movement of a substance (liquid or gas) from an area of higher concentration to one of lower concentration i.e., along concentration gradient. Because a cell does not expend energy when molecules diffuse across its membrane, the diffusion of molecules is a type of **passive transport**

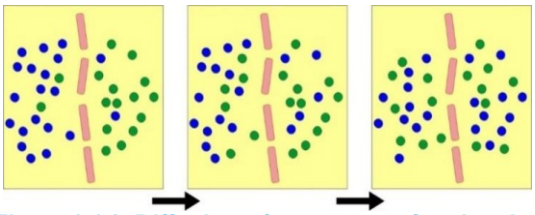


Figure 3.34: Diffusion of two types of molecules

Facilitated Diffusion

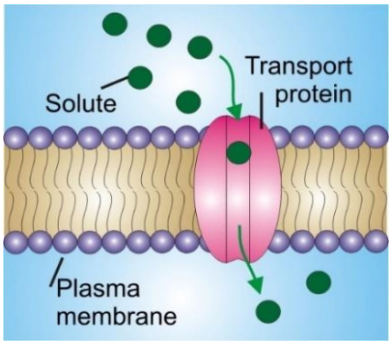


Figure 3.35: Facilitated diffusion

Some molecules are taken into or out of the cells with the help of **transport-proteins** present in plasma membranes. When a transport protein helps a substance to move it down its concentration gradient (from higher to lower concentration), the process is called facilitated diffusion. It is also a type of passive transport because no energy is used in facilitated diffusion. The rate of facilitated diffusion depends on how many transport-protein molecules are available in the membrane. The main types of transport proteins involved in facilitated diffusion are:

1. Channel Proteins: These proteins form hydrophilic channels across the membrane that allow specific molecules or ions to pass through. They can be gated or non-gated. Gated channels open or close in response to specific stimuli (such as voltage changes, ligand binding, or mechanical stress). Examples include ion channels (allow the passage of specific ions e.g., Na^+, K^+, Ca^{2+}, Cl^-) and aquaporins (facilitate the rapid transport of water molecules).

2. Carrier Proteins (Transporters): These proteins bind to the specific molecule they transport, undergo a conformational change, and move the molecule across the membrane. They are highly specific for the molecule they transport. They can become saturated, meaning there is a maximum rate of transport when all carrier proteins are occupied. Examples include glucose transporters (facilitate the transport of glucose) and amino acid transporters (transport specific amino acids into or out of the cell).

Difference between Simple and Facilitated Diffusion		
	Simple Diffusion	**Facilitated Diffusion**
Mechanism	• Substances move from higher concentration to lower concentration directly through	• Substances move from higher concentration to lower concentration through specific

Difference between Simple and Facilitated Diffusion		
	the lipid bilayer of plasma membrane.	transport proteins embedded in plasma membrane.
Energy Requirement	• It is a passive transport mechanism, requiring no energy input from cell.	• It is also a passive transport mechanism and does not require energy.
Types of Molecules	• Typically involves small, nonpolar molecules such as oxygen, carbon dioxide, and lipid-soluble substances.	• Primarily involves polar or charged molecules, such as glucose, amino acids, and ions, which cannot easily pass through the hydrophobic core of the lipid bilayer.
Rate of Movement	• The rate depends on the concentration gradient, temperature, and the permeability of the membrane.	• The rate can be affected by the number and availability of transport proteins and can reach a maximum rate when all transport proteins are saturated.

Osmosis

The process by which water molecules diffuse across a cell membrane from an area of higher concentration to an area of lower concentration is called osmosis. Because water is moving from a higher to lower concentration, osmosis does not require cells to expend energy. Therefore, osmosis is the passive transport of water. The direction of osmosis depends on the concentration of solutes on the two sides of membrane. Water always moves from hypotonic solution (with lower solute concentration) hypertonic solution (with higher solute concentration).

The term **tonicity** refers to the relative concentration of solutes in the solutions.
Hypertonic solutions are those in which more solute is present.
Hypotonic solutions are those with less solute.
Isotonic solutions have equal concentrations of solutes.

Osmosis occurs through selectively permeable membrane, which allows water to pass while restricting many solutes. Osmosis is crucial for maintaining cell turgor, which is vital for plant cells, and for balancing the internal water content in cells. The direction and rate of osmosis are influenced by the osmotic gradient and the permeability of the membrane to water. Specialized proteins called aquaporins facilitate the rapid transport of water molecules across the cell membrane, ensuring efficient regulation of cellular hydration and volume.

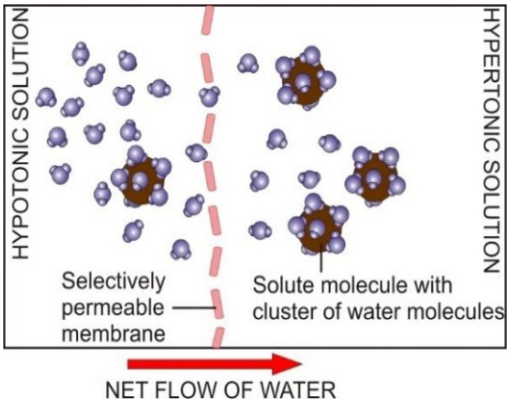
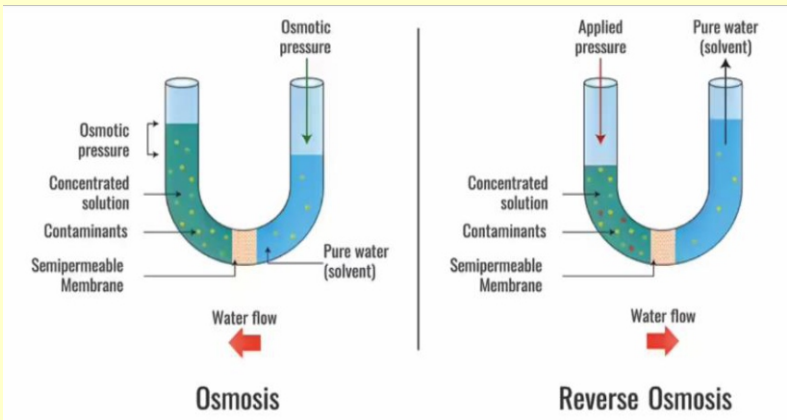


Figure 3.36: Osmosis at molecular level

Reverse osmosis

It is a widely used technology for purifying water by removing contaminants and impurities. Unlike natural osmosis, which moves water from a lower to a higher solute concentration, reverse osmosis applies external pressure to push water through a semi-permeable membrane from a higher to a lower solute concentration. This process effectively filters out dissolved salts and other impurities, providing clean and safe drinking water. Reverse osmosis is commonly used in water treatment plants, desalination facilities, and even in household water purification systems.



Active Transport

The movement of substances across plasma membrane from lower concentration to higher concentration with the expenditure of energy is known as active transport. Following types of active transport occur through plasma membrane.

Active transport through carrier proteins

In this process, carrier (transport) proteins in the plasma membrane use energy to move the molecules against the concentration gradient. For example, the membranes of nerve cells have carrier proteins in the form of **"sodium-potassium pump"**. In a resting (not conducting nerve impulse) nerve cell, this pump spends energy (ATP) to maintain higher concentrations of K^+ and lower concentrations of Na^+

inside the cell. For this purpose, the pump actively moves Na^+ to the outside of the cell and K^+ to the inside of the cell.

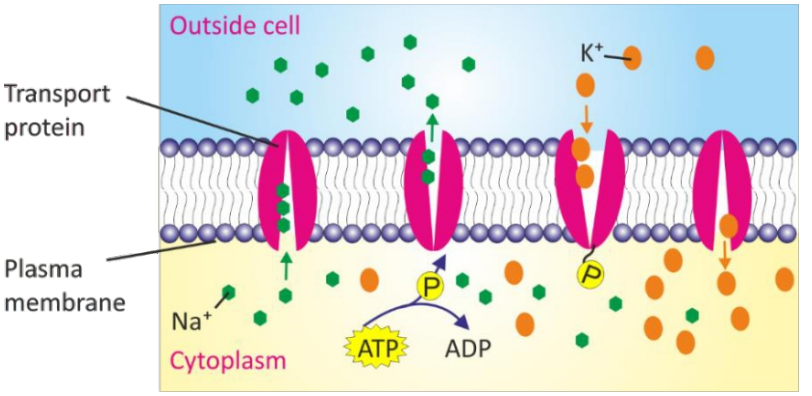


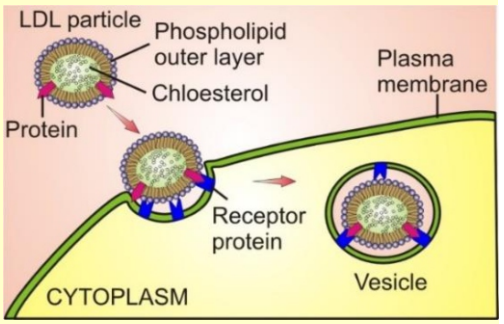
Figure 3.37: Active transport through carrier proteins

Endocytosis

In endocytosis, bulky materials are moved into the cell across plasma membrane. During endocytosis a portion of plasma membrane invaginates (depressed inward). The material from outside is taken inside the invagination, and its ends seal. Thus, a small vesicle is formed. It detaches from the plasma membrane and moves into cytoplasm. The two common forms of endocytosis are phagocytosis and pinocytosis. In **phagocytosis** cell takes in solid material while in **pinocytosis** cell takes in liquids in the form of droplets.

Receptor-mediated endocytosis

Specific receptor proteins of plasma membrane pick up material from outside and pinch inside to form a vesicle. For example, the cells of liver have receptor proteins for cholesterol. Cholesterol circulates in our blood in the form of low-density-lipoproteins (LDLs). The receptor proteins of plasma membrane of liver cells, recognize and take up LDLs from the blood by receptor-mediated endocytosis.



Exocytosis

It is the process through which bulky material is exported out of cell. In exocytosis, the bulky material is packed inside a membrane and a vesicle is formed. The vesicle moves to the plasma membrane and fuses with it to release its contents into the extracellular environment.

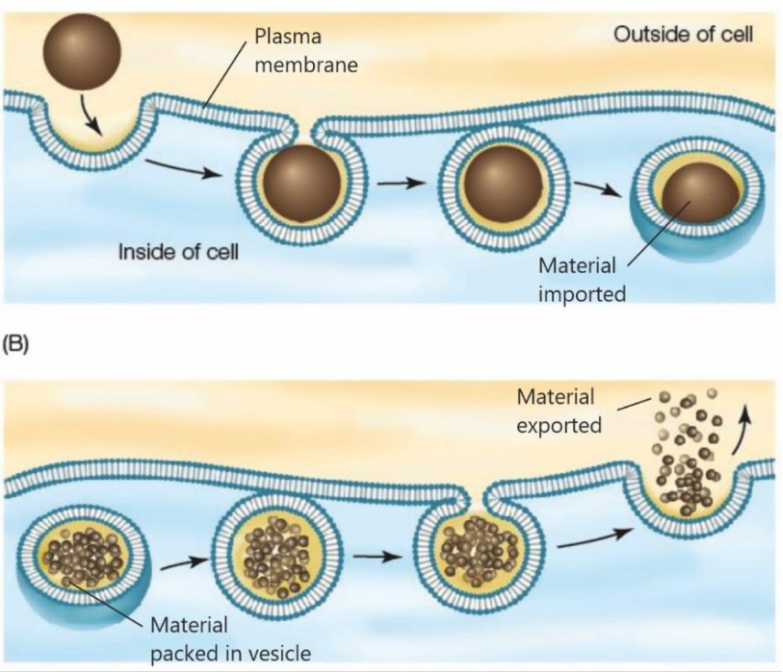


Figure 3.38: (A) Endocytosis, (B)Exocytosis

3.8- STEM CELLS

Stem cells are unique cells with the remarkable ability to develop into many different cell types in the body. When a stem cell divides, each new cell has the potential either to remain a stem cell or to become specialized cell, such as a muscle cell, a red blood cell, or a brain cell. The following are the major categories of stem cells on the basis of the number of types of cells which they can make.

1. **Totipotent:** These stem cells can differentiate into all possible cell types. For example, zygote and the cells produced by the first few divisions in zygote.
2. **Pluripotent:** These cells can turn into almost any cell. For example, cells from the early embryo.
3. **Multipotent:** These cells can differentiate into a closely related family of cells. For example, the hematopoietic stem cells can become red and white blood cells or platelets.
4. **Oligopotent:** These can differentiate into a few different cell types. For example, adult lymphoid or myeloid stem cells.
5. **Unipotent:** These can only produce cells of one kind, which is their own type. However, they are still stem cells because they can renew themselves. For example, adult muscle stem cells.

Use of Stem Cells

1. **Regenerative Medicine:** Stem cells have the potential to repair or replace damaged tissues and organs. Therefore, they are used for treating conditions such as spinal cord injuries, type 1 diabetes, Parkinson's disease, and heart disease.
2. **Drug Testing and Development:** By differentiating stem cells into specific cell types, researchers can create models of human diseases, allowing for more accurate testing of drug effects and reducing the reliance on animal models.
3. **Personalized Medicine:** Stem cells can be derived from a patient's own cells, reducing the risk of immune rejection when used in treatments. This personalized approach can lead to more effective and safer therapies.

Categories of Stem Cells

The following are the major categories of stem cells on the basis of their origin.

1- Embryonic Stem Cells (ESCs)

ESCs are derived from the inner cell mass of blastocysts (early-stage embryos). These stems cells are pluripotent, meaning they can differentiate into nearly all cell types in the body. They have high differentiation potential, making them extremely versatile for research and therapy. Ethical concerns of using ESCs include the use of human embryos, risk of teratoma formation, and potential immune rejection.

2- Adult Stem Cells (ASCs)

These stem cells are found in various tissues throughout the body, such as bone marrow, fat, and blood. They are multipotent, meaning they can differentiate into a limited range of cell types related to their tissue of origin. Using them involves less ethical controversy, lower risk of immune rejection when derived from the patient's own tissues. However, they have limited differentiation potential and are harder to isolate and culture.

3- Induced Pluripotent Stem Cells (iPSCs)

They are generated in the lab by reprogramming adult somatic cells to a pluripotent state using specific transcription factors. They are pluripotent, similar to embryonic stem cells.

Advantages of using iPSCs: They do not have the ethical controversies linked to embryonic stem cells, as they do not require the destruction of embryos. They can be generated from a patient's own cells, minimizing the risk of immune rejection. They offer potential for regenerating damaged tissues and organs (e.g., new heart cells for patients with heart disease or new neurons for patients with neurodegenerative conditions).

Disadvantages of using iPSCs: The reprogramming process can introduce genetic changes that may affect iPSCs. They could form tumours (teratomas) when transplanted into patients. Directing iPSCs to differentiate into specific, fully functional cell types remains a complex task. It is still difficult to ensure that these cells function properly.

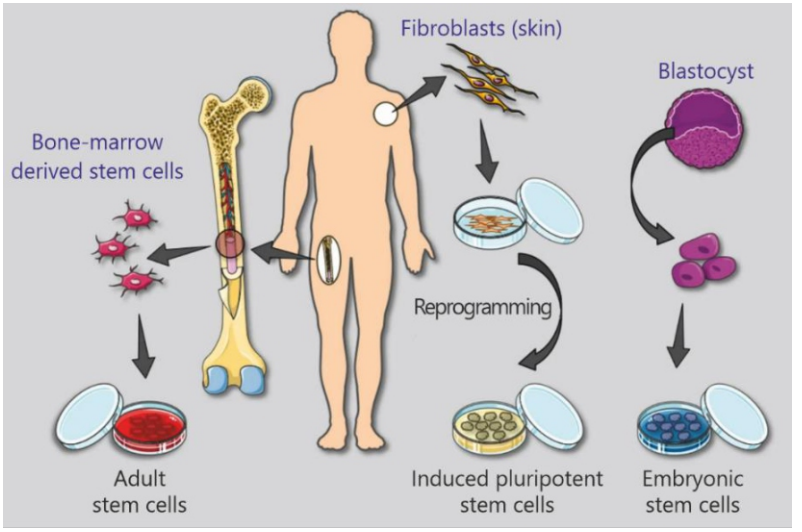


Figure 3.39: Stem cells- Sources and types

EXERCISE

SECTION 1:MULTIPLE CHOICE QUESTIONS

1. Which one of the following eukaryotic cell structures does not contain DNA?
   (a) Nucleus (b) Mitochondrion
   (c) Endoplasmic reticulum (d) Chloroplast
2. Which of the following is not an accurate description of a chromosome?
   (a) It is a coloured body localized in the nucleus
   (b) It is a protein and nucleic acid complex
   (c) It is the cellular structure that contains the genetic material
   (d) In eukaryotes, it is composed of many DNA molecules attached end to end
3. A centriole is an organelle that is:
   (a) Present in the centre of a cell's cytoplasm
   (b) Composed of microtubules and important for organizing the spindle fibres
   (c) Surrounded by a membrane
   (d) Part of a chromosome

4. The rough endoplasmic reticulum is:
   (a) An intracellular double-membrane system to which ribosomes are attached
   (b) b) An intracellular membrane that is studded with microtubular structures
   (c) c) A membranous structure found within mitochondria
   (d) d) Only found in prokaryotic cells
5. In the nucleus of eukaryotic cells, the genetic material is complexed with protein and organized into linear structures called:
   (a) Centrioles (b) Histones
   (c) Chromosomes (d) Plasmids
6. Which of the following statements does not apply to the nuclear envelope?
   (a) It is a double membrane
   (b) It is continuous with the endoplasmic reticulum
   (c) It has pores through which material enters and leaves
   (d) It has infoldings to form cristae
7. Lysosomes are formed by budding from which cellular organelle?
   (a) Smooth endoplasmic reticulum (b) Golgi apparatus
   (c) Rough endoplasmic reticulum (d) Nucleus
8. All peroxisomes carry out this function:
   (a) Break down fats and amino acids into smaller molecules that can be used for energy production by mitochondria
   (b) Digest macromolecules using the hydrolytic enzymes they contain
   (c) Synthesize membrane components such as fatty acids and phospholipids
   (d) Control the flow of ions into and out of the cell
9. How would the absence of peroxisomes in a cell affect its metabolism, and what would be the likely symptoms?
   (a) The cell would be unable to carry out oxidative phosphorylation, leading to reduced ATP production.
   (b) The cell would accumulate hydrogen peroxide, leading to oxidative stress and potential cellular damage.
   (c) The cell would have impaired protein synthesis, leading to muscle weakness.
   (d) The cell would fail to produce lipids, causing membrane instability

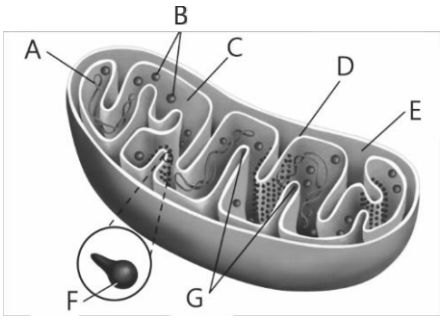
10. Which of the following does not apply to chloroplasts?
    (a) They contain chlorophyll and the enzymes required for photosynthesis.
    (b) They contain an internal membrane system consisting of thylakoids.
    (c) They synthesize ATP.
    (d) They are bounded by two membranes, the inner of which is folded into the cristae.
11. What is the correct sequence of membrane compartments through which a secretory protein moves from synthesis to release from the cell?
    (a) SER → Golgi apparatus → RER → Cell membrane
    (b) Cell membrane → Golgi apparatus → RER → SER
    (c) RER → Golgi → Cell membrane → SER
    (d) RER → SER → Golgi apparatus → Cell membrane
12. How does the process of facilitated diffusion differ from active transport?
    (a) Facilitated diffusion requires energy, active transport does not
    (b) Facilitated diffusion does not require energy, active transport does
    (c) Both processes require energy
    (d) Both processes do not require energy

SECTION 2:SHORT QUESTIONS

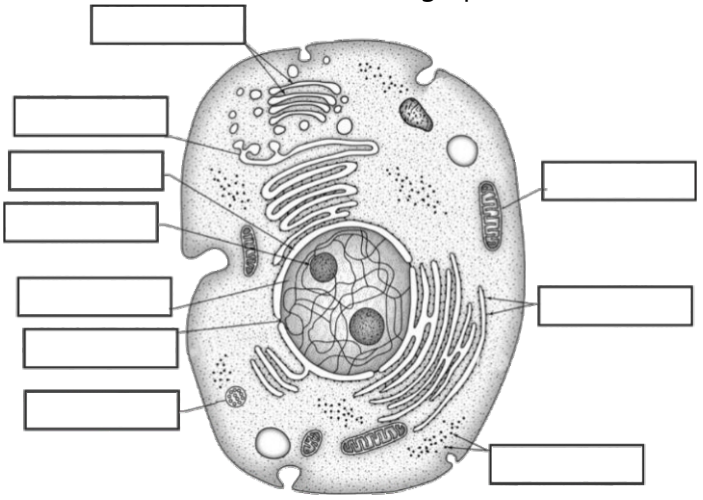
1. Compare the resolution and magnification of light microscope and electron microscope?
2. State the cell theory. How we can validate it? What are the exceptions to cell theory?
3. The table below compares the process of diffusion, facilitated diffusion and active transport. Fill in the blank cells , using the words "YES" or "NO".

	Process		
Description	Simple Diffusion	Facilitated Diffusion	Active Transport
Is ATP required?			
Are carrier proteins involved?			
Is direction of transport always from higher to lower concentration?			

4. Categorize the organelles as (i) single membrane bounded, (ii) double membrane bounded and (iii) lacking any membrane.
5. State two functions of the proteins in the plasma membrane.
6. State two features that mitochondria have in common with prokaryotes.
7. List three ways in which prokaryotic cells differ from eukaryotic cells.
8. List the structures and molecules, which can cross the nuclear envelope.
9. Distinguish each of the following pairs.
   a- exocytosis and endocytosis
   b- phagocytosis and pinocytosis
   c- peroxisome and glyoxysomes
10. What are the main functions of lysosomes?]
11. Describe the role of the Golgi body in forming lysosomes.
12. What are histones? Where are these found in eukaryotic cells?
13. What do you mean by "stem cell"? What are the main usages of stem cells?
14. The following diagram shows the structure of a mitochondrion. Name structures A to G.



15. The diagram below shows an electron micrograph of a cell.



a- Label the parts of the cell.
b- What evidence can be seen in the diagram that suggests that the cell is metabolically active and involved in secretion of enzymes?

SECTION 3: LONG QUESTIONS

1. Write details of the structure and the chemical composition of cell walls of eukaryotes and prokaryotes.
2. Explain the chemical composition and the functions of plasma membrane.
3. Identify the role of glycolipids and glycoproteins as the cell surface markers.
4. Explain the structure, chemical composition and function of ribosomes.
5. Explain the structure, and functions of Golgi complex.
6. Describe the structure, chemical composition and function of chromosome.
7. Discuss nuclear envelope and nuclear pore complex in detail.
8. Explain how Golgi apparatus is involved in making cell secretions.
9. Describe the structure and functions of smooth and rough endoplasmic reticulum.
10. Explain the role of lysosomes and peroxisomes in regulating the amounts of cellular contents.
11. Describe the structures of the three fibres that make the cytoskeleton.
12. Describe the formation and functions of lysosomes.
13. Compare mitochondria and chloroplasts as the organelles that are involved in cellular energetics.
14. Describe the basic structure of a mitochondrion, from outside inward.
15. Describe the pathway of protein signal and steroid signal from outside of a cell to inside.
16. Categorize and explain different types of stem cells.
17. What are the advantages and disadvantages of using induced Pluripotent Stem Cells?

INQUISITIVE QUESTIONS

1. If a researcher observes that a certain cell type has an exceptionally large Golgi apparatus, what can be inferred about the function of this cell?
2. If a signalling molecule is lipid-soluble, like a steroid hormone, what is the most likely mechanism for its action within the target cell?
3. Why do we categorize endocytosis and exocytosis in active transport?
4. Justify why the membrane may be described as fluid.

Chapter 4

BIOMOLECULES

STUDENTS'LEARNING OUTCOMES

After studying this chapter, the students will be able to:

- Define biochemistry/molecular biology.
- Describe Briefly the different types of bonds found in biology (hydrogen bonds, covalent bonds, interactions, Ionic, hydrophobic and hydrophilic interactions etc.).
- Distinguish carbohydrates, proteins, lipids and nucleic acids as the four fundamental biological molecules.
- Describe and draw sketches of the condensation synthesis and hydrolysis. reactions for making and breaking of macromolecule polymers.
- 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) which allow it to be the medium of life.
- Define carbohydrates and classify them.
- Compare and contrast the properties and roles of monosaccharides and write their formulae.
- Compare the isomers and stereoisomers of glucose.
- Distinguish the properties and roles of disaccharides.
- Describe glycosidic bond in disaccharides.
- Describe the structure properties and roles of polysaccharides starch, glycogen, cellulose and chitin.
- Define protein, amino acid and recognized essential amino acid and structural formula of amino acid.
- Outline the synthesis and breakage of peptide linkages.
- Justify the significance of the sequence of amino acids through the example of sickle cell haemoglobin.
- Classify proteins as globular and fibrous proteins.
- List the roles of structural proteins and functional proteins with 3 examples.
- Define lipids.
- Describe the properties and roles of acylglycerols, phospholipids, terpenes and waxes.
- Illustrate the molecular structure (making and breaking) of an acylglycerol, a phospholipid and a terpene.
- Evaluate steroids and prostaglandins as important groups of lipids.
- Describe nucleic acids and molecular structure of nucleotides.
- Distinguish among the nitrogenous bases found in the nucleotides of nucleic acids.
- Outline the examples of a mononucleotide (ATP) and a dinucleotide (NAD).
- Illustrate the formation of phosphodiester bond.
- Explain the double helical structure of DNA as proposed by Watson and Crick.
- Explain the general structure of RNA.
- Distinguish in terms of functions and roles, the three types of RNA.
- Discuss the Central Dogma.
- Define conjugated molecules and describe the roles of common conjugated molecules i.e. glycolipids, glycoproteins, lipoproteins and nucleoproteins.

Recall "levels of biological organization" that you have studied in your previous classes. You got a brief introduction about biological molecules in reference of levels of biological organization. Now you would get detailed study of carbohydrates, proteins, lipids and nucleic acids as well as the importance of water and the role of conjugated molecules.

Biochemistry

Biochemistry is the study of chemical components and chemical processes, occurring in living organism. All structures of living organisms have biochemical organization and all functions occurring in them are due to biochemical processes taking place in this organization. Therefore, a basic knowledge of biochemistry is helpful to understand anatomy and physiology of living organisms. Photosynthesis, respiration, digestion, contraction etc. can be described in biochemical terms.

Recalling

Life of an organism depends upon the ceaseless chemical activities in its cells. All the chemical reactions taking place within a cell are collectively called metabolism. The processes in metabolism may be either anabolism or catabolism. In anabolism, simpler substances are combined to form complex substances and in catabolism complex molecules are broken down into simpler ones.

4.1- BIOLOGICAL MOLECULES

Life on Earth evolved in water, and all life still depends on water. At least 80% of the mass of living organisms (protoplasm) is water, and almost all chemical reactions of life take place in aqueous solutions. The other chemicals that make up living things are mostly organic macromolecules and certain inorganic molecules. The molecules synthesized by cells and containing carbon are known as organic molecules. They occur naturally only in the bodies of living organisms or in their products and remains. Carbohydrates, proteins, lipids and nucleic acids are important organic molecules in living organisms. They make 93% of the dry mass of living organisms (Table 4.1). The remaining 7% comprises of small organic molecules (like vitamins) and inorganic molecules (like carbon dioxide, acids, bases, and salts).

Organic molecules have carbon-based core with special groups of atoms attached. These groups are called **functional groups** for example OH, CO, COOH, NH_2 etc. Most biochemical reactions involve the transfer of a functional group from one molecule to another, or the breaking of carbon-carbon bond.

Table 4.1: %age of major organic molecules in the dry mass of

Group name	% Dry mass
Proteins	50
Nucleic acids	18
Carbohydrates	15
Lipids	10

Most of the organic molecules are large in size and biologists call them macromolecules. Many macromolecules are in the form of polymers. A polymer is a molecule consisting of many identical molecular units, called monomers. Important macromolecules like carbohydrates, proteins, and nucleic acids are the polymers of simple monomers i.e., sugars, amino acids and nucleotides respectively.

4.2- TYPES OF BONDS IN BIOLOGY

Different types of bonds and interactions play vital roles in the structure and function of biological molecules.

Carbon is the basic element of organic molecules. It is tetravalent and can react with many other known elements like H, O, N, P and S. Carbon and hydrogen bond (C-H bond) is the potential source of chemical energy for cellular activities. Carbon-oxygen association in glycosidic linkages provides stability to the complex carbohydrate molecules. Carbon combines with nitrogen in amino acid linkages to form peptide bonds and forms proteins which are very important due to their diversity in structure and functions.

Covalent bonds form when two atoms share electrons (Figure 4.1). These bonds are often found in organic molecules like proteins and nucleic acids, providing stability to the molecules.

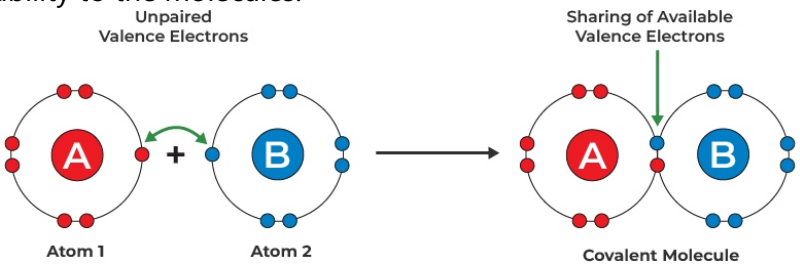


Figure 4.1: Covalent bond between two atoms

Ionic bonds are formed when one atom donates an electron (becomes a positive ion, or cation) and another atom accepts the electron (becomes a negative ion, or anion) (Figure 4.2). The electrostatic attraction between these oppositely charged ions forms the ionic bond. Ionic bonds are relatively strong in the solid state and are formed mostly in inorganic molecules like sodium chloride.

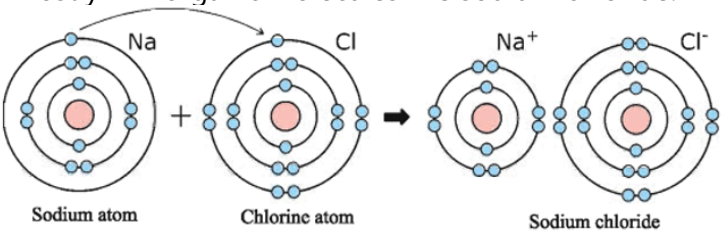


Figure 4.2: Ionic bond between sodium and chlorine atoms

Hydrogen bonds are weak attractions that occur between a hydrogen atom and an electronegative atom (such as oxygen or nitrogen). These bonds are important in maintaining the structure of large molecules like proteins and nucleic acids, as well as in various biological processes like DNA replication.

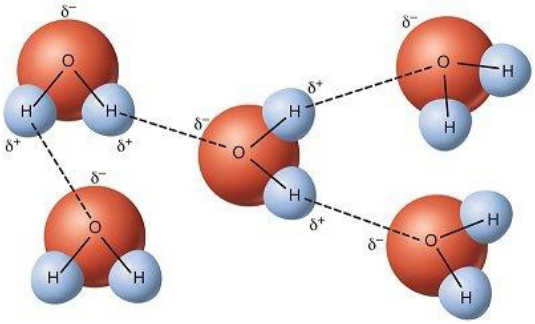


Figure 4.3: Hydrogen bond between water molecules

Hydrophobic interactions occur between nonpolar molecules and polar molecules (like water). Nonpolar molecules tend to cluster together in aqueous environments to minimize contact with water molecules. This phenomenon is crucial for the folding of proteins and the formation of lipid bilayers in cell membranes.

Hydrophilic interactions occur between polar molecules and water molecules. These interactions are essential for the dissolution of polar and ionic compounds in water. These interactions help in various biological processes such as nutrient transport and chemical reactions within cells.

4.3- CONDENSATION (SYNTHESIS) AND HYDROLYSIS

Energy is required to break chemical bonds when water is extracted from monomers. So, cells must supply energy to make macromolecules.

Proteins, nucleic acids, carbohydrates, and lipids are assembled from different kinds of monomers. All these biomolecules join their monomers by condensation or dehydration process. During condensation, an -OH group is removed from one monomer and an -H atom is removed from another monomer. It is also known as dehydration synthesis because the removal of OH and H groups means the removal of a water molecule. The formation of maltose by two glucose monomers is an example of a condensation reaction.

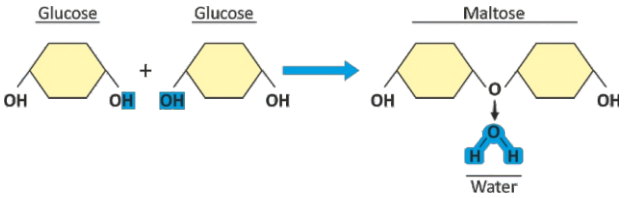


Figure 4.4: Making of macromolecules (Dehydration synthesis)

Along with making polymers by combining their monomers, cells keep on breaking polymers too. Hydrolysis is a chemical process in which macromolecule (polymer) is broken down into smaller fragments by the addition of water molecules. It is the reverse of dehydration synthesis. Cells break bonds between monomers by adding water to them. In this process, OH group from a water molecule joins to one monomer and hydrogen joins to the second monomer. Breakdown of maltose into two glucose monomers by the addition of a water molecule is an example of hydrolysis.

This breakdown of macromolecules is essential in various biological processes, such as digestion and cellular respiration, where smaller molecules are needed for energy production.

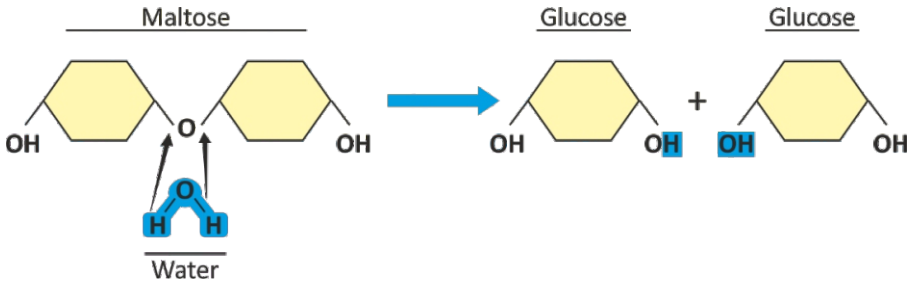


Figure 4.5: Breaking of macromolecules (Hydrolysis)

4.4- IMPORTANCE OF WATER

An oxide of hydrogen, water has the chemical formula H_2O. This seemingly simple molecule has many surprising properties, which give it the status of "the medium of life". About two third of our bodies are composed of water and we cannot exist without it. In fact, it is the most abundant compound found in all organisms. Its concentration varies from 65 to 89 percent in different organisms. In multicellular organisms, its concentration varies from tissue to tissue. For example, bone cells are made up of about 20 percent water and brain cells contain 85 percent water. Water plays important roles in making and maintaining the matter of life (protoplasm) and in establishing suitable environment, necessary for the working of life. Water has many important properties which make it essential for life.

Solvent Properties

The ability of water to dissolve a wide variety of substances is due to its two properties, the **polarity of water molecules** and the ability of water molecules to form **hydrogen bonds**.

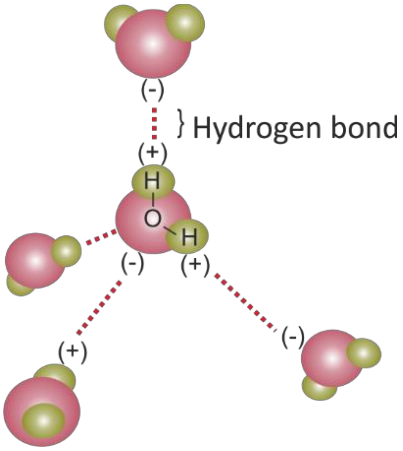
The water molecule has distinct ends, each with a partial charge. Hydrogen atom is partially positive and oxygen atom is partially

Hydrogen bonds help in maintaining the three-dimensional structures of proteins and the double helix structure of DNA.

negative. Such molecules are called polar molecules.

Without hydrogen bonding water would boil at – 80 ℃ and freeze at – 100 ℃. making life impossible.

Partial negative charge at one end of a water molecule is attracted to partial positive of another water molecule. This weak attraction is called a **hydrogen bond**. Water forms a network of such bonds. Many of the properties of water are due to hydrogen bonds in water.



Charged or polar molecules such as salts, sugars, amino acids dissolve readily in water and so are called hydrophilic ("water loving"). Uncharged or non-polar molecules such as lipids do not dissolve in water and are called hydrophobic ("water hating").

Figure 4.6: Hydrogen bonds among water molecules

Due to the polar nature of water molecules, they gather around any other molecule that has an electrical charge, whether in the form of full charge (ions) or partial charge (polar molecules). For example, when sodium chloride (a salt) is placed in water, it breaks into positive (Na^+) and negative ions (Cl^-). These ions are surrounded by opposite polar ends of water molecules (Figure 4.7).

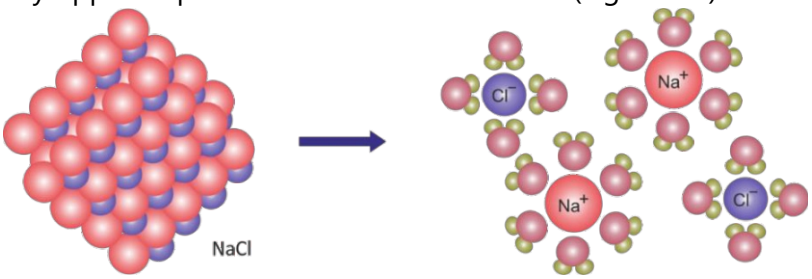


Figure 4.7: Water as a solvent of inorganic molecules (NaCl)

Similarly, when a glucose is placed in water, the molecules of water form hydrogen bonds with polar hydroxyl groups of glucose molecules. In this way, glucose dissolves in water (Figure 4.8). It means that charged or polar molecules are soluble in water. In the state of solution, ions and molecules can react with each other easily. So, water provides a medium for chemical reactions i.e., metabolism of cells.

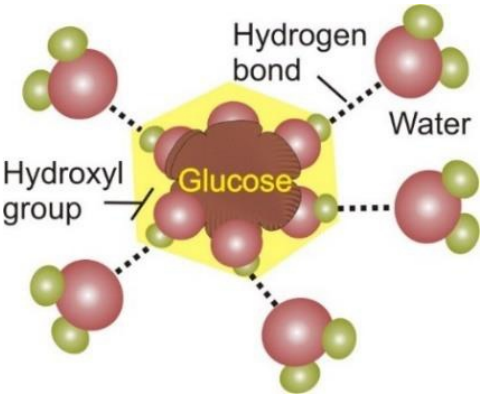


Figure 4.8: Water as a solvent of organic molecules (glucose)

So, charged or polar molecules are soluble in water. In the state of solution, ions and molecules can react with each other easily. So, water provides a medium for metabolism (chemical reactions in cells).

Polar molecules such as salts, sugars, and amino acids dissolve readily in water and are called hydrophilic (water-loving). Uncharged or non-polar molecules such as lipids do not dissolve in water and are called hydrophobic (water-hating).

Hydrophobic Exclusion

Non-polar or uncharged molecules are insoluble in water because water molecules do not make hydrogen bonds with them. When they are placed in water, water molecules move them out. The insoluble molecules make hydrophobic associations with one another. For example, lipids molecules are insoluble in water. When they are excluded from water, they make strong associations among themselves. Therefore, lipids help to maintain membranes of cells.

Figure 4.9: Hydrophobic association of oil (lipid) with water molecules

Heat Capacity

Specific heat of water is twice than that of most carbon compounds and is nine times more than that of iron.

Specific heat capacity is defined as the number of calories (amount of heat) required to raise the temperature of 1 gram of a substance from 15°C to 16°C (i.e.,1°C). Water has a high specific heat capacity i.e., 4.184 Joules. It means that water has great ability to absorb and releasing heat with minimum change in its own temperature. Most of the heat energy absorbed by water is used to break hydrogen bonds between its molecules. Due to this breakage of hydrogen bonds, individual water molecules start moving more freely and temperature of water rises.

Due to high specific heat capacity, water heats up more slowly. Similarly, when it is given a cooler environment, it holds its temperature longer. Water thus works as temperature stabilizer not only for organisms' internal environment but also for their external environment.

Heat of Vaporization

Evaporation of 2ml of water out of 1 litre lowers the temperature of the remaining 998 ml water by 1 °C.

It is the amount of heat required to change a liquid to gas. Water has high heat of vaporization. So, it absorbs much heat while changing from liquid state to gas. Its heat of vaporization is 574 Kcal/kg which means a considerable amount of heat energy (574 Kcal) is required to change 1kg of liquid water into vapours.

Due to this property, Earth's temperature is kept moderate. It also provides cooling effects to plants and animals when they transpire and perspire (sweat). Every gram of water that evaporates from plant or animals' body surface removes 574 calories of heat from the body.

Cohesion

Figure 4.10: A water strider walking on the surface of water

Hydrogen bonds among water molecules enable them to "stick together". This type of attraction between same type of molecules is called cohesion. Inside water, molecules have high cohesion. The cohesion of water is important for living world. Plants depend on cohesion among water molecules for the transport of water and nutrients from roots to leaves. The evaporation of water from a leaf exerts a pulling force on water within xylem vessels of the leaf. Because of this cohesion, the force is relayed through xylem vessels all the way down to roots. As a result, water rises against the force of gravity.

Hydrogen bonds also give water high surface tension. Water behaves as if it were coated with some invisible film. You can see in Figure 4.10, the insect water-strider walks on water without breaking surface.

Ionization of Water

When the covalent bonds among the atoms of water molecule break, water is ionized to form hydrogen ions (H+) and hydroxyl ions (OH-). At normal conditions, this reaction is reversible and equilibrium is maintained. At room temperature (25 °C), in a litre of water one molecule out of each 550 million is ionized and thus the concentration of each of H^+ and OH^- in pure water remains at 10^{-7} moles/litre.

Acids combine with OH^- ions, leaving H^+ ions in medium and make medium acidic. Similarly bases combine with H^+ ions, leaving OH^- ions in medium, and make medium basic.

H+ and OH- ions take part in many chemical reactions in the cells e.g., hydrolysis of macromolecules. Relative concentrations of H+ and OH- ions determine the acidity and alkalinity of medium i.e., pH of medium. The pH affects the biochemical reactions. Enzymes work best at specific pH.

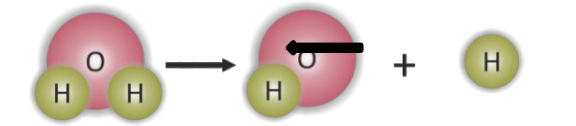


Figure 4.11 : Ionization of water

Maximum Density at 4°C

Water exhibits its maximum density at 4°C. Its density decreases when the temperature lowers. It is because of the hydrogen bonds which keep water molecules relatively far apart. When temperature falls to 0°C, water freezes but the resulting ice is less dense than liquid water, because at this temperature, hydrogen bonding keeps water molecules further apart than in liquid water.

In rivers, streams or lakes, ice is formed on the surface water due to falling of temperature. As ice is less dense than water, it floats on surface. It acts as an insulator and does not allow heat to escape from the water beneath it. In this way aquatic organisms are protected.

Table 4.2: Properties of water and benefits to life

Properties	Bonding	Benefits to life
Best solvent	Polarity	Provides medium for chemical reactions
Maximum heat capacity	Hydrogen bonding	Keeps temperature constant internally and externally for organism

Maximum density at 4 °C	Change in hydrogen bonding	Ice floats on water
High heat of vaporization	Hydrogen bonding	Moderates Earth's temperature
Ionization	Covalent bond breaks	Determine the acidity and alkalinity of medium
Cohesion	Polarity, Hydrogen bonding	Water and nutrients are transported from roots to leaves

4.5- CARBOHYDRATES

Carbohydrate are naturally occurring organic compounds. The word "carbohydrate" literally means "hydrated carbon". Carbohydrates are synthesized as the primary products of photosynthesis. During photosynthesis, when reduction of CO_2 occurs, the resulting carbohydrate molecule contains carbon, hydrogen and oxygen in the molar ratio of 1:2:1. Their empirical formula is **$C(H_2O)n$** where 'n' is the number of carbon atoms.

Classification of Carbohydrates

Carbohydrates are also known as "Saccharides" (Latin: "Saccharum" meaning sugar) and are classified into three groups after this name: 1. Monosaccharides 2. Disaccharides, and 3. Polysaccharides.

1- Monosaccharides

Monosaccharides (simple sugars) are made of single sugar molecule. They are easily soluble in water. They may have 3 – 7 carbon atoms. They are further classified into subgroups on the basis of number of carbon atoms. Pentoses and hexoses are most common and found in all living organisms. Hexoses play central role in energy storage. The primary energy-storage molecule is **glucose** with seven energy-storing CH bonds. Its empirical formula is **$C_6H_{12}O_6$ or $(CH_2O)_6$**

Table 4.3: Classification of monosaccharides

Monosaccharides	Carbon atoms	Formula	Examples
Trioses	3	$C_3H_6O_3$	Glyceraldehyde, Dihydroxyacetone
Tetroses	4	$C_4H_8O_4$	Erythrose, Erythrulose (intermediate in photosynthesis in bacteria)
Pentoses	5	$C_5H_{10}O_5$	Ribose, Deoxyribose ($C_5H_{10}O_4$), Ribulose
Hexoses	6	$C_6H_{12}O_6$	Glucose, Fructose, Galactose
Heptoses	7	$C_7H_{14}O_7$	Rare in nature (intermediate in photosynthesis)

Isomers of monosaccharides

The molecules which have the same number of atoms (same molecular formula) but differ in how the atoms are arranged (different structural formula) are called isomers of each other. For example, glucose is not the only monosaccharide with the formula $C_6H_{12}O_6$. **Fructose** and **galactose** also have the same molecular formula but their structural formulas are different. The structural and orientation differences have important consequences in the making of polymers.

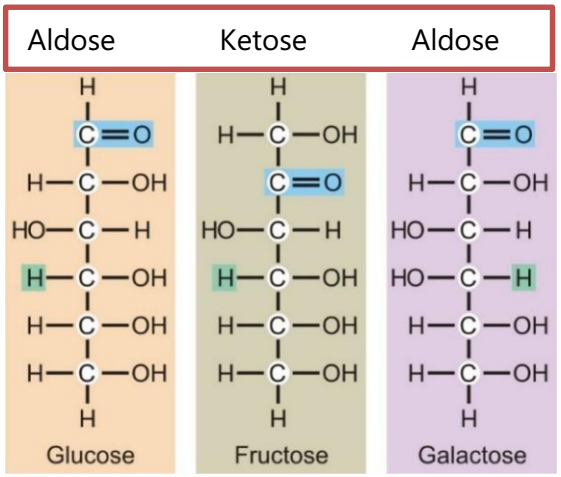


Figure 4.12: Structural and stereoisomers of glucose

In fructose, the double-bonded oxygen is attached to an internal carbon (no. 2) rather than to a terminal one. In other words, glucose and fructose are **structural isomers** Glucose and galactose have a difference in the orientation of one hydroxyl (OH) group at carbon no. 4 (Figure 4.12). It means that glucose and galactose are **stereoisomers**

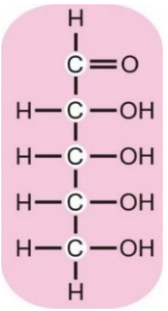
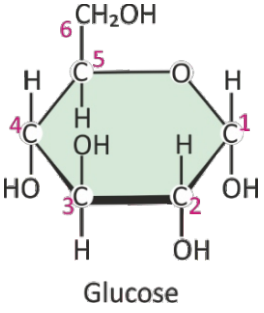


Figure 4.13: Structure of Ribose

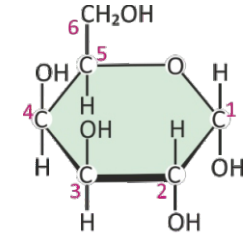
Common five-carbon or pentose sugars include ribose and deoxyribose (found in nucleic acids and ATP) and ribulose (which occurs as a precursor in photosynthesis).

Ring Structures of Monosaccharides

When in solution, most of the monosaccharides form ring structures. Ring formation occurs when an oxygen-bridge develops between two carbon atoms of the same sugar molecule (Figure 4.14).

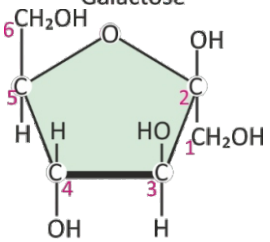


In case of glucose, oxygen-bridge develops between carbon number 1 and 5. So, a six cornered ring (Pyran) is formed.



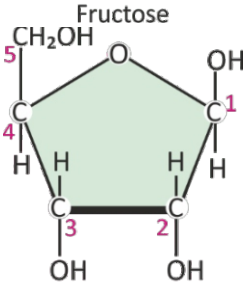
Galactose

In galactose too, oxygen-bridge is formed between carbon number 1 and 5. It again gives a six-cornered (Pyran) ring.



Fructose

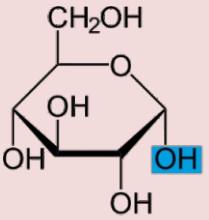
In fructose, oxygen-bridge is formed between carbon number 2 and 5. So, a five cornered ring (Furan) is formed.



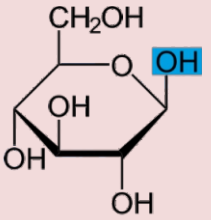
Ribose

When ribose goes in solution, oxygen-bridge develops between carbon number 1 and 4. So, a five cornered ring (Furan) is formed.

There are two forms of D-glucose i.e., alpha-D-glucose and beta-D-glucose. They differ only in the direction of OH groups on carbon 1. The α-D-glucose has OH group on the lower side while the β-D-glucose has OH- on above side. When many alpha-D-glucose molecules join together, they form a polymer called starch. When many beta-D-glucose molecules join together, they form a polymer called cellulose.



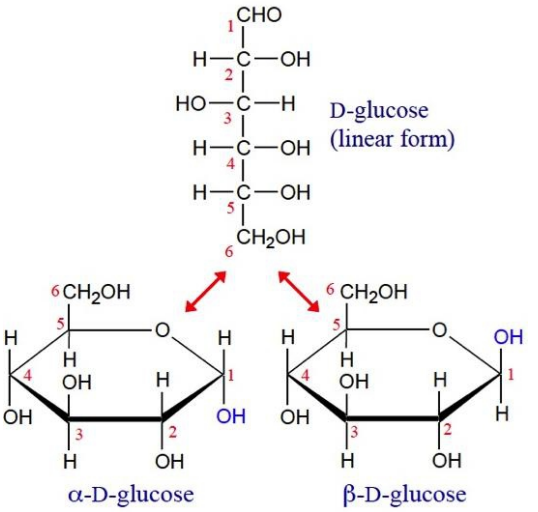
α-D-glucose



β-D-glucose

Figure 4.14: Ring structures of glucose, galactose, fructose, and ribose

Fischer and Haworth projections are two ways to represent the structure of sugar molecules. The Fischer projection was devised by German chemist Emil Fischer in 1891, In a Fischer projection the carbohydrate is shown in its open chain form, rather than a cyclical one. The Haworth projection is named after British chemist Sir Norman Haworth. It shows sugars in their cyclic forms.



2. Disaccharides

They are made from two monosaccharides by the process of dehydration synthesis. The covalent bond between two monosaccharides is called **glycosidic bond** On hydrolysis, they yield monosaccharide monomers, of which they are made. As compared to monosaccharides, they are less soluble in water. Physiologically important disaccharides are:

Maltose (Malt Sugar)

It is made up of two glucose monomers. The glucose molecules are attached by 1,4-glycosidic bond between carbon 1 of one and carbon 4 of the other glucose. It is found in many cereals (wheat, corn etc.) and is also formed (as an intermediate product) during the digestion of starch (Figure 4.15).

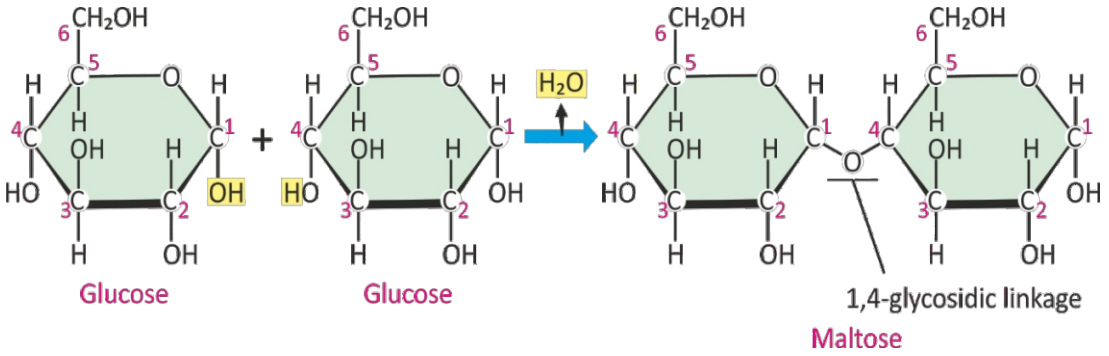


Figure 4.15: Dehydration synthesis of one maltose by the condensation of two glucose

Lactose (Milk Sugar)

It is made up of one glucose and one galactose subunit i.e., it is galactose 1-4 glucose. It is found only in mammalian milk, and is the main source of energy for infant mammals.

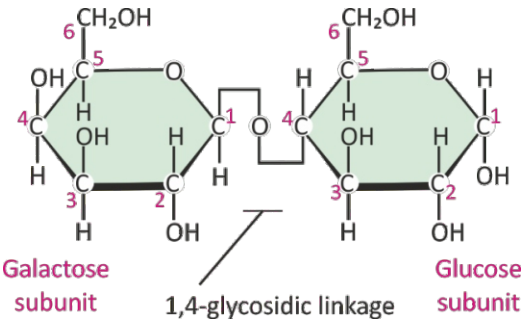


Figure 4.16: Structure of lactose

Sucrose (Cane Sugar)

It is made up of one glucose and one fructose subunits i.e., it is glucose 1-2 fructose. It is the most familiar disaccharide and is also known as table sugar. It acts as a sweetener in our food. Its molecular formula is ($C_{11}H_{22}O_{11}$). It is also found in phloem vessels of higher plants where it acts as a transport product for the conduction of glucose to and from different parts of plant. That is why it is also known as transport disaccharide.

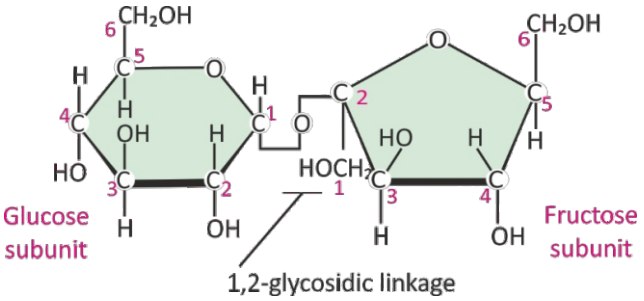


Figure 4.17: Structure of sucrose

By 1950, food sweeteners were taken from sucrose extracted from sugarcane and beet. In a small part of market, sweeteners were obtained by breaking down the starch of corn into glucose monomers. Because glucose is only half as sweet as sucrose, this method was not a serious rival to cane and beet sugar. In 1980s, a method was developed to convert the glucose, obtained from corn starch, into its isomer i.e., fructose. Fructose is even sweeter than sucrose. The resulting high-fructose corn syrup is inexpensive and has replaced sucrose in many prepared foods. The manufacturers of soft drinks "Cola", were the largest commercial users of sucrose in the world. Now they have almost completely replaced sucrose with high-fructose corn syrup.

3. Polysaccharides

Polysaccharides are the most complex and most abundant carbohydrates found in nature. They are long chains of many monosaccharides joined together by glycosidic bonds. There are three important polysaccharides:

Starch

Starch is the plant storage polysaccharide. It is insoluble and forms starch granules inside many plant cells. Because it is insoluble, it does not change water

potential of plant cells. So, it does not cause the cells to take up water by osmosis. Starch is not a pure substance, but is a mixture of amylose and amylopectin (Figure 4.18).

Amylose is a chain made of glucose monomers (with 1,4-glycosidic linkages). It is straight and unbranched. However, it tends to coil up into a helix.

Amylopectin is also a chain of glucose monomers (with 1,4-glycosidic linkages). It also has branches (with 1,6-glycosidic linkages). In this way, it has more ends that can be broken more quickly by amylase enzymes. Both amylase and amylopectin are broken down by the enzyme amylase into maltose, though at different rates.

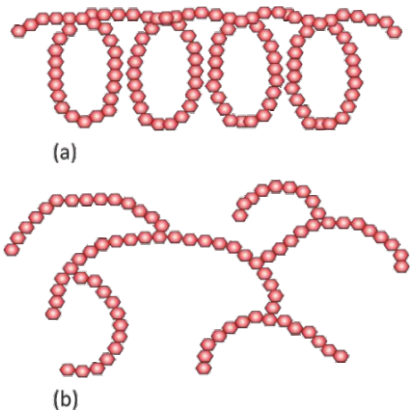


Figure 4.18: (a) amylose, (b) amylopectin

Glycogen

It is similar in structure to amylopectin. It is a chain of glucose monomers (with 1,4-glycosidic linkages) with branches (with 1,6-glycosidic linkages). It is made by animals as their storage polysaccharide, and is found mainly in muscles and liver. Because it is so highly branched, it can be broken down to glucose very quickly.

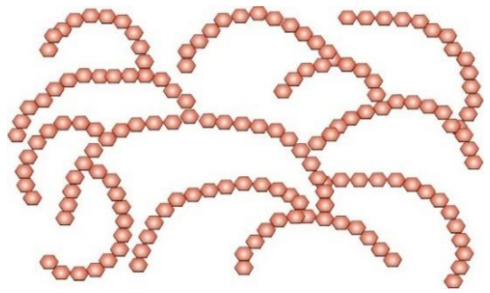


Figure 4.19: Glycogen

Cellulose

Cellulose is only found in plants, where it is the main component of cell walls It is a chain of glucose monomers (with 1,4-glycosidic linkages), but with a different isomer of glucose. Starch and glycogen contain alpha-glucose, in which OH group on carbon 1 sticks down from the ring, while cellulose contains beta-glucose, in which OH group on carbon 1 sticks up. This means that in cellulose, alternate glucose molecules are inverted (Figure 4.20).

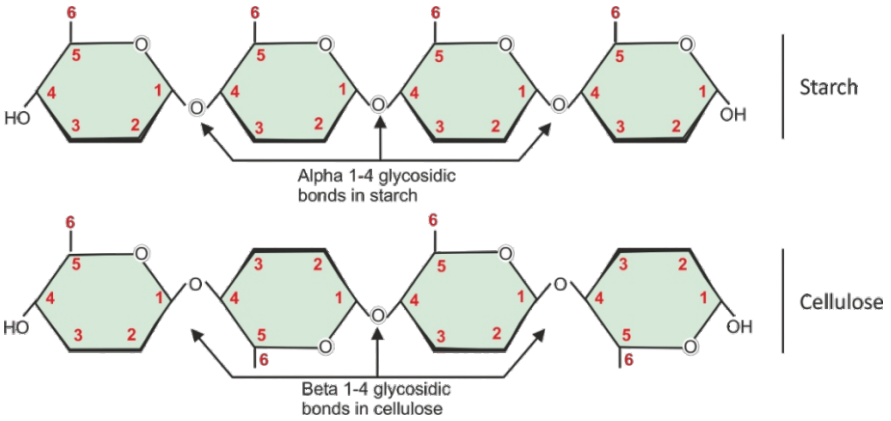


Figure 4.20: Difference between starch and cellulose

This apparently tiny difference makes a huge difference in structure and properties. The alpha 1-4 glucose polymer in starch coils up to form granules. On the other hand, the beta 1-4 glucose polymer in cellulose forms straight chains. Hundreds of these chains are linked together by hydrogen bonds to form cellulose microfibrils. These microfibrils make cellulose fibrils (Figure 4.21). They are very strong and rigid, and give strength to plant cells, and therefore to young plants and also to materials such as paper, cotton etc.

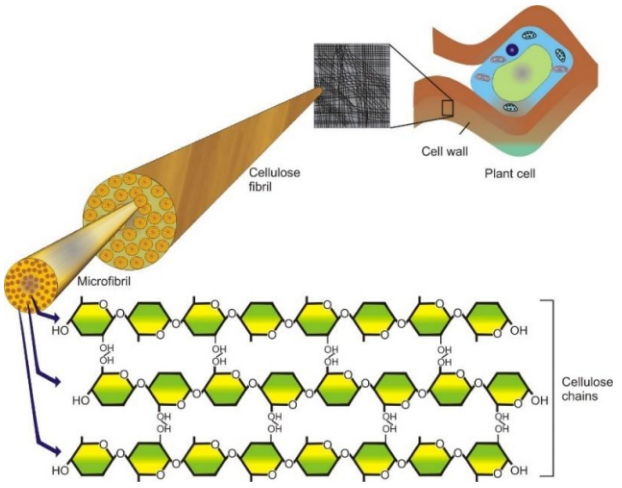


Figure 4.21: Cellulose fibrils in plant cell wall

The beta-glycosidic bond cannot be broken by amylase. It requires a specific **cellulase** enzyme. Some bacteria and some protozoans are only organisms that possess cellulase enzyme. Herbivore animals, like cows and termites whose diet is mainly cellulose, have mutualistic bacteria in their guts. These bacteria digest their cellulose. Humans cannot digest cellulose, and it is referred to as dietary fibre.

Chitin

It is a modified form of cellulose. It is found in the exoskeletons of crabs, lobsters and insects. It also makes the cell wall of fungi. Like cellulose, it is also a polymer of glucose. The linkage between glucose monomers is also like that found in cellulose. However, in chitin each glucose molecule has been modified by the

addition of a nitrogen-containing group (Figure 4.22). Only few organisms can digest it.

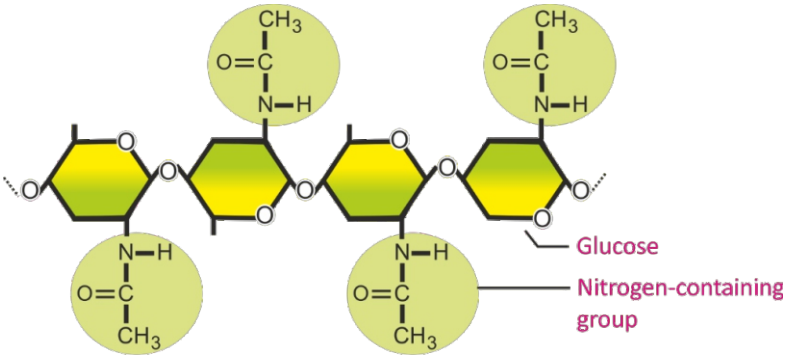


Figure 4.22: A part of the chitin molecule

Pectin and Lignin: They are also the polysaccharides used as building material. They are present in the cell walls of plant cells.

Agar: It is found in the cell walls of red algae. It is used as a thickener in foods. It is also used as a medium on which bacteria and fungi are grown in laboratories.

Murein: It is a sugar-peptide polymer and is found in the cell walls of prokaryotes.

4.6- PROTEINS

The most abundant organic compounds in cell are proteins. They may be defined as the polymers of **amino acids**. Proteins are regarded as the principal compounds of cells. J. J. Berzelius (in 1938) coined the term "protein" (Greek "Proteios"- molecules of the first rank) to emphasize the importance of this group of macromolecules. Proteins are important for the structures of cells and organisms and participate in everything they do. In this way, they act as the building blocks of life.

The diversity in biological world is the reflection of the diversity of structure and function that exists in proteins.

Structure of Proteins

Proteins are the polymers formed by the inter-linkage of monomers called amino acids. Different proteins may have a few to 3000 amino acids in their make-up (e.g., Insulin has 51 amino acids, Haemoglobin has 574 amino acids).

Amino acid

Amino acid is the basic structural unit of proteins. It is an organic molecule, in which four groups; an amino group (NH_2), a carboxyl group (COOH), a hydrogen group (H) and a side group (R); are attached to the same carbon atom (alpha carbon).

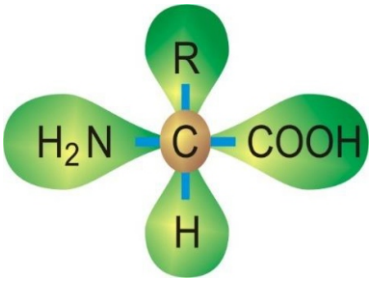


Figure 4.23: Structure of an amino acid

Although many different amino acids occur in nature, about 170 types of amino acids have been reported to occur in living organisms (in cells and tissues). Of these, about 25 types of amino acids may take part as building units of proteins. Most of the proteins are, however, made of 20 types of amino acids.

The identity and unique chemical properties of each amino acid are determined by the nature of its side group (R), covalently bonded to alpha carbon. For example, R may be a hydrogen atom as in glycine, or CH_3 as in alanine, or any other group. (Figure 4.24).

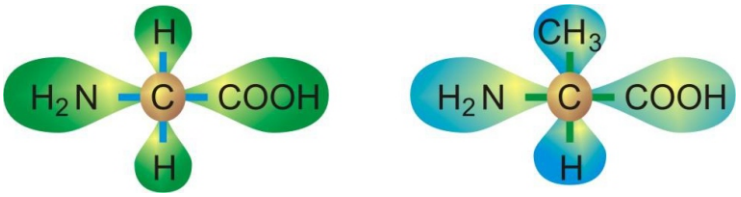


Figure 4.24: General structures of glycine and alanine

Essential and Non-essential Amino acids

Out of 20 amino acids, our bodies can make eleven amino acids. These are called **non-essential amino acids** and include alanine, arginine, asparagine, aspartic acid, cysteine, glutamic acid, glutamine, glycine, proline, serine, and tyrosine. The remaining nine amino acids cannot make our bodies on its own and must obtain these amino acids by eating various foods. These are called **essential amino acids** and include methionine, valine, tryptophan, isoleucine, leucine, lysine, threonine, phenylalanine and histidine (necessary only for babies).

A covalent bond that links two amino acids is known as a **peptide bond**. Note that each amino acid has an amino group at one end and a carboxyl group at the other end. When two amino acids are brought closer, dehydration synthesis occurs between the amino group of one and the carboxyl group of second amino acid. It results in the release of a molecule of water and formation of a peptide bond between "N" and "C" of adjacent amino acids.

Like disaccharide, the production of a dipeptide is dehydration synthesis.

The amino acids, which are linked by peptide bond, are called **peptides**. A dipeptide is formed by the linkage of two amino acids. For example, glycylalanine (a dipeptide) is formed by the linking of glycine and alanine (Figure 4.25).

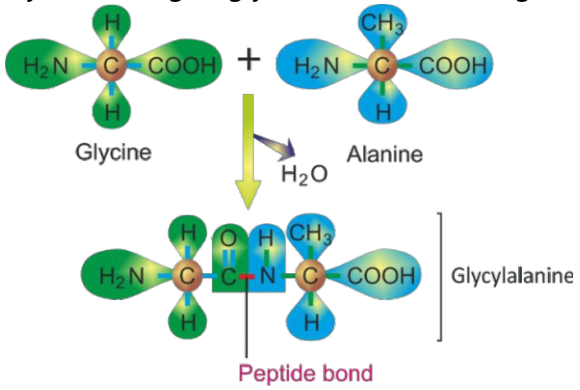


Figure 4.25: Formation of peptide bond between glycine and alanine

A dipeptide has an amino group at one end and a carboxyl group at the other end of molecule. So, both reactive parts are available for further peptide bonds. Addition of amino acids ultimately leads to **polypeptide** chains (Figure 4.26). A protein is composed of one or more polypeptide chains, e.g., insulin protein contains two polypeptide chains while haemoglobin protein has four polypeptide chains. Polypeptide chains assume different shapes on the basis of number, types and sequence of amino acids. It gives different levels of structure to proteins.

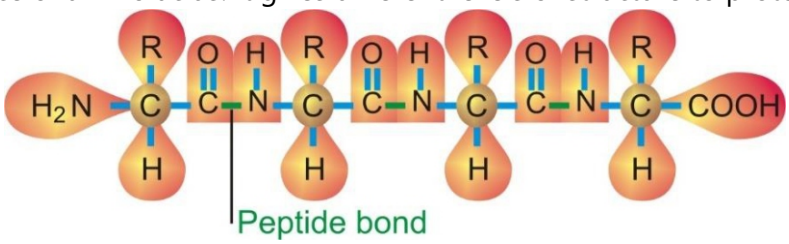


Figure 4.26: Section from a polypeptide chain

Structural Levels of Proteins

The diversity of proteins ranges from simpler (consisting of linear chains of amino acids) to complex proteins (structural modifications in linear chains). The following are different levels at which proteins are built (Figure 4.27).

Primary Structure

The primary structure of a protein molecule is formed by the **linear arrangement** of amino acids. It represents the number and sequence of amino acid molecules in a polypeptide chain. All protein molecules (whether simple or complex) have specific

These are over 10,000 proteins in human body and each of these has its specific primary structure, i.e., specific number, specific sequence and specific types of amino acids.

primary structures. The primary structure of insulin reveals that it is composed of two polypeptide chains. The smaller alpha chain has 21 amino acids while the longer beta chain is made of 30 amino acids (Figure 4.27).

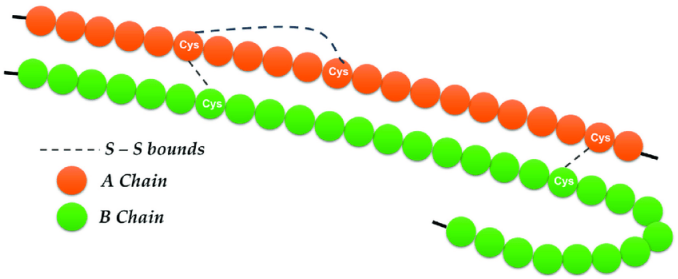


Figure 4.27: Chains of Insulin

Similarly, the primary structure of haemoglobin shows that it is made of four polypeptide chains i.e., two alpha (141 amino acids in each chain) and two beta chains (146 amino acids in each chain).

The number, sequence and types of amino acids is highly specific in the primary structure of a protein, for its proper functioning. This specificity in primary structure is determined by the order of nucleotides in DNA. Any change results in abnormal protein that fails to carry out its normal function. For example, **sickle cell haemoglobin** is formed by a mistake in the arrangement of only one amino acid in position six in each beta chain. In sickle cell haemoglobin, amino acid **valine** is present in the place of **glutamic acid**. Due to sickle cell haemoglobin, red blood cells get sickle shapes and abnormal haemoglobin cannot transport sufficient oxygen. This disease is known as **sickle cell anaemia**(Figure 4.28).

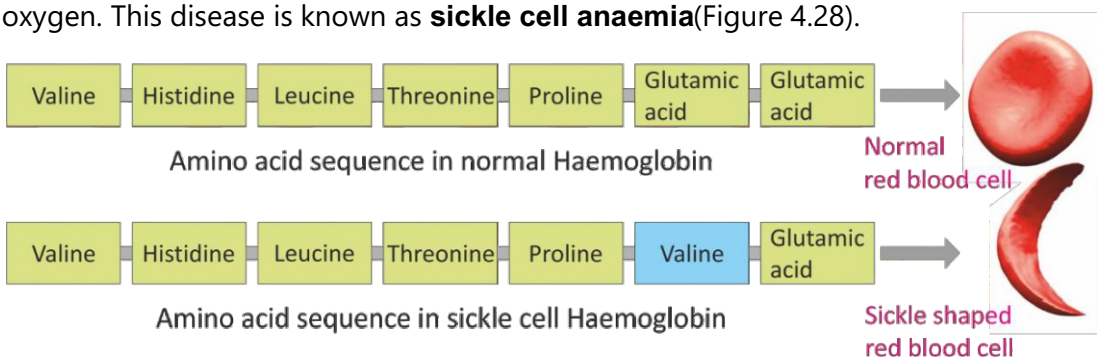


Figure 4.28: Difference in amino acid sequence in normal and sickle cell haemoglobin

Secondary Structure

In many proteins folding or coiling patterns occur within a polypeptide chain. This structure is called secondary structure. Coiling of a polypeptide chain results in **alpha helix** while folding makes a **pleated sheet**. Both these structures are

maintained by hydrogen bonds between amino and carboxyl groups of nearby amino acids in the chain.

Tertiary Structure

When the secondary structure further folds up and gets a complicated globular shape. It is called the tertiary structure of protein. These are more complex proteins. The globular shape is maintained by ionic, hydrogen and disulphide bonds. These bonds contribute to the overall stability and shape of the protein.

Amino acids in a polypeptide chain interact with water to give the most stable tertiary structure in the form of a globular shape. These are hydrophilic and hydrophobic interactions. The hydrophobic (non-polar) amino acids aggregate in such a way that they disrupt hydrogen bonding of water molecules and so are buried inside. At the same time the hydrophilic (polar) amino acids turn out, towards the surface of water.

Quaternary Structure

When two or more polypeptide chains with tertiary structures are held together by hydrophobic interactions, hydrogen bonds and ionic bonds, they form most complex proteins. This **aggregation of tertiary structures** makes the quaternary structure of protein.

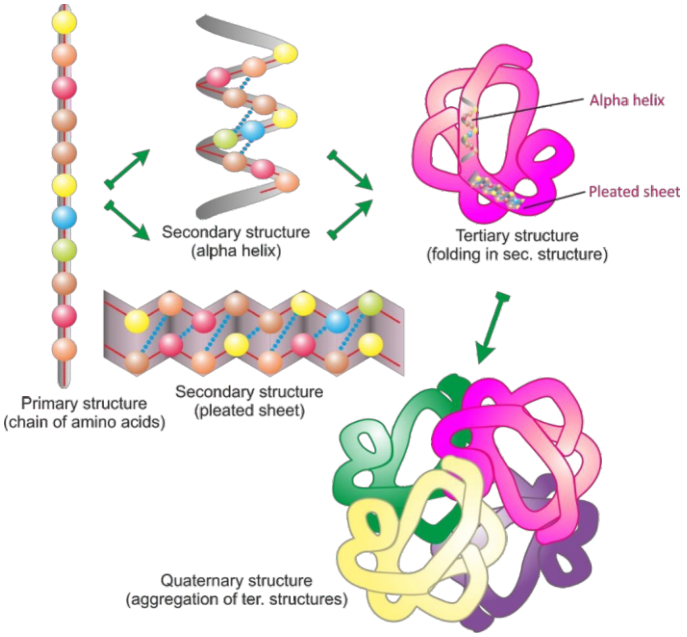


Figure 4.29: Levels of protein structure

Classification of Proteins

Proteins make a very diverse group of organic compounds in living organisms. They can be classified on different basis. For example, on the basis of their role in living organisms, these are "structural proteins" and "functional proteins". The recommended classification of proteins is based on their structure. In this classification proteins are classified as "fibrous proteins" and "globular proteins". We can describe the characteristics of both these classes by a comparison in table 4.4.

Table 4.4: Characteristics of Fibrous and Globular Proteins

Characteristics	Fibrous proteins	Globular proteins
Shape	In the form of fibrils	Spherical or ellipsoidal
Structure	Primary or secondary	Tertiary or quaternary
Role	Structural	Functional
Crystallization	Non crystalline and elastic	Can be crystallized
Solubility	Insoluble	Soluble in salt, acid or base solutions and in aqueous alcohol
Disorganization	Do not disorganize easily	Disorganized with changes in environment
Examples	Silk fibre-form the webs of silk worm and spider Actin in muscle cells Fibrin –in blood clots Keratin – in nails, hairs, beak, skin etc. Collagen – in matrix of connective tissues	Enzymes – biocatalyst Antibodies – active against invading antigens Some hormones – regulate body's activities Haemoglobin – oxygen carrying protein

Role of Proteins in life

Proteins carry out virtually all activities of living organisms. Some of their remarkable structural and functional roles are given below.

- Proteins are an important part of the composition of all plasma membranes.
- Channel proteins in the membranes of cells control the movement of materials in and out of cells. For example, proteins make **sodium–potassium pump** in the cell membrane of neurons. This pump controls the movement of Na^+ and K^+ ions in and out of nerve cell.

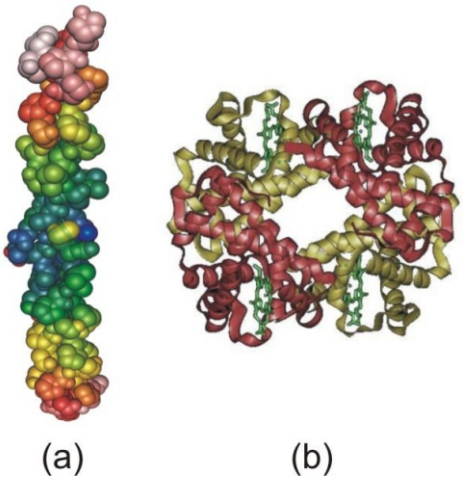


Figure 4.30: (a) Collagen – a fibrous protein, (b) haemoglobin – a globular protein

- Some fibrous proteins e.g., **collagen** and **keratin** make almost whole structures of cartilage and hair, nails respectively.
- **Enzymes** are a class of proteins that catalyse the metabolism of cells. They are a much diverse class of proteins. For example, proteases catalyse the breakdown of proteins, polymerases catalyse the synthesis of polymers.

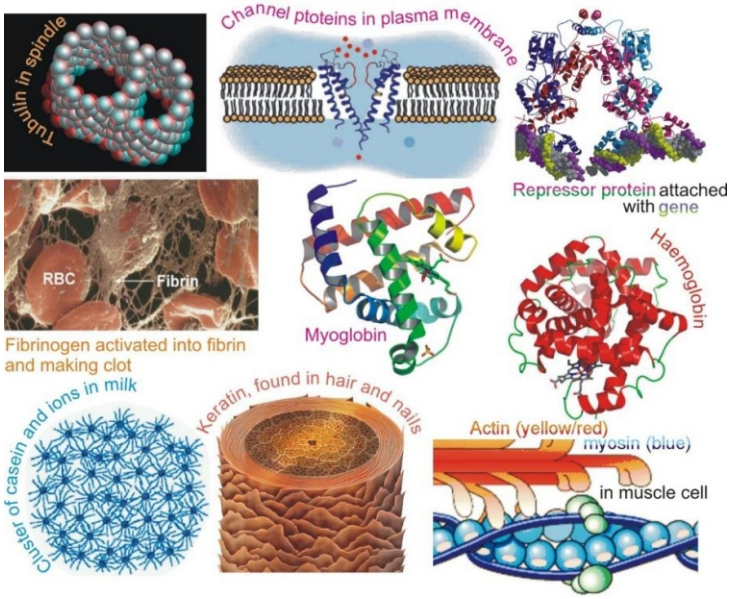


Figure 4.31: Different proteins of human body

- Some very important hormones of animals are proteins or peptides in nature. For example; **insulin** (controls blood glucose level), **antidiuretic hormone** (increases water retention by kidneys), **oxytocin** (regulates milk production).
- Some globular proteins work to transport different materials throughout the body. For example; **haemoglobin** and **myoglobin** transport O_2 and some CO_2, and **cytochromes** work in electron transport chain as electron carriers.
- **Albumin** is a blood protein that maintains osmotic concentration of blood and keeps its ability to flow.
- Blood clotting is important to prevent the loss of blood after an injury. **Fibrinogen** protein is present in blood. When an injury occurs, fibrinogen is activated into fibrin. The fibrin makes fibres and a clot is formed.
- All types of contractions in living matter are due to the actions of proteins. For example, **actin** and **myosin** are main proteins of muscles. They are responsible for muscular contractions. **Tubulin** protein makes spindle fibres.
- **Antibodies** are important proteins. They recognize and combine with foreign substances (antigens) and convert them into harmless products.
- Some ion-binding proteins store ions in different parts of body. For example, **ferritin** is the main intracellular iron storage protein. Similarly, casein is a milk protein that stores potassium and calcium ions.
- **Repressors** are the proteins that regulate gene action by preventing the synthesis of RNA. These proteins allow genes to work where and when required.

Blood ferritin levels are measured in patients as a diagnostic tool of anaemia. If ferritin is high there is iron in excess. If ferritin is low there is a risk for lack of iron which sooner or later could lead to anaemia.

4.7- LIPIDS

Lipids are a loosely defined group of non-polar molecules that are insoluble in water but soluble in organic solvents (e.g., ether, alcohol, etc.). They are a diverse group of molecules and are classified as acylglycerols, waxes, phospholipids, terpenes, steroids and prostaglandins.

Acylglycerols (Fats and Oils)

Acylglycerols are composed of two subunits; glycerol and fatty acid. The acylglycerols which are liquid at room temperature, are called **oils**. The acylglycerols which are solid at room temperature, are called **fats**. In animals, most acylglycerols are fats. In plants, most acylglycerols are oils; for example, peanut oil, corn oil, castor oil etc.

An ester is the compound produced as the result of a chemical reaction of an alcohol with an acid and a water molecule is released

Chemically, acylglycerols are the esters of fatty acids and alcohol. They are synthesized through dehydration synthesis (OH is released from alcohol and H from an acid) as shown below.

$$\underset{\text{alcohol}}{C_2H_5OH} + \underset{\text{acetic acid}}{HOOCCH_3} \longrightarrow \underset{\text{an ester}}{C_2H_5OCOCH_3} + H_20$$

The most widely found acylglycerols are **triacylglycerol** (triglycerides), also called neutral lipids. In triacylglycerols, three molecules of fatty acid (same or different) are joined to a single glycerol backbone.

Glycerol: It is a 3C alcohol and each of its carbon bears a hydroxyl group. The 3 carbons of glycerol form the backbone of acylglycerol molecule, to which three fatty acids are attached.

Fatty acids: These are responsible for all the characteristics of acylglycerols. Fatty acids are long hydrocarbon chains (with carbon in even number 4 – 30), ending in a carboxyl (-COOH) group. They vary in length and may be as straight chains (in animals) or branched or ringed (in plants). They are of two types:

If a fatty acid has one double bond it is called mono-unsaturated and if there are more than one double bond, it is called poly-unsaturated.

- **Saturated** fatty acids contain no double bond in their hydrocarbon chain. In saturated fatty acids, all internal carbon atoms possess hydrogen side-groups. These fatty acids make straight chains, and have a high melting point.
- **Unsaturated** fatty acids have double bonds (6 maximum) between one or more pairs of carbon atoms. The double bonds replace some of the hydrogen atoms. Therefore, unsaturated fatty acids contain fewer than the maximum number of hydrogen atoms. These fatty acids form bent chains, and have a low melting point.

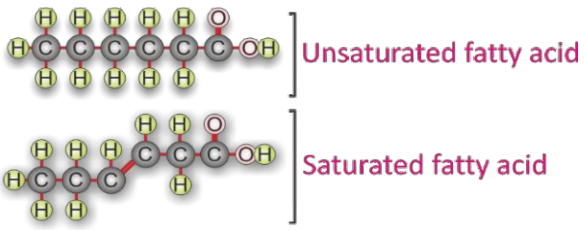


Figure 4.32 Fatty acids

Solubility of fatty acids (in organic solvents) and their melting points increase with increasing number of carbon atoms in their chains.

Acylglycerols are efficient energy-storage molecules. It is due to higher number of C-H bonds in them. They are insoluble, because of their non-polar structure. Therefore, they can be deposited at specific storage locations within organism. Animal fats contain more energy than do plant oils, because they contain

saturated fatty acids and so contain more C-H bonds. On the other hand, plant oils have unsaturated fatty acids and contain comparatively lesser number of C-H bonds. When organisms have to store glucose for long periods, they usually convert it into fats or oils.

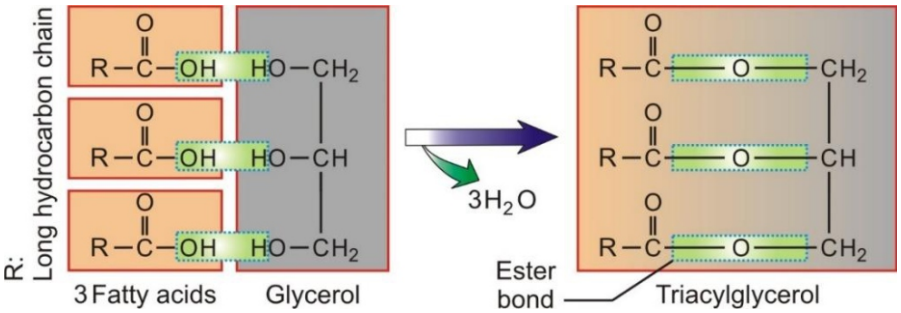


Figure 4.33: Dehydration synthesis of a triacylglycerol

Waxes

Honeybees produce waxes and use it to make six sided (hexagonal) chambers of their combs, where honey is stored. In humans, wax is secreted by glands of the outer ear canal.

Waxed are derived from acylglycerols. They have high melting points, because of large number of C atoms and so are solid at room temperature. Chemically, waxes do not have any well-defined structure and composition. They are mixtures of long chain alkanes (with carbon atoms in odd number; 25-35), alcohols (other than glycerol), ketones and long chain fatty acids.

Waxes are chemically inert. Like other lipids, waxes are strongly hydrophobic. So, they act as protective coverings and water barriers for living organisms. Waxes are widespread as protective coatings on fruits and leaves. Some animals like insects, birds, sheep etc. also secrete waxes over their skin.

Waxes are used to waterproof paper and cards. Waxes are also used in wax polishes for furniture, footwear and vehicles. Waxes are also used to make candles. Waxes with coloured pigments are used in making crayons and coloured pencils.

Figure 4.34: Some uses of waxes

Phospholipids

Phospholipids play important structural roles in making plasma membranes. Chemically they are the derivatives of **phosphatidic acid** Phosphatidic acid is composed of one glycerol, two fatty acids and one phosphoric acid (phosphate). Any nitrogenous base e.g., choline, ethanolamine or serine attaches with its phosphoric acid and makes phospholipid. Common examples are phosphatidyl choline (lecithin), phosphatidyl ethanolamine and phosphatidyl serine. Phosphatidyl choline (Figure 4.35) forms lipid bilayer in plasma membranes.

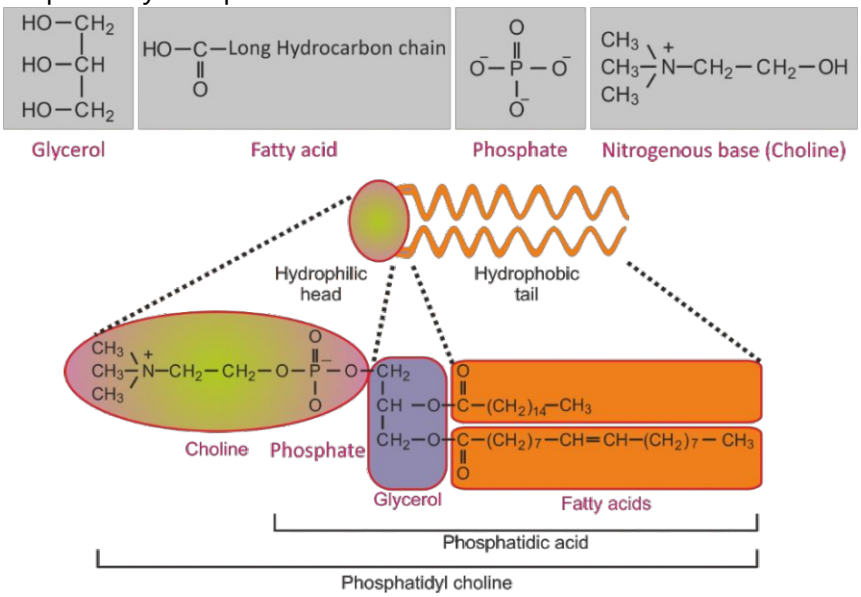


Figure 4.35: Phosphatidyl choline– a phospholipid

Phospholipids have two parts of their molecules i.e., head and tail. Head is polar and contains nitrogenous base and phosphate group while tail is non polar and contains the two fatty acids.

Terpenes

It is a very large and diverse group of lipids. All terpenes are made of isoprene units. An isoprene unit is a branched unsaturated hydrocarbon chain with the formula $CH_2=C(CH_3)-CH=CH_2$. Terpenes form many biologically important pigments, such as chlorophyll in plants and retinal pigments in eyes. Vitamin A and rubber are also terpenes.

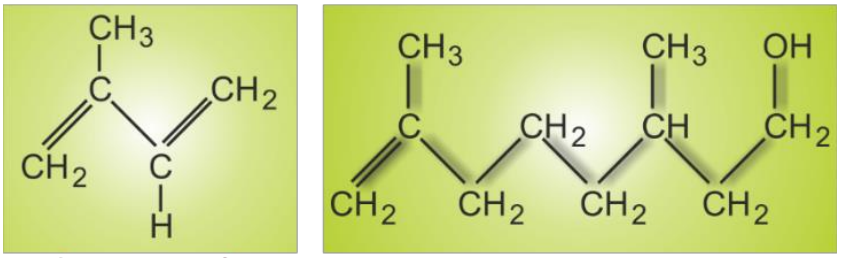


Figure 4.36: Structure of terpenes

Steroids

Steroids are lipids whose carbon skeleton is bent to form four fused rings. All steroids have the same ring pattern i.e., three 6-cornored rings and one 5-cornored ring. Cholesterol is a common steroid in animal cell membranes. Animal cells also use it for making other steroids e.g., male and female sex hormones.

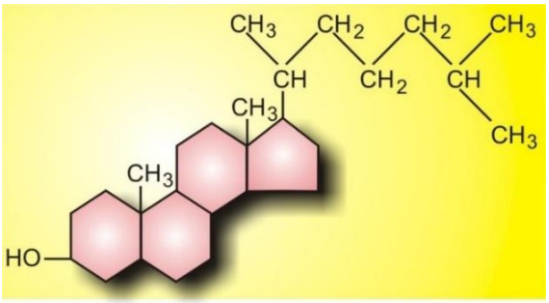


Figure 4.37: Chdesterol: a steroid

The synthesized anabolic steroids resemble male sex hormone (testosterone) and cause general build-up in muscles and bone mass during puberty in males. In 1950s some pharmaceutical companies produced anabolic steroids for the treatment of general anaemia. Some athletes began using anabolic steroids to build-up their muscles quickly and enhance their performance. Today, anabolic steroids are banned. Anabolic steroids can cause serious physical and mental problems e.g., deep depression, liver damage etc.

Prostaglandins

Prostaglandins are a group of lipids that are modified fatty acids, with non-polar tails attached to a five-carbon ring. They occur in many tissues of vertebrates, where they act as local chemical messengers. Some of them stimulate smooth muscles to contract and relax; others constrict or expand the diameter of blood vessels. They are also involved in inflammatory response to infection.

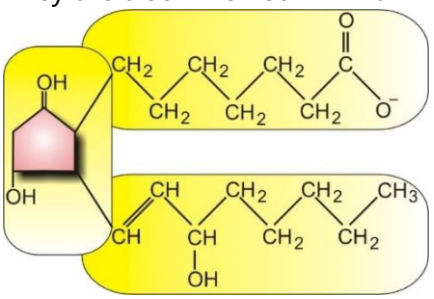


Figure 4.38: A prostaglandin

Aspirin is a prostaglandin inhibitor and that is why it reduces inflammation, pain, and fever.

Role of lipids in life

Lipids are important sources of energy (ATP). In fact, lipids are the most energy rich of all nutrients. One gram of lipids provides 9.5 kilocalories of energy. The same amount of protein provides 5.6 kilocalories while that of carbohydrate provides 4.1 kilocalories.

Lipids are essential components of all cellular and subcellular membranes.

They serve as biological carriers for the absorption of fat-soluble vitamins A, D, E and K.

Lipids are a source of fatty acids, which are essential for various metabolisms.

Lipids play a role as a mechanical cushion/support for vital body organs.

The lipids (fats) present beneath skin, insulate the body from extreme temperatures.

Steroids perform a wide range of important biological functions. For example, cholesterol is involved in the maintenance of membranes. It also helps in lipid transport. It as a precursor of vitamin D, bile acids, and steroid hormones (androgens, oestrogens), adrenal hormones and corticosteroids.

4.8- NUCLEIC ACIDS

Nucleic acids are the polymers of nucleotide units. There are two main types of nucleic acids i.e., deoxyribonucleic acid (DNA) and ribonucleic acid (RNA). DNA is found mainly in chromosomes, with small amounts in mitochondria and chloroplasts. RNA is found in nucleolus, ribosomes and cytosol. A nucleotide is made up of a nucleoside and phosphoric acid. A **nucleoside** is made of a nitrogen base and a pentose sugar (Figure 4.39).

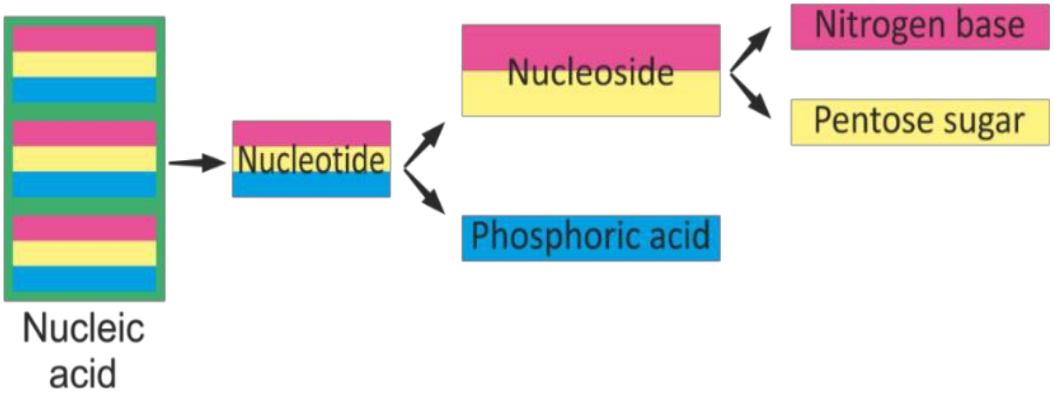


Figure 4.39: Components of nucleic acids

Pentose sugars: RNA contains ribose while DNA contains deoxyribose as their pentoses.

Nitrogenous bases: There are two types of nitrogenous bases in nucleic acids i.e., pyrimidine bases and purine bases. Pyrimidine is a single ringed nitrogenous base. There are three pyrimidine bases in nucleic acids. Cytosine (C) is present in both DNA and RNA, thymine (T) is present only in DNA, and uracil (U) is present only in RNA. Purine is a double ring nitrogenous base. Both DNA & RNA contain two purine bases i.e., adenine (A) and guanine (G). One nitrogenous base is attached with carbon 1 of pentose sugar and makes a nucleoside.

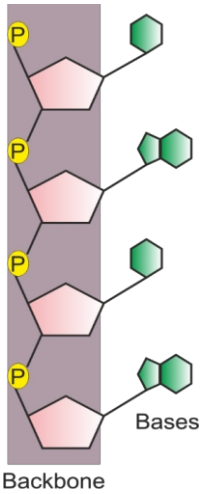


Figure 4.40: Sugar-phosphate backbone of nucleic acids

Phosphoric acid: A nucleoside develops ester linkage with a phosphoric acid and becomes nucleotide. In this ester linkage, phosphoric acid is linked with C-5 of pentose sugar. The backbone of the structure of nucleic acids is made of sugars and phosphates (Figure 4.40).

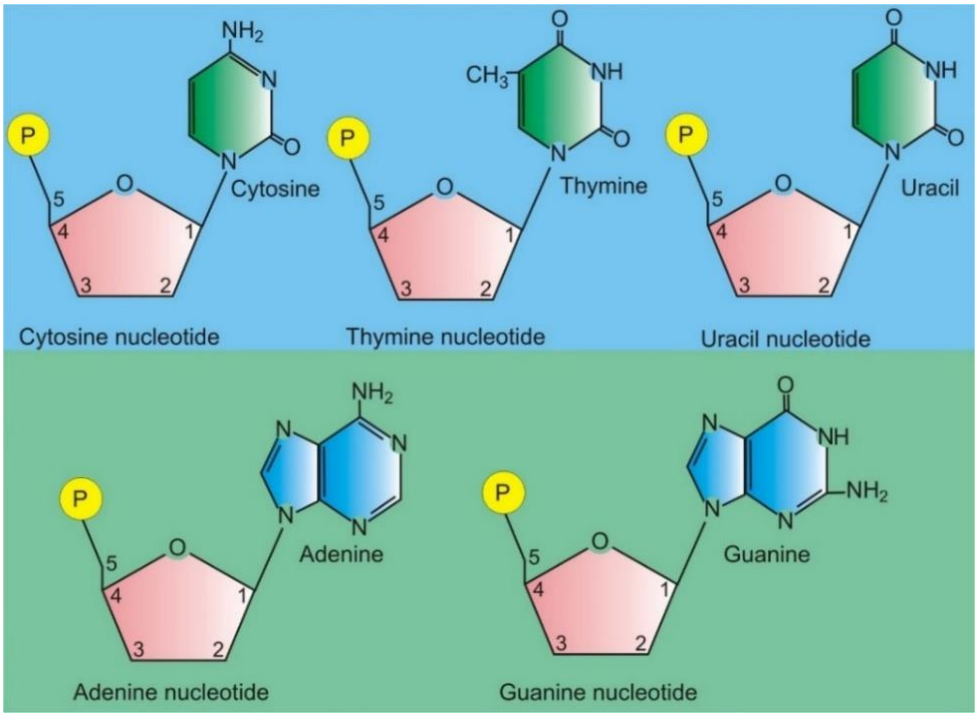


Figure 4.41: Nucleotides of RNA and DNA

Formation of Phosphodiester Bond

We know that in one nucleotide, phosphoric acid has an ester linkage at C-5 of pentose sugar. This phosphoric acid develops another ester linkage at C-3 of pentose sugar of another nucleotide. In this way, each phosphoric acid has two ester linkages with two pentose sugars (one at C-5 and other at C-3). The two ester linkages developed by phosphoric acid with two pentose sugars are known as **phosphodiester linkage** (Figure 4.42). This linkage joins two nucleotides.

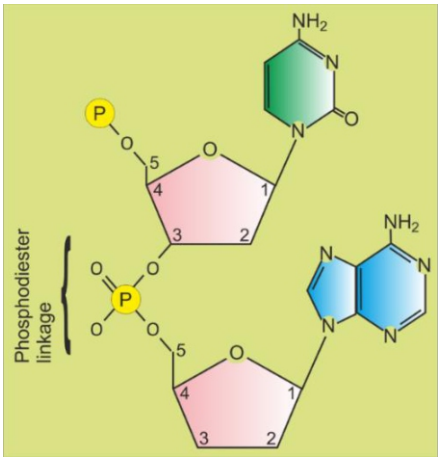


Figure 4.42: A dinucleotide

The nucleotides of RNA are known as ribonucleotides and those of DNA are known as deoxyribonucleotides. Nucleotides are named after the type of nitrogenous base. The ribonucleotides and deoxyribonucleotides are:

Nucleotides also play other critical roles in the life of cell. For example; **ATP** is a triphosphate nucleotide of adenine. In ATP, three phosphate groups are attached with one ribose sugar. You know that ATP is the "energy currency" of cell. It provides energy by successively detaching its two phosphate groups and changing to ADP and AMP. Similarly, Nicotinamide Adenine Dinucleotide (NAD) is a co-enzyme. It acts as a hydrogen acceptor in oxidation–reduction reactions in cell.

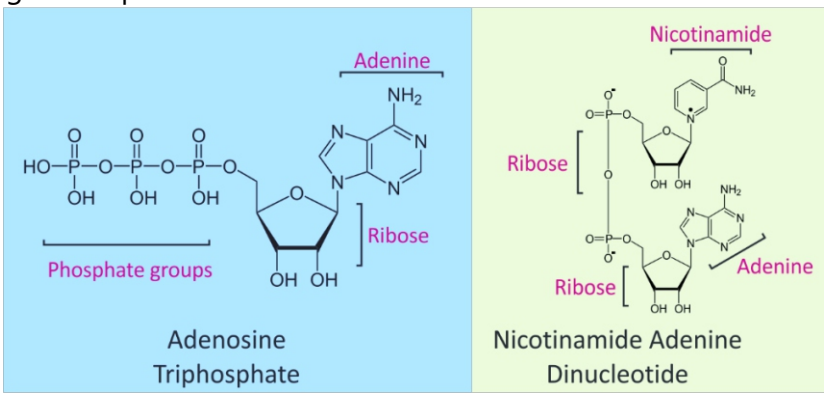


Figure 4.43: ATP and NAD

Nucleotides join together through phosphodiester linkages to form long polynucleotide chains. In a polynucleotide chain, phosphate group at 5′ end and OH group at 3′ are always free. RNA is made of a single polynucleotide chain. On the other hand, DNA is a **double helix** and is made of two polynucleotide chains.

Deoxyribonucleic Acid(DNA)

Rosalind Franklin (1953) and Maurice Wilkins (1967) studied the molecular architecture of DNA. James D. **Watson** and Francis **Crick**, in 1953 put forward the model of DNA. The observation by Chargaff was also of basic importance in working out the structure of DNA. Watson and Crick's Model of DNA suggests the following points:

In 1950, Linus Pauling concluded that DNA is a fibrous substance and the fibre is coiled into a helix. In 1951 Erwin Chargaff provided an informative data and it was found that adenine and thymine are equal in ratio in DNA and so are guanine and cytosine.

- DNA is made of two polynucleotide chains or strands.
- The two strands are coiled around each other and make a double helix.
- The double helix is like a ladder. Its poles are made of sugars and phosphate groups. Its rungs are made of nitrogenous base pairs.
- Each base pair (rung) is made of one purine (A or G) and one pyrimidine (C or T) base.
- Two strands are held together by weak hydrogen bonds between their bases.

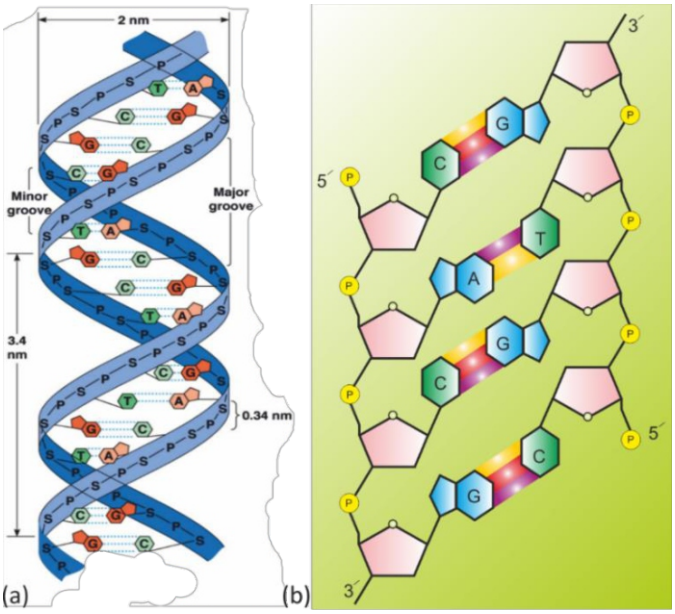


Figure 4.44: (a) Watson and Crick model of DNA, (b) The detailed structure of DNA

- Adenine in one chain makes hydrogen bonds with thymine in second chain, or vice versa. Guanine in one chain makes hydrogen bonds with cytosine in second chain, or vice versa.
- There are two hydrogen bonds between A and T pair and three hydrogen bonds between G and C pair.
- Two strands are not in the same direction with respect to their phosphodiester linkages, but are anti-parallel to each other.

DNA is the fundamental part of chromosomes and so is located inside nucleus in eukaryotes. As there is no distinct nucleus in prokaryotes, their DNA is present in cytoplasm. In viruses, DNA is located as a core molecule, covered by a protein coat.

Recalling:
In eukaryotes, small amount (about 2%) of DNA are also present in mitochondria and chloroplasts.

DNA is the hereditary material for all organisms (except some viruses). DNA contains the "program" that ultimately directs all cellular activities. The program in DNA is in the form of genes. A **gene** is a sequence of nucleotides of DNA, which codes for the formation of a polypeptide. When a gene is turned "ON", the sequence of DNA nucleotides is transcribed into RNA and then translated into specific proteins. In this way DNA controls the properties and activities of a cell.

In the chromosome of bacterium *E. coli*, each strand of DNA contains about 5 million bases arranged in a particular linear order. It has genes, each consisting of several hundred bases.

Ribonucleic Acid RNA

It is composed by ribonucleotides. RNA is synthesized by joining ribonucleotides in front of deoxyribonucleotides of DNA by transcription process. All living cells contain three types of RNA.

1. Messenger RNA (mRNA)

It consists of a single strand of ribonucleotides. Its sequence of nucleotides is complimentary to the sequence of nucleotides of one of the strands of DNA. mRNA is about 3-4% of the total amount of RNA in cell. It carries the genetic message of DNA to ribosomes to form particular protein.

2. Transfer RNA (tRNA)

It is comparatively small. It is a helical structure and its molecule resembles a clover leaf. It consists of 10-15% of the total amount of RNA in cell. tRNAs transport amino acids to ribosome and mRNA, in the process of protein synthesis.

3. Ribosomal RNA (rRNA)

It is synthesized by the DNA of nucleoli. After its synthesis, ribosomal RNA is joined with ribosomal protein and ribosomes are formed. It comprises about 80% of the total RNA in cell. rRNA acts as the machinery for synthesis of proteins in ribosomes.

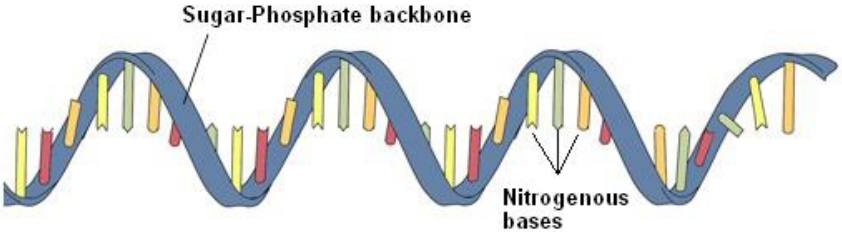


Figure 4 45: A model of RNA structure

Central Dogma

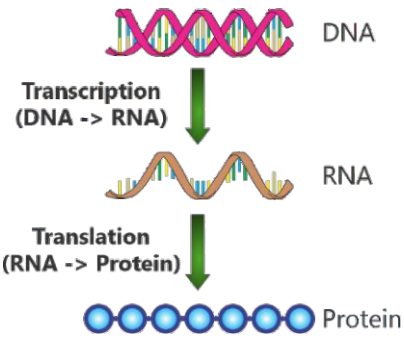


Figure 4.46: Flow sheet of Central dogma

All organisms use the same basic mechanism of reading and expressing genes, which is often referred to as central dogma. The first step of central dogma is the transfer of information from DNA to RNA, which occurs when an RNA copy of the gene is produced. The process is called **transcription**. The second step of the central dogma is the transfer of information from RNA to proteins, which occurs when the information contained in the RNA is used to direct the synthesis of proteins. This process is called **translation**. In this way DNA controls the properties and activities of a cell.

4.9- Conjugated Molecules

Conjugated molecules are formed by the combination of two or more molecules belonging to different categories. Some important conjugated molecules are as follows.

Glycoproteins

They are formed by covalent linkage between a protein and a carbohydrate polymer. They occur widely in nature as integral structural component of membranes; in blood serum; as cellular secretions; and in cartilage, eyes, skin etc.

Glycolipids

They are formed by a covalent linkage between a lipid and a carbohydrate. They are an integral structural component of membranes.

Lipoproteins

They are a class of biomolecules which are formed by hydrophobic interactions (not covalent or ionic bonds) between lipids and proteins. Lipoproteins are the basic structural framework of all types of plasma membranes. Lipids are transported in blood as very low-density lipoproteins.

Nucleoproteins

They are formed by ionic bonds between chromosomal DNA and proteins. For example, histone proteins are bound to DNA to form nucleosomes. They stabilize chromosomal structure in eukaryotes and also play an important role in the regulation of gene expression.

EXERCISE

SECTION 1: MULTIPLE CHOICE QUESTIONS

1. Which domain of life is characterized by organisms that often inhabit extreme environments and have cell membranes with ether-linked lipids?
   (a) Bacteria (b) Archaea (c) Eukarya (d) Protista
2. Which characteristic of water molecules is responsible for most of the unique properties of water?
   (a) Small in size (b) Held together by covalent bonds
   (c) Can easily separate from one another (d) Stick together
3. To which group of lipids, the human sex hormones belong?
   (a) Steroid (b) Waxes (c) Prostaglandins (d) Phospholipids
4. Which of the following is NOT a protein?
   (a) Haemoglobin (b) Cholesterol (c) Pepsin (d) Antibody
5. Which one is the largest carbohydrate?
   (a) Cellulose (b) Ribose (c) Glyceraldehyde (d) Glucose
6. What compound would be manufactured difficultly when soil has a shortage of phosphorous?
   (a) DNA (b) Fatty acids (c) Proteins (d) Cellulose
7. A compound whose chemical composition is most closely related to maltose is;
   (a) Starch (b) Protein (c) ATP (d) RNA
8. Which group is found in all fatty acids?
   (a) PO4 (b) SO_4 (c) C-N (d) COOH
9. Haemoglobin has:
   (a) Primary structure (b) Secondary structure
   (c) Tertiary stru cture (d) Quaternary structure
10. Which process produces peptide bonds?
    (a) Digestion (b) Dehydration synthesis
    (c) Hydrolysis (d) Enzyme deactivation

SECTION 2:SHORT QUESTIONS

1. Draw a sketch of hydrolysis reactions.
2. Draw the ring structure of glucose and fructose.

3. Define isomers and stereoisomers.
4. Draw the sketch of amino acid.
5. Outline the synthesis of peptide linkages.
6. Draw the sketch of acylglycerol, phospholipid and terpene.
7. Differentiate between nucleoside and nucleotide.
8. Illustrate the formation of phosphodiester bond.
9. State the central dogma of gene expression.

SECTION 3: LONG QUESTIONS

1. Distinguish carbohydrates, proteins, lipids and nucleic acids as the four fundamental biological molecules.
2. Describe and draw sketches of dehydration synthesis reactions.
3. Explain how the properties of water make it the medium of life.
4. Distinguish the properties and roles of monosaccharides and classify them.
5. Compare the structural isomers and stereoisomers of glucose.
6. Distinguish the properties and roles of disaccharides.
7. Define proteins and amino acids and outline the synthesis and breakage of peptide linkages.
8. Justify the significance of the sequence of amino acids through the example of sickle cell haemoglobin.
9. Describe the properties and roles of acylglycerols, phospholipids, terpenes and waxes.
10. Describe the molecular level structure of nucleotide.
11. Explain the double helical structure of DNA as proposed by Watson and Crick.
12. Explain the general structure of RNA and differentiate between the three types of RNA.
13. Define conjugated molecules and describe the roles of common conjugated molecules.

INQUISITIVE QUESTIONS

1. What happens if even one amino acid is substituted for another in a polypeptide chain? Provide a specific example.
2. How does the three-dimensional structure of a protein relate to its function?
3. How do nucleic acids encode genetic information, and how is this information translated into proteins?

Chapter 5

ENZYMES

STUDENTS'LEARNING OUTCOMES

After studying this chapter, the students will be able to:

- Identify the role and component parts of the active site of an enzyme.
- Differentiate among the three types of co-factors i.e., in organic ions, prosthetic group and co-enzymes, with examples.
- Explain the mechanism of enzyme action through the Induced Fit Model, including comparing it with Lock and Key Model.
- Explain enzyme catalysis with example of specific reactions.
- Define energy of activation and discuss through graph how an enzyme speeds up a reaction by lowering the energy of activation.
- Explain the effect of temperature on the rate of enzyme action with example of human and thermophilic bacteria
- Investigate the effect of pH on enzyme activity Compare the optimum pH of different enzymes like trypsin, pepsin, papain.
- Demonstrate that the concentration of enzyme affects the rate of enzyme action.
- Describe enzymatic inhibition, its types and its significance with examples.
- Name the molecules which act as inhibitors.
- Categorize inhibitors into competitive and non-competitive inhibitors.
- Explain feedback inhibition.
- Classify enzymes on the basis of the reactions catalyzed (oxidoreductases, transferases, hydrolases, isomerases, and ligases).
- Classify enzymes on the basis of the substrates they use (lipases, diastase, amylase, proteases etc.)

You know that the life of living organisms is a reflection of what is going on in their bodies. The sum of all chemical activities occurring in living organisms i.e., metabolism is regulated by enzymes.

5.1- ENZYMES

Enzymes may be defined as specific proteins that speed up specific chemical reactions by lowering the required activation energy, but are unaltered themselves in the process. Enzymes are also known as **biocatalysts** Rates of enzyme-catalysed reactions may be 10^3 to 10^8 times greater than the rates of corresponding uncatalyzed reactions.

All cells do not have the same set of enzymes. The chemical reactions going on in red blood cells are very different from those going on within a nerve cell because red blood cells and nerve cells contain different sets of enzymes.

All enzymes are synthesized inside cells by ribosomes. After their synthesis, either they stay and work inside cell or they are secreted out to work at other sites.

A reaction that is catalysed by an enzyme and is completed in 30 minutes, would take one year to get completed without being catalysed by enzyme. Thus, we can say that without enzymes there would have been no life at all.

Inside cell, many enzymes are dissolved in cytoplasm; for example, the enzymes of glycolysis. Many are tightly bound to membranes of certain organelles, for example, the enzyme of Calvin cycle and Krebs cycle. Some enzymes are integral part of ribosomes; for example, the enzymes of protein synthesis.

Active Site of Enzyme

Enzymes are three-dimensional globular proteins. They are made of polypeptide chains that are coiled upon themselves. There is a small cleft or depression on the surface of globular enzyme molecule. It consists of only a few amino acids. This site is known as **active site**. It is the location at which catalysis occurs.

Some enzymes may prove harmful, if become active at wrong place. For example; pepsin is a protein digesting enzyme. It can destroy protein-made structures present inside cells where it is synthesized. That is why it is produced in inactive form (pepsinogen) and is secreted out of cells. When it reaches its target site of action, it is activated (pepsin).

The shape of active site of each enzyme is very specific. So, only a certain substrate molecule can fit into it. It is three-dimensional and bears a specific charge. Active site has two distinct regions i.e., **binding site** and **catalytic site**. Substrate molecule fits into binding site by weak chemical forces, such as hydrogen bonds. Catalytic site catalyses the reaction and substrate is transformed into products.

5.2- Cofactors And Coenzymes

Many enzymes use additional chemical components to aid in catalysis. These additional non-protein components are called **cofactors**. There are three kinds of cofactor: metal ions, prosthetic groups, and coenzymes.

The protein part of enzyme is called **apoenzyme** and complete enzyme including co-factor is called **holoenzyme**.

Many enzymes use **metal ions**, such as Ca^{+2}, Mg^{+2}, Mn^{+2}, Cu^{+2}, and Zn^{+2} as their cofactors. These metal ions change the non-functional active sites of enzymes into functional sites. The attachment of a cofactor also changes the shape of enzyme and allows it to combine with substrate (Figure 5.1).

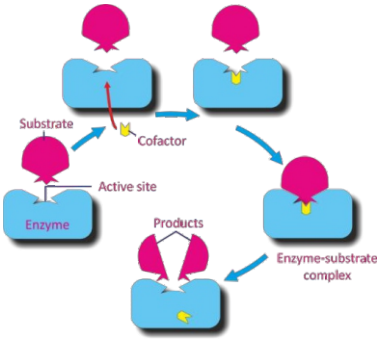


Figure 5.1: Cofactor, changing the shape of active site

Some cofactors form covalent bonds with enzyme and are known as **prosthetic groups**. Prosthetic group may be an organic compound e.g., hematin.

When the cofactor is a non-protein organic molecule and is loosely attached with enzyme, it is called a **coenzyme**. Coenzymes participate in enzyme-catalysed reactions, often by transporting electrons (hydrogen atoms), from one enzyme to another. Many vitamins (e.g., niacin and riboflavin) function as coenzymes. Some are part of coenzymes. The most important coenzyme in cell is the hydrogen acceptor nicotinamide adenine dinucleotide (NAD^+). When NAD^+ acquires a hydrogen atom from an enzyme, it reduces to NADH. The electron of hydrogen atom contains energy that NADH molecule carries. For example, when food is oxidized in cell, enzymes draw electrons from food molecules and transfer them to NAD^+, which reduces to NADH.

Many trace elements such as molybdenum and manganese, which are necessary for our health, are used by enzymes as cofactors.

5.3- Mechanism Of Enzyme Action

The speed of a chemical reaction depends on the amount of activation energy required to initiate it. **Activation energy** is the energy which works to destabilize existing chemical bonds. Enzymes bring reactants together in correct orientation or stress particular chemical bonds of reactants. Thus, they lower the activation energy required for new bonds to form and speed up the rate of reactions (Figure 5.2). Reactions proceed much faster than their normal speed.

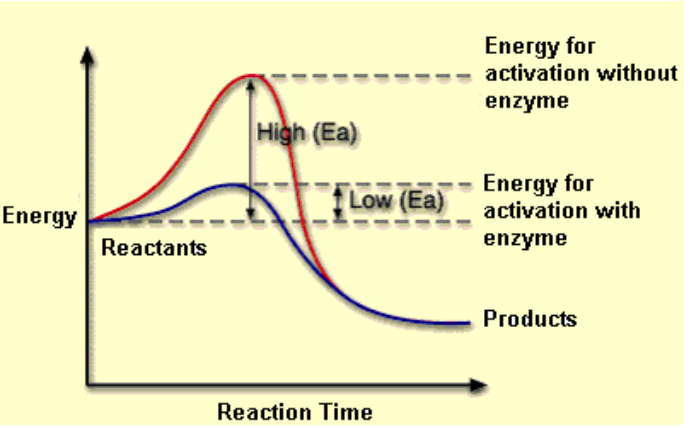


Figure 5.2: Enzymes lower theactivation energy

The presence of enzymes does not affect the nature or properties of end products. For example, sucrose (substrate) will always be hydrolysed into glucose and fructose (products) whether sucrase (enzyme) is present or not.

Due to its specificity, an enzyme recognizes a specific substrate. The substrate binds with the active site of enzyme. In this way, an enzyme-substrate complex (ES complex) is formed and catalytic site is activated. The atoms of catalytic site stress and

destabilize particular bonds of substrate. So, activation energy is lowered. This action initiates the reaction and substrate is transformed into products. After it, enzyme detaches itself from the products, in an unaltered state. The mechanism of enzyme action can be summarised as follows:

$$E + S \longrightarrow ES \longrightarrow E + P$$

Enzyme Substrate — Enzyme-substrate complex — Enzyme Product

In complex metabolic pathways e.g., respiration, photosynthesis, protein synthesis etc., many enzymes act in a sequence and regulate the steps of pathway. The successive enzymes controlling these steps are present together along with their cofactors. The products from one enzyme's catalysis serve as substrate for the enzyme of next step and are transformed into next products. The series goes on and finally end products are formed that inhibit (through feedback) the first enzyme.

Models for Mechanism of Action of Enzymes

Lock-and-Key Model

In 1894 a German chemist **Emil Fischer** proposed lock-and-key model. According to this model, "as a specific key can open only a specific lock, in the same manner a specific enzyme can transform only one specific substrate into products". This model postulates that active site is a rigid structure and there is no modification or flexibility in it before, during or after the enzyme action (Figure 5.3).

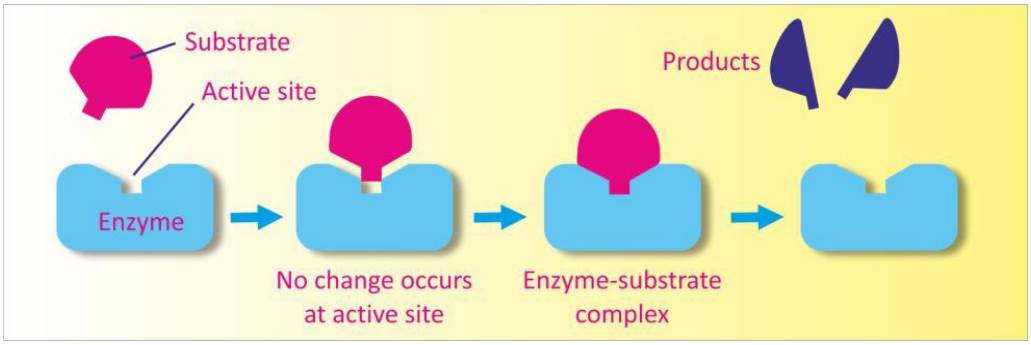


Figure 5.3: Lock-and-key model of enzyme action

Induced Fit Model

Later studies did not support lock-and-key model in all reactions. On the basis of new evidence, an American biochemist **Daniel Koshland**(1958) presented induced fit model. According to this model, "when a substrate combines with the binding site of an enzyme, it induces **changes** in enzyme structure. These changes enable the enzyme to perform its catalytic activity more effectively." This model postulates that active site is not a rigid structure and is capable of going under modification and flexibility, before the enzyme action (catalysis) starts (Figure 5.4).

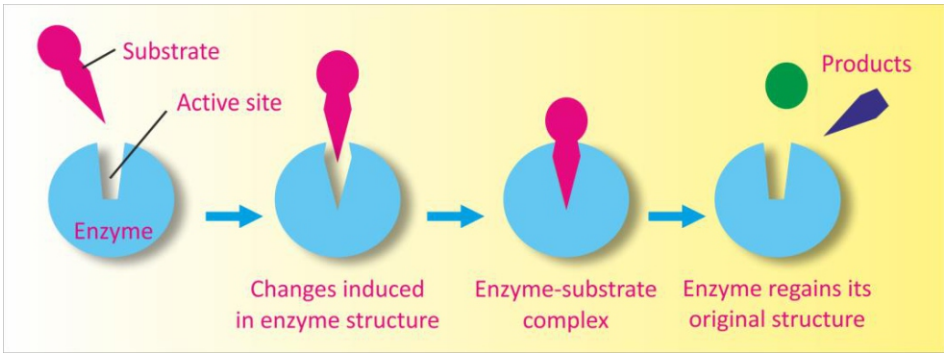


Figure 5.4: Induced-fit model of enzyme action

5.4- Factors Affecting The Rate Of Enzyme Action

Enzymes are very sensitive to the environment in which they work. The activity of an enzyme is affected by any change that alters its chemistry and its three-dimensional shape. Some of the factors that can affect the rate of enzyme action are being discussed next.

1. Temperature

The shape of a protein is determined by the hydrogen bonds and hydrophobic interactions that hold its polypeptide chains in particular position. Both the hydrogen bonds and hydrophobic interactions are easily disrupted by slight changes in temperature. Every enzyme works at its maximum rate at a specific temperature called its **optimum temperature**. The optimum temperature for human enzymes is 37 °C.

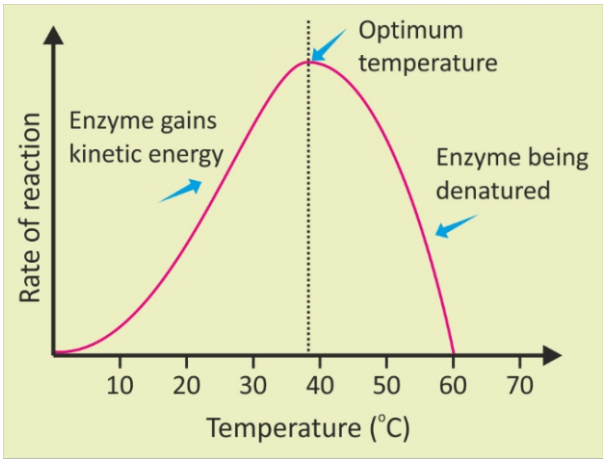


Figure 5.5: Effect of temperature on enzyme activity

When temperature fall below optimum temperature, the bonds that determine enzymes shape become less flexible. They do not permit the induced change in active sites that is necessary for enzyme action and so reaction rate is slow. When temperature is raised up to a certain limit, the heat adds in activation energy and so reactions are accelerated. Heat also provides kinetic energy to substrate and enzyme molecules. It causes them to move rapidly. Thus, they collide more frequently and reaction rate is increased. When temperature is raised well above

Thermophilic bacteria live in hot springs. They have proteins with stronger bonding between their polypeptide arms and can function at temperature of 70 °C or higher.

optimum temperature, the heat energy increases the vibrations of atoms of enzyme molecules. When vibrations become too violent, bonds cannot hold polypeptide chains in the proper position and globular structure of enzyme is lost. This phenomenon is known as **denaturation** of enzyme. It results in a rapid decrease in the rate of enzyme action and it may be blocked completely.

2. pH

All enzymes work at their maximum rate at a narrow range of pH. A slight change (increase or decrease) in this pH causes retardation in enzyme activity or blocks it completely. Every enzyme works its best at a specific pH, called its **optimum pH**. For example, **pepsin** is active in acidic medium (low pH) while **trypsin** shows its optimum activity in alkaline medium (high pH). Some enzymes like **papain** from green papaya work both in acidic and alkaline media.

In the globular structure of an enzyme, polypeptide chains are held by bonds between oppositely charged amino acids, such as glutamic acid (-) and lysine (+). These bonds are sensitive to hydrogen ion concentration. Any change in pH can change the ionization of amino acids at active site. Moreover, it may affect the ionization of substrate. Extreme change in pH can break the bonds in enzymes, resulting in enzyme denaturation.

Table: Optimum pH of important human enzymes

Enzyme	Optimum pH
Pepsin	1.5–1.6
Salivary amylase	4.6–5.2
Sucrase	6.2
Pancreatic amylase	6.7–7.0
Catalase	7.0
Urease	7.0
Trypsin	7.8–8.7
Pancreatic lipase	8.0
Arginase	10.0

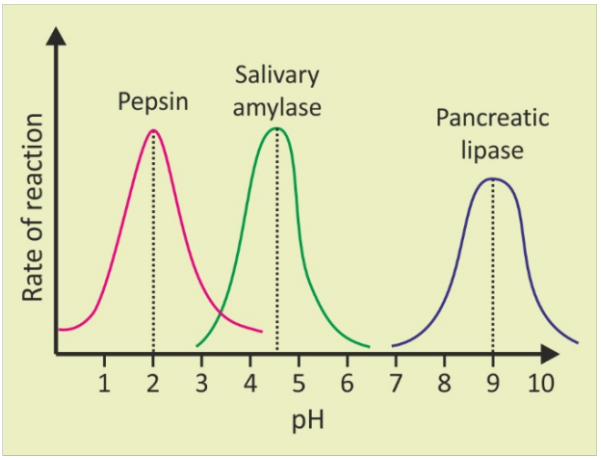


Figure 5.6: Optimum pH of some enzyme and effect of change of pH on enzyme activity

3. Enzyme Concentration

Enzymes are very efficient and a small number of enzyme molecules can catalyse reactions of large amount of substrate. The overall rate of enzyme-controlled reactions depends directly on the amount of enzyme present at a specific time (if substrate concentration is unlimited). When enzyme concentration increases, there are more enzyme molecules and more active sites. So, more substrate molecules bind with new active sites and are transformed into products. If enzyme concentration goes on

increasing but substrate concentration remains the same, no more substrate molecules will attach with enzymes. So, the rate of reaction stays constant and does not increase further (Fig.5.7).

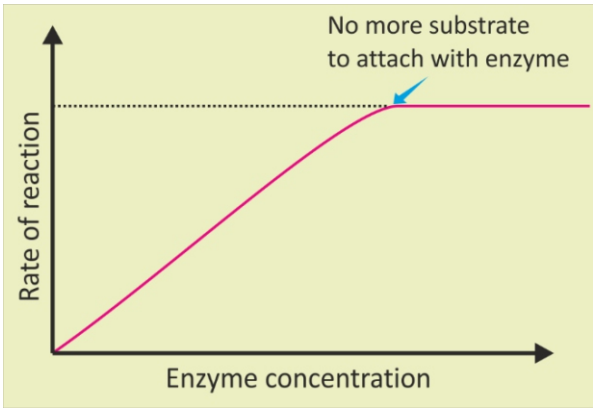


Figure 5.7: Effect of enzyme concentration on enzyme activity

4. Substrate Concentration

If there are enzyme molecules with vacant active sites, an increase in substrate concentration will increase the rate of reaction. If enzyme concentration is kept constant and the amount of substrate is increased, a point is reached where any further increase in substrate does not increase the rate of reaction any more.

When enzyme molecules are free (at low substrate concentration) new substrate molecules bind with the available active sites and so more products are formed in the given time i.e., rate of enzyme action is increased. But when all active sites of enzymes are occupied (at high substrate concentration), any more substrate molecules do not find free active sites and so reaction rate does not increase (Fig.5.8)

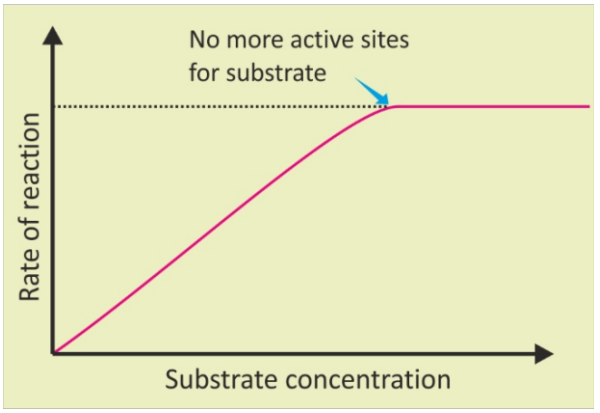


Figure 5.8: Effect of substrate concentration on enzyme activity

5.6-ENZYME INHIBITION

A chemical that interferes and blocks an enzyme's activity is called an **inhibitor**. Inhibitors attach with enzymes but are not transformed into products and thus block active sites temporarily or permanently. This phenomenon is known as enzyme **inhibition**. The final products of complex enzymatic reactions also act as the inhibitors of the enzyme of the first step.

Inhibitors are often used as drugs, but they can also act as poisons. An example of an enzyme inhibitor being used as a drug is aspirin. It inhibits the enzymes that produce prostaglandin (that causes inflammation). Thus, aspirin suppresses pain and inflammation. The poison cyanide is an irreversible enzyme inhibitor that combines with copper and iron in the active site of enzyme cytochrome oxidase and blocks cellular respiration.

Types of Inhibitors

Competitive and non-competitive inhibitors

Two general classes of inhibitors are recognized; competitive and non-competitive inhibitors. A **competitive inhibitor** resembles the enzyme's substrate. It competes with substrate for the same binding site on enzyme. When competitive inhibitor is selected by binding site, it blocks active site and does not permit substrate from attaching. Thus, it prevents enzyme from acting (Figure 5.9).

Competitive inhibitors are used as antibiotics to kill bacteria. These inhibitor molecules are similar in structure to bacterial enzymes which are necessary for their life. The inhibitors bind and inhibit the enzymes of bacteria.

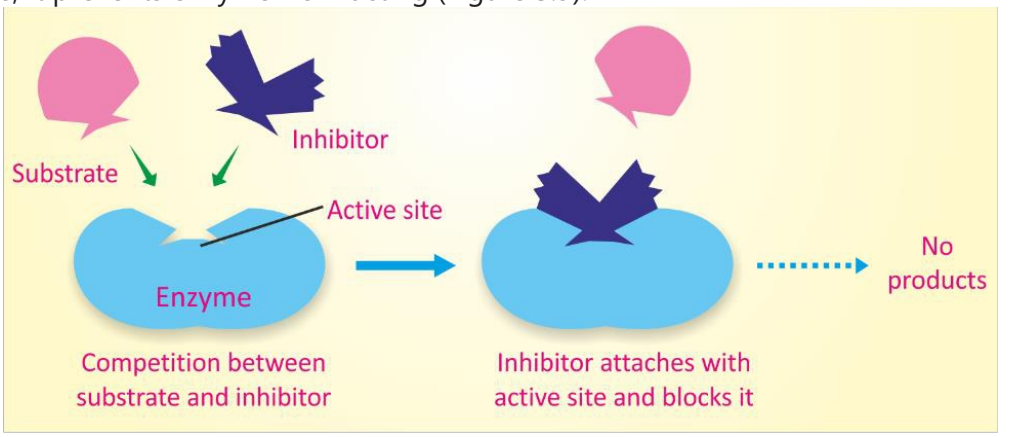


Figure 5.9: Competitive inhibition of an enzyme

The enzyme succinic dehydrogenase catalyses the oxidation of succinic acid to fumaric acid. Malonic acid has structural similarity with substrate (succinic acid). So, both of them compete for active site of enzyme. Malonic acid is selected by active site and thus blocks it.

A **non-competitive inhibitor** has no real structural similarity to substrate. So, it does not enter active site. Instead, it binds enzyme at other places. Its binding alters the shape of enzyme so that active site does not fit substrate and so enzyme is inhibited (Figure 5.10).

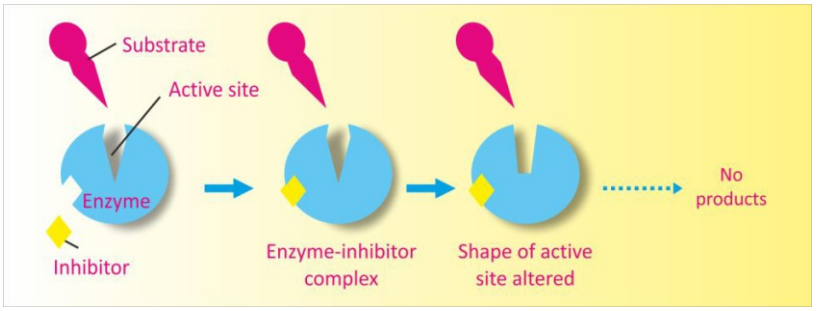


Figure 5.10: Non-competitive inhibition of an enzyme

For example; two substrates i.e., succinic acid and CoA react to form succinyl-CoA. This reaction is catalysed by enzyme succinyl-CoA synthetase. After its formation, the product i.e., succinyl CoA acts as a non-competitive inhibitor and binds with enzyme. Thus, enzyme is inhibited and no more succinyl-CoA is produced.

Reversible and Irreversible Inhibitors

The action of any inhibitor can be irreversible or reversible, depending upon the kind of bond formed between inhibitor and enzyme.

Irreversible inhibitors make covalent bonds with enzyme. Such inhibitors cannot be released by dilution or dialysis or by increasing the concentration of substrate. for example, penicillin permanently disables the enzyme responsible for building bacterial cell walls.

Reversible inhibitors make weak bonds (e.g., hydrogen bonds) with enzyme. Such inhibitors can be released and the inhibition caused by them can be neutralized by increasing the concentration of substrate. for example, malonate is a reversible inhibitor. It temporarily slows down the reaction by blocking the enzyme succinate dehydrogenase, which is involved in cellular respiration. This inhibition can be reversed when malonate is removed.

Significance of Enzyme inhibition

Enzyme inhibition is crucial in various biological processes.

1. Enzyme inhibition plays a vital role in regulating metabolic pathways. By inhibiting specific enzymes, the rate of a metabolic reaction can be controlled.
2. Many drugs work as inhibitors. For example, antibiotics inhibit the enzymes of bacteria, while cancer drugs may inhibit enzymes involved in cell division.
3. Enzyme inhibitors are used to manage various medical conditions. For example, some inhibitors of enzymes involved in blood clotting are used as anticoagulants.
4. Some toxins and poisons inhibit important enzymes in the body. Understanding how these inhibitors affect enzymes can be critical in treating cases of poisoning.
5. Enzyme inhibitors serve as valuable tools in pharmaceutical research. They are used to study the function of specific enzymes, and potential drugs.

Enzyme inhibition is an important part of studying enzyme kinetics. It helps to understand the factors that influence enzyme activity.

Feedback Inhibition of Enzymes

We know that in metabolic pathways, the product of one reaction becomes the substrate for next reaction. At the end of pathway, a desired product is synthesized. In order to regulate the concentration of that product, pathway needs to be shut down. This is done through feedback inhibition. The final product of pathway acts as inhibitor. It reacts with some initial enzyme and changes its conformation. That

enzyme can no longer bind to its substrate. So, pathway closes and no more product is prepared (Figure 5.11).

For example, when a cell has a greater number of ATP than its requirement, ATP itself acts as a non-competitive inhibitor and blocks the enzyme that catalyses ATP synthesis.

Feedback inhibition is the phenomenon where the product of a process controls the process itself, oftentimes limiting the production of more products.

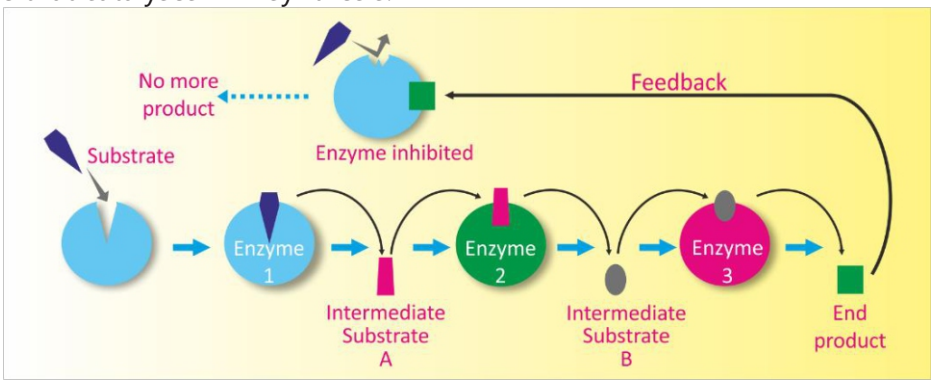


Figure 5.11: Feedback inhibition of enzyme action

5.7 - CLASSIFICATION OF ENZYMES

Enzymes are classified on the basis of reactions they catalyse and also on the basis of substrates they use.

Classification on the Basis of Reactions

According to the general type of reaction, enzymes are classified into six classes.

1- Oxidoreductases: These enzymes catalyse the oxidation / reduction of their substrates. They add or remove H^+ ions or electrons from substrates. For example, **cytochrome oxidase** catalyses the oxidation of cytochrome.

2- Transferases: The enzymes of this class catalyse the transfer of a specific functional group (e.g., methyl, acyl, amino, or phosphate) from one substrate to another. For example, **hexokinase transfers** phosphate group from ATP to glucose.

3- Hydrolases: These enzymes catalyse hydrolysis reactions. They break their substrates into monomers by adding water. For example; **lipase, amylase, peptidase,** and other digestive enzymes catalyse the hydrolysis of food molecules.

4- Lyases: These enzymes catalyse non-hydrolytic addition or removal of groups (e.g., CO_2, NH_2 etc.) from substrates. For example, **pyruvate decarboxylase** removes CO_2 from pyruvic acid.

5- Isomerases: These enzymes catalyse the intra-molecular rearrangement i.e., one isomer is converted into another. For example, **hexose isomerase** converts glucose to fructose.

6- Ligases: These enzymes catalyse the reactions in which two molecules join by forming new C-C, C-N, C-O, or C-S bonds, using energy from ATP. For example, **polymerase** enzymes join monomers by using ATP.

Classification on the Basis of Substrates

Enzymes are also classified into following groups on the basis of their substrates.

1- Proteases: This group included the enzymes which catalyse the breakdown of proteins. For example, **pepsin** and trypsin enzymes catalyse the breakdown of large polypeptides into smaller polypeptides. Similarly, **aminopeptidases** further breakdown small polypeptides into dipeptides and erypsin breaks dipeptides into amino acids.

2- Lipases: These enzymes act upon lipids and catalyse their breakdown. For example, pancreatic **lipase** hydrolyses lipids into fatty acids and glycerol.

3- Carbohydrases: These enzymes act upon bigger carbohydrates and break them into smaller units. For example, **amylase** acts upon starch or glycogen and breaks them into maltose. **Cellulase** breaks cellulose into cellobiose (a disaccharide) or glucose. Similarly, **maltase** breaks down maltose into glucose, **sucrase** breaks sucrose into glucose and fructose, and **lactase** breaks lactose into glucose and galactose.

4- Nucleases: These enzymes act upon nucleic acids and catalyse their breakdown. For example, **RNAase**, **DNAase**, **ATPase** are responsible for the breakdown of RNA, DNA and ATP respectively.

Class	Reaction type	Important subclasses
1- Oxidoreductases	A + B ⇌ A + B (red, ox, ox, red)	Dehydrogenases Oxidases Reductases
2- Transferases	AB + C ⇌ A + CB	Phospho-transferases Amino-transferases Acyl-transferases
3- Hydrases	AB + H_2O ⇌ C + D	Peptidases Lipases Glycodsidases
4- Lyases	A–B ⇌ C + B	Decarboxylases Aldolases Synthases
5- Isomerases	A ⇌ A	Epimerases Mutases *cis trans* isomerases
6- Ligases	A + B + ATP ⇌ AB + ADP	C-C ligases C-O ligases C-N ligases

Figure 5.12: Enzyme classification on the basis of reactions

SECTION 1: MULTIPLE CHOICE QUESTIONS

1. What roles does nicotinamide adenine dinucleotide play in oxidative pathways?
   (a) Enzyme (b) Coenzyme (c) Prosthetic group (d) Inhibitor
2. The enzymes that catalyse the reactions in which two molecules are joined together by synthesis of new bonds, using energy from ATP, are placed in group;
   (a) Hydrolase (b) Ligase (c) Lyase d) Transferase
3. Which of the following is an example of hydrolases?
   (a) Lipase (b) Glycogen phosphorylase
   (c) Pyruvate decarboxylase (d) Cytochrome oxidase
4. Which of the following statements about enzymes is correct?
   (a) They increase the activation energy of a reaction.
   (b) They are consumed during the reaction.
   (c) They are specific in terms of the reactions they catalyse.
   (d) They always work optimally at high temperatures.
5. Enzyme B requires Zn2+ to catalyse the conversion of substrate X. The zinc is best identified as a(n):
   (a) Coenzyme (b) Activator (c) Substrate (d) Product
6. If an enzyme solution is saturated with substrate, the most effective way to obtain an even faster yield of products would be
   (a) Add more of the enzymes (b) Add more substrate
   (c) Add an allosteric inhibitor (d) Add a non-competitive inhibitor
7. How does a non-competitive inhibitor decrease the rate of an enzyme-catalysed reaction?
   (a) By binding the active site of the enzyme
   (b) By changing the shape of the enzyme
   (c) By changing the free energy change of the reaction
   (d) By acting as a coenzyme for the reaction
8. Which enzyme class is responsible for catalysing the addition of water to a substrate molecule?
   (a) Ligase (b) Lyase (c) Hydrolase (d) Isomerase

SECTION 2: SHORT QUESTIONS

1. Define enzyme and co-factor.
2. Differentiate between co-enzyme and prosthetic group.
3. What do you mean by hydrolases? Give two examples.
4. What is meant by activation energy?
5. Define feedback inhibition.
6. Give examples of competitive and non-competitive inhibitors.

7. What is optimum pH? Give optimum pH of three human enzymes.

SECTION 3: LONG QUESTIONS

1. Describe the structure of enzyme, explaining the role and component parts of the active site of an enzyme.
2. Differentiate among the three types of co-factors, by giving examples.
3. Explain the mechanism of enzyme action through Induced Fit Model, comparing it with Lock and Key Model.
4. Define activation energy and explain through graph how an enzyme speeds up a reaction by lowering activation energy.
5. Describe the effect of temperature on the rate of enzyme action.
6. Compare the optimum temperatures of enzymes of human and thermophilic bacteria.
7. Describe how the concentration of enzyme affects the rate of enzyme action.
8. Explain the effect of substrate concentration on the rate of enzyme action.
9. Describe enzymatic inhibition, its types and its significance.
10. Categorize inhibitors into competitive and non-competitive inhibitors.
11. Explain feedback inhibition.
12. Classify enzymes on the basis of the reactions catalysed.
13. Give examples of enzymes' naming according to substrates.

INQUISITIVE QUESTIONS

1. Does physical exercise involve anabolic processes, catabolic processes, or both? Give evidence for your answer.
2. If a chemical reaction could occur without an enzyme, why is it important to have one?
3. Construct and interpret graphs based on data about the effect of temperature, enzyme concentration and substrate concentration on the rate of enzyme action.
4. Identify the competitive and non-competitive inhibitors from a list of chemicals used in daily life.

Chapter 6

BIOENERGETICS

STUDENTS'LEARNING OUTCOMES

After studying this chapter, the students will be able to:

- Explain the role of light, carbon dioxide and water in photosynthesis.
- Identify the two general kinds of photosynthetic pigments (carotenoids and chlorophylls).
- Describe the roles of photosynthetic pigments in the absorption and conversion of light energy.
- Differentiate between the absorption spectra of chlorophyll 'a' and 'b'.
- Draw the molecular structure of chlorophyll.
- Describe the arrangements of photosynthetic pigments in the form of photosystem-I and II.
- Describe the events of non-cyclic photophosphorylation and outline the cyclic photophosphorylation.
- Draw the Z-scheme for explaining the events the light dependent reactions.
- Explain the Calvin cycle.
- Develop a flow chart for explaining the events of light reactions.
- Describe the features of ATP that make it suitable as the universal energy currency.
- Describe the synthesis and breakdown of ATP.
- Describe the four stages in aerobic respiration in eukaryotic cells:
- Explain the process of anaerobic respiration in terms of glycolysis and conversion of pyruvate into lactic acid or ethanol.
- Outline the events of glycolysis (naming the reactants and products of each step).
- Describe the link reaction, including the role of coenzyme A.
- Outline the Krebs cycle (naming the reactants and products of each step).
- Describe the role of NAD and FAD in cellular respiration.
- Explain that passage of electrons through electron transport chain highlighting the oxidation and reduction reactions (details of carriers are not required).
- Describe chemiosmosis and relate it to electron transport chain.
- Explain why the energy yield from respiration in aerobic conditions is much greater than the energy yield from respiration in anaerobic conditions.

Every living organism, from the smallest bacterium to the largest whale, is driven by energy. This energy fuels their growth, reproduction, and daily survival, making it a fundamental aspect of life. But where does this energy come from? How is it harnessed and utilized by cells to perform countless activities essential for life? The answer lies in the fascinating field of bioenergetics.

Bioenergetics is the study of how energy flows through living systems. It explores the processes through which cells store and expend energy. The processes of photosynthesis and

Nearly all the energy used by living organisms on Earth comes from photosynthesis. Plants, algae, and certain bacteria capture sunlight and convert it into chemical energy, forming the base of the food chain.

respiration help to understand some of the principles of bioenergetics. Photosynthesis acts as an energy–capturing while respiration as an energy-releasing process.

ATP: The Energy Currency of Cells

Cells use a special energy currency for their reactions. This currency is actually a **nucleotide** called **adenosine triphosphate (ATP)**. When cells store energy, they make ATP. When cells need energy, they break ATP. A molecule of ATP has three subunits i.e. **adenine**, (a nitrogen containing base); **ribose** (a five-carbon sugar) and three **phosphate** groups.

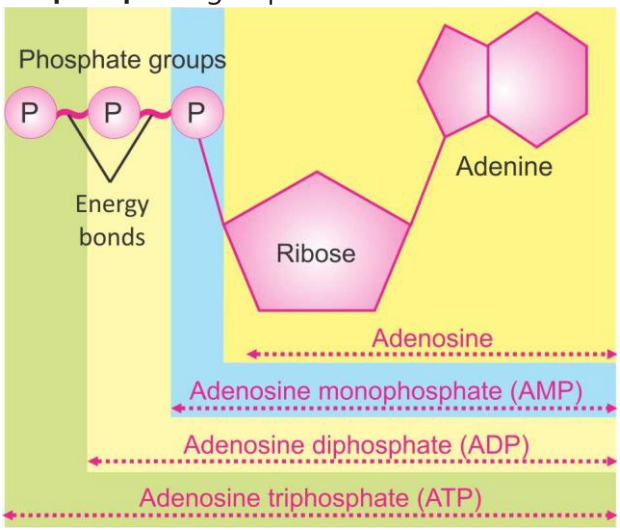


Figure 5.1: Molecular structure of ATP

ATP was discovered in 1929 by **Karl Lohmann**.
In 1941, the Nobel prize winner, **Fritz Lipmann** proposed that ATP is the main energy-transfer molecule in the cell.

The covalent bonds between two phosphates are high-energy bonds. When one of these bonds is broken, inorganic phosphate (Pi) separates and energy is released. The breaking of one phosphate bond releases about 7.3 kcal (7,300 calories) per mole of ATP.

$$ATP + H_2O \rightarrow ADP + P_i + \text{energy (7.3 kcal/mole)}$$

In common energy reactions only the outer P-P high-energy bond breaks. When this happens, ATP becomes **ADP (adenosine diphosphate)** and one Pi is released.

In some cases, ADP is further broken down to **AMP (adenosine monophosphate)** and Pi:

$$ADP + H_2O \rightarrow AMP + P_i + \text{energy (7.3 kcal/mole)}$$

Cells get energy from the oxidation of food. They store this energy by combining ADP with P_i to form ATP. So, we can summarize that ATP is made during energy-releasing processes and it is broken down during energy-consuming processes. In this way ATP transfers energy between metabolic reactions.

5.1- PHOTOSYNTHESIS

Photosynthesis involves the use of light energy that is absorbed and converted into chemical energy by photosynthetic pigments. Photosynthesis in plants can be summarized as:

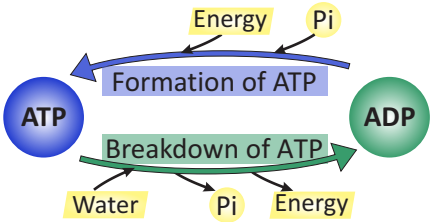


Figure 5.2: ATP-ADP Cycle

$$6CO_2 + 12H_2O + Light \longrightarrow C_6H_{12}O_6 + 6O_2 + 6H_2O$$

Carbon dioxide, water and light are the reactants while glucose and oxygen are the products. Water appears on both sides of the equation because water is used as reactant in some reactions and released as product in others. However, there is no net yield of water.

Recalling:
Photosynthesis is the process in which the energy-poor inorganic compounds of carbon (i.e., CO_2) are reduced to energy-rich carbohydrates.

Compensation Point: Photosynthesis uses the products of respiration and respiration uses the products of photosynthesis. Photosynthesis occurs only during day time but respiration goes on day and night. During darkness, leaves and other parts respire and utilize oxygen and release carbon dioxide. At dawn and dusk, when light intensity is low, the rate of photosynthesis and respiration may be equal for a short time. Thus, the oxygen released from photosynthesis is just equal to the amount required for cellular respiration. Also, the carbon dioxide released by respiration is just equal to the amount required by photosynthesizing cells. At this moment there is no net gas exchange between leaves and atmosphere. This is termed as compensation point. At noon, when the light intensity increases, the rate of photosynthesis also increases. At this time, there is more requirement of carbon dioxide. Respiration alone cannot supply this carbon dioxide. Similarly, the oxygen produced during photosynthesis is more than the need of the respiring cells. So, the result is the net release of oxygen coupled with the uptake of carbon dioxide.

Role of Light

Light plays a crucial role in photosynthesis, providing the energy required to drive the chemical reactions that transform simple molecules into complex organic compounds. Light energy is absorbed by chlorophyll. The absorbed light energy is converted into chemical energy, which is in turn stored in organic compounds in the form of C-H bond energy. It happens like this;

Plants convert only about 1-2% of the solar energy they receive into chemical energy during photosynthesis. Despite this seemingly low efficiency, this conversion is enough to sustain almost all life on Earth.

Action Spectrum

Photosynthetic pigments absorb different wavelengths of light at different rates. Moreover, the different wavelengths are also differently effective in photosynthesis. The effectiveness of different wavelengths of light is determined in terms of action spectrum. For getting action spectrum of light, a plant is illuminated with different colours of light one by one. While providing each colour, the rate of

photosynthesis is measured by measuring the amount of oxygen emitted from leaves. The data is plotted in a graph called action spectrum. The first action spectrum was made by a German biologist, T. W. Engelmann in 1883. He worked on the photosynthetic pigments of *Spirogyra* When the cells of a filament of *Spirogyra* were illuminated with different wavelengths of light, maximum photosynthesis occurred in the cells which received blue and red spectrum of light and so maximum oxygen was emitted from these cells.

Role of Carbon Dioxide

Sugar is formed by the reduction of CO_2 by using ATP and NADPH. In this way, CO_2 acts as the source of carbon for making sugars. Carbon dioxide enters the leaves through stomata and gets dissolved in water absorbed by the cell walls of mesophyll cells. Stomata are found in large numbers in leaves. The entry of CO_2 into the leaves is dependent upon the opening of stomata.

About 10% of total photosynthesis is carried out by terrestrial plants, the rest occurs in oceans, lakes and ponds. Aquatic photosynthetic organisms use dissolved CO_2, bicarbonates and soluble carbonates as carbon source. Land photosynthetic organisms use atmospheric CO_2 as carbon source.

Neil's hypothesis was based on the investigations on photosynthetic bacteria that make carbohydrate from carbon dioxide, but do not release oxygen.

Role of Water

Water is the source of hydrogen, for the reduction of CO_2 during photosynthesis. Oxygen released during photosynthesis comes from water, and so water is an important source of atmospheric oxygen which most organisms need for aerobic respiration and thus for obtaining energy to live.

In 1930s, **Van Neil** hypothesized that plant splits water as a source of hydrogen, releasing oxygen as a by-product. Neil's hypothesis was later confirmed by scientists during 1940s. An experiment was conducted in which isotopic tracer (^{18}O) of oxygen was used. In laboratory, scientists

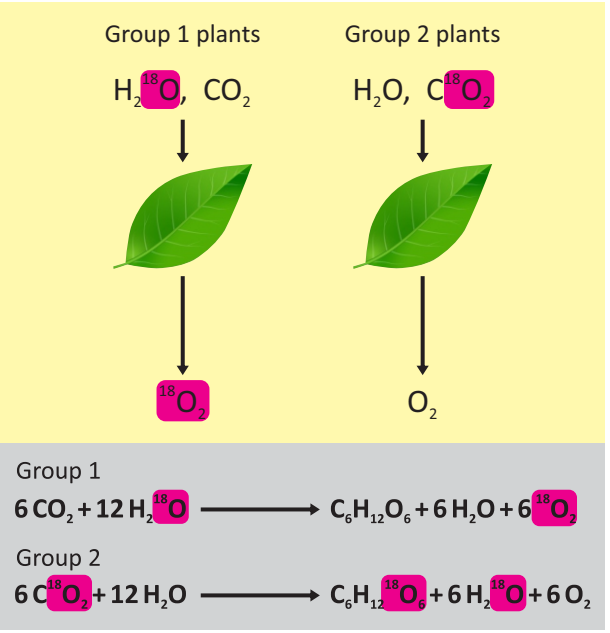


Figure 5.3: Experiment to prove that water is the source of oxygen released in photosynthesis

prepared water with heavy-oxygen i.e., $H_2{}^{18}O$. They also prepared carbon dioxide with heavy oxygen i.e., $C^{18}O_2$. Experimental green plants in one group were given water $H_2{}^{18}O$ and normal carbon dioxide i.e., $C^{16}O_2$. Plants in the second group were given $C^{18}O_2$ and normal water i.e., $H_2{}^{16}O$. Both plants were given an environment to conduct photosynthesis. Oxygen released during photosynthesis of both plants was collected and tested. It was found that plants of first group produced ^{18}O but the plants of second group produced normal oxygen (^{16}O).

In photosynthesis water is split to release hydrogen. This hydrogen reduces the coenzyme nicotinamide adenine dinucleotide phosphate (NADP) to NADPH. The reduced coenzyme i.e., NADPH serves as the "reducing power" for the reduction of CO_2 to form sugar.

Role of Photosynthetic Pigments

Photosynthetic pigments are present in thylakoid membranes. These pigments capture light energy necessary for photosynthesis. Soe of the pigments are chlorophyll a, chlorophyll b, xanthophylls, carotenes. Different pigments absorb light of different wavelengths (colours). Light behaves like a stream of particles called photons. Pigment molecules absorb one photon at a time.

Short wavelength photons (blue) have a higher energy than long wavelength (red) photons. More energetic photons (shorter wavelength) promote electrons to higher energy levels.

When a pigment molecule absorbs a photon, its electrons move to higher energy level, So, it becomes energy-rich or excited.

Chlorophylls

Chlorophyll is a lipid molecule. Chlorophylls are of different kinds. Chlorophyll a, b, c and d are found in plants and algae, while the others are found in photosynthetic bacteria and are known as bacteriochlorophylls.

A molecule of chlorophyll consists of two parts i.e., a hydrophilic head and a hydrophobic tail. The head is made of a porphyrin ring, which further consists of four pyrrole rings (5-sided N-containing compounds). The four pyrrole rings are held together by a magnesium atom in the centre. In chlorophyll-a, the second pyrrole ring has methyl (CH_3) group while in chlorophyll-b, it has aldehyde (CHO) group at the same spot. The porphyrin ring of chlorophyll absorbs light. The tail is made of long hydrocarbon chain. It anchors the molecule in the thylakoid membrane.

Chlorophylls absorb mainly violet-blue and orange-red wavelengths of light. Green wavelengths are least absorbed by chlorophylls and are transmitted or reflected.

Carotenoids, such as beta-carotene, play dual role in photosynthesis. They capture light energy in the blue and green regions of the spectrum and protect the photosynthetic apparatus from damage by excess light.

Accessory Pigments

Accessory pigments include all the pigments, other than chlorophyll-a, which can gather light for photosynthesis. Chlorophyll b is an accessory pigment and others are carotenoids (carotenes and xanthophylls) and phycobilins. Chlorophyll b and carotenoids are found in plants while phycobilins are found in the red algae and cyanobacteria.

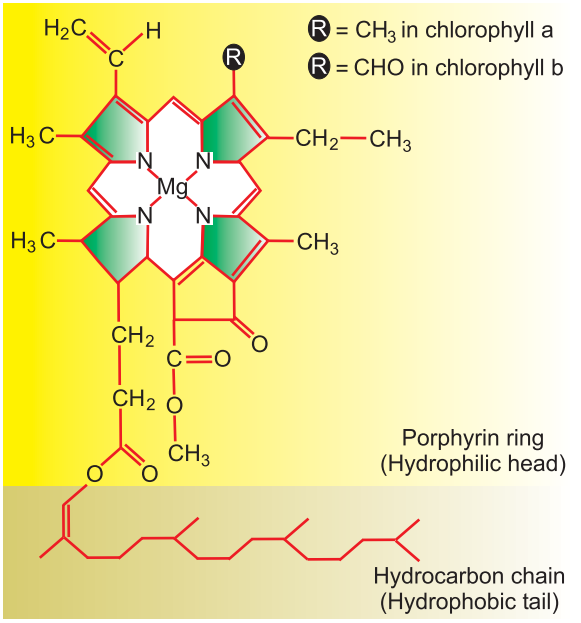


Figure 5.4: Molecular structure of chlorophyll a and chlorophyll b

When accessory pigments absorb light, they pass on the energy towards chlorophyll a. It is generally believed that the order of transfer of energy in plants is;

Carotenoids → Chlorophyll b → Chlorophyll a

Absorption Spectrum

A graph showing different wavelengths absorbed by a pigment, is called absorption spectrum of the pigment. Absorption spectrum of chlorophylls indicates that absorption of blue light (430 nm) and red light (670 nm) is maximum. Absorption peaks of carotenoids are different from those of chlorophylls (Fig 5.5-a). Action spectrum of photosynthesis also shows that blue and red parts lights are the most effective. This means that the action spectrum of photosynthesis coincides with the absorption spectrum of photosynthetic pigments.

Some wavelengths not absorbed by chlorophyll-a are very affectively absorbed by chlorophyll-b and vice-versa. Such differences increase the range of light absorbed by both chlorophylls.

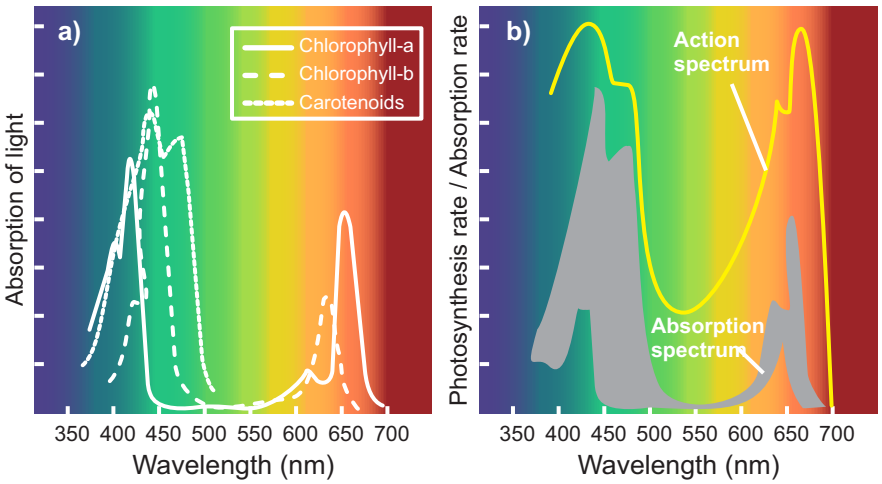


Figure 5.5: (a)- Absorption spectrum; (b)- Action spectrum

Organization of Photosynthetic Pigments (Photosystems)

For efficient absorption and utilization of solar energy, photosynthetic pigments are organized into clusters, called photosystems. These photosystems are embedded in thylakoid membranes of chloroplasts.

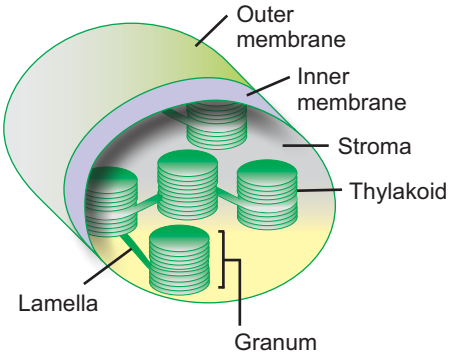


Figure 5.6: Structure of Chloroplast

Photosystems contain photosynthetic pigments and the carriers of electron transport chain. Each photosystem consists of a light gathering **'antenna complex'** and a **'reaction centre'** (Fig 5.7). Antenna complex has many pigment molecules which capture light energy and pass the excitation energy (in the form of high-energy electrons) to the reaction centre. The reaction centre has one or more molecules of chlorophyll-a, which pass the high-energy electrons to a primary electron acceptor. The electron acceptor passes them on to the series of electron carriers, collectively called electron transport chain.

In chloroplast, there are two photosystems, photosystem-I (PS-I) and photosystem-II (PS-II). These are named so in order of their discovery. PS-I has P700 chlorophyll-a molecule in its reaction centre and it absorbs maximum light of 700 nm.

The reaction centre of PS-II has P680 chlorophyll-a, which absorbs best the light of 680 nm.

Mechanism of Photosynthesis

Photosynthesis is a redox (oxidation-reduction) process. As indicated in the photosynthesis equation below, when water molecules are split apart, they are actually oxidized (they lose electrons and hydrogen ions) and yield oxygen. Meanwhile, CO_2 is reduced to sugar as electrons and hydrogen ions are added to it. In this way oxidation and reduction go hand in hand.

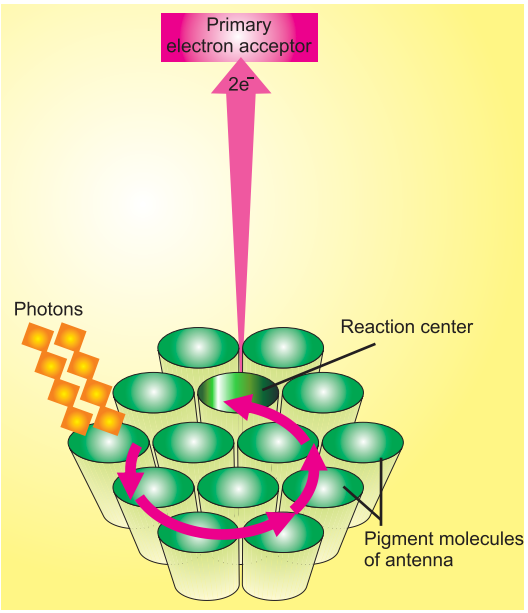
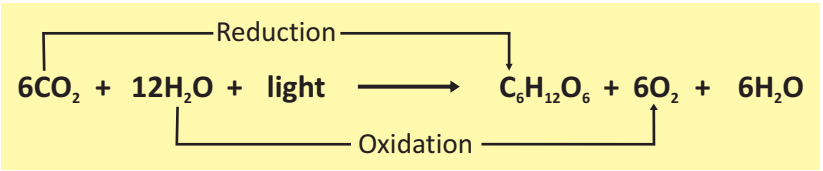


Figure 5.7: Photosystem



However, it is not a simple, single-step process. Rather, it is a complex metabolic pathway consisting of a series of reactions. The light-dependent reactions take place on the thylakoid membranes of the grana while the light-independent reactions take place in the stroma of the chloroplasts. Figure 5.8 shows the summary of these reactions.

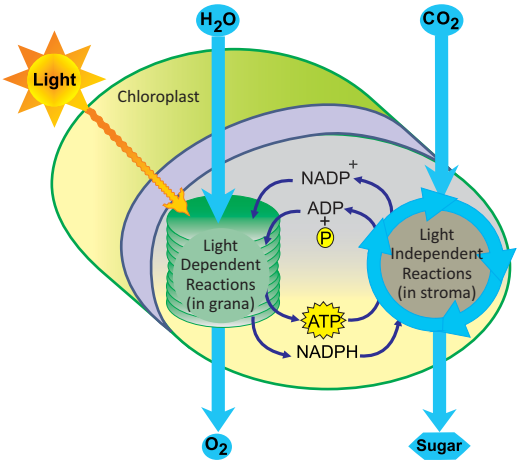


Figure 5.8: Overview of photosynthesis

1- Light- Dependent Reactions

The key events in the light-dependent reactions of photosynthesis are (1) the absorption of light energy by photosynthetic pigments, (2) the excitation of electrons by that energy, and (3) the formation of ATP and NADPH.

During light dependent reactions, light energy is absorbed and converted into chemical energy, which is in the form of reducing and assimilating powers i.e., NADPH and ATP.
Light independent reactions use NADPH and ATP for the reduction CO_2 and thus store chemical energy in the form of C-H bond energy

The formation of ATP is the most important step of light-dependent reactions. It is called photophosphorylation. This process is either non-cyclic photophosphorylation or cyclic photophosphorylation.

a)- Non-Cyclic Photophosphorylation

It is the usual way of the production of ATPs during light-dependent reactions. In non-cyclic pathway, both photosystems i.e., PS-I and PS-II participate and two electron chains are involved (Fig. 5.9). It happens in the following way.

1- **Absorption of light by PS-II:** When light falls on PS-II, the energy level of chlorophyll molecules of its antenna centre rises. Two excited electrons move from them and pass to different chlorophyll molecules. The excited electrons reach P680 chlorophyl present in the reaction centre. Due to energy boost of P680 chlorophyll, its two excited electrons pass to the primary electron acceptor of photosystem-II. Due to it, an electron "hole" is created in p680 chlorophyll, which has become a strong oxidizing agent.

2- **Photolysis of water:** The electron "hole" in chlorophyll molecule is filled by the electrons from water. When water molecule reacts with oxidized chlorophyll in PS-II, it breaks into two hydrogen ions, an oxygen atom (which immediately combines with another oxygen to form O_2), and two electrons. These two electrons fill the "hole" in P680 chlorophyll. This water splitting step of photosynthesis is called **photolysis**.

The oxygen produced during photolysis is the main source of atmospheric oxygen.

3- **Electron flow from PS-II to PS-I:** In step 1, the photoexcited electrons of P680 chlorophyll were received by primary electron acceptor of PS-II. Now, these electrons pass to PS-I via an electron transport chain of PS-II. This chain consists of electron carriers called plastoquinone (PQ), cytochrome complex, and plastocyanin (PC). As electrons move down the chain, their energy goes on decreasing and is used by thylakoid membrane to produce ATP through the process of chemiosmosis.

4- **Absorption of light by PS-I:** In the next step light energy is absorbed by PS-I. The energy level of its chlorophyll molecules boosts to very hight level. The excited

electrons of P700 chlorophyll of the reaction centre pass to the primary electron acceptor of PS-I. The electrons coming from PS-II fill the electron "hole" of P700 chlorophyll of PS-I.

5- Electron flow from PS-I to $NADP^+$: The primary electron acceptor of PS-I passes the photoexcited electrons to a second electron transport chain. These electrons are received by ferredoxin (FD). An enzyme NADP reductase transfers these electrons from FD to $NADP^+$. When $NADP^+$ gets two electrons and an H^+ ion, it is reduced to NADPH. This reaction stores the high-energy electrons in NADPH.

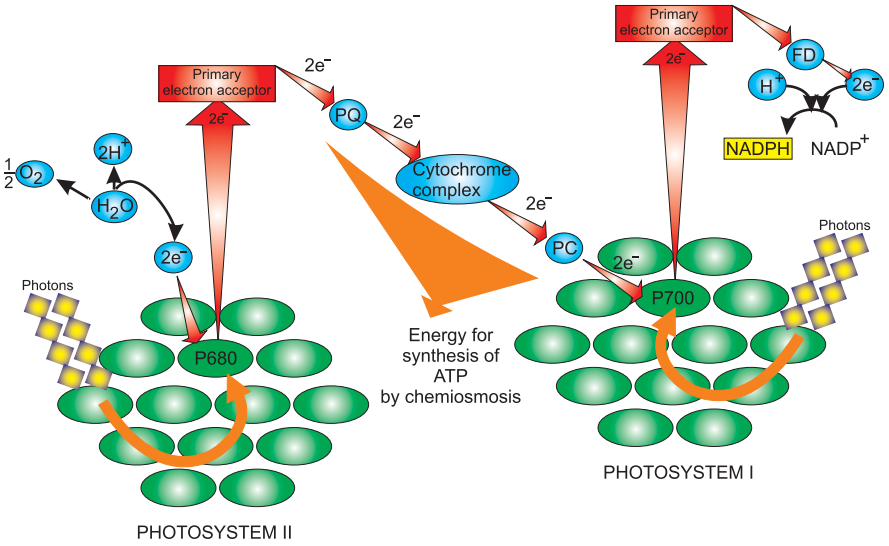


Figure 5.9: Light-dependent reactions (noncyclic photophosphorylation)

So, the light energy gets converted into chemical energy (ATP and NADPH). The zigzag path taken by electrons through PS-II and PS-II and electron transport chains, is called **Z-scheme**

b)- CyclicPhotophosphorylation

Under certain conditions, photoexcited electrons of PS-I take an alternative path called cyclic electron flow. This path uses PS-I but not PS-II. These electrons cycle-back from primary electron acceptor of PS-I to P700 chlorophyll via the electron transport chain. There is no production of NADPH and no release of oxygen. Cyclic flow however generates ATP (Fig 5.10). It happens when Calvin cycle slows down and NADPH accumulates in chloroplast.

Chemiosmosis

During light-dependent reactions when electrons are transferred to the series of carriers of electron transport chain, it results in oxidation and reduction reactions. A carrier is oxidized when it loses electrons and next carrier is reduced when it gets

electrons. Electrons lose energy during this carrier-to-carrier transport. Chemiosmosis is the mechanism in which thylakoid membranes couple these redox reactions with the synthesis of ATPs.

How does chemiosmosis use the energy released from electrons to synthesize ATP? Actually, this energy is spent for the active transport of H^+ ions from the stroma of chloroplast to its inner compartment (lumen). In this way many H^+ ions are deposited in the lumen. This H^+ ion gradient in lumen has potential energy. The H^+ ions diffuse back from lumen in stroma (from higher concentration in lumen to lower concentration). While diffusing, they pass through a special protein of the membrane of thylakoid cells. This protein is an enzyme called ATP synthase. This enzyme uses the energy yielded from the flow of H^+ ions to make a bond between ADP and inorganic phosphate (Pi). So, ADP is converted into ATP and energy is packed in it (Fig 5.11).

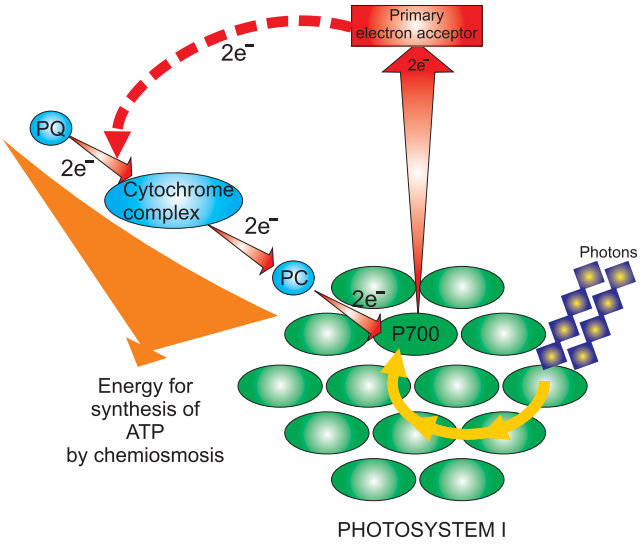


Figure 5.10: Cyclic Photophosphorylation

The electron transport chains in mitochondria and chloroplasts generate ATP by the same mechanism of chemiosmosis.

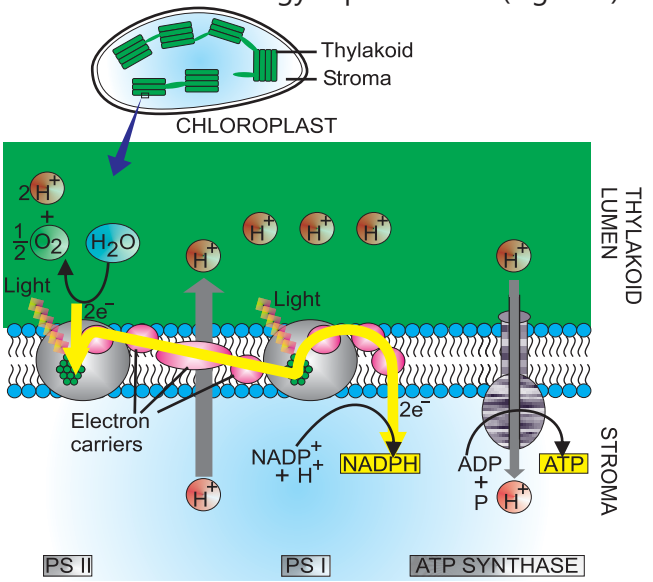


Figure 5.11: Electron transport chain and chemiosmosis in chloroplast

2- Light-Independent Reactions

Light-independent reactions are a series of reactions which happen in the stroma of chloroplast. These reactions use carbon from CO_2, energy from ATP, and hydrogen ions from NADPH to construct energy-rich sugar molecules. These are also called **dark reactions**. These reactions can occur in the absence as well as in the presence of light, as long as ATP and NADPH are available (Fig 5.11). The Calvin cycle is divided into the following phases.

The details of dark reactions were discovered by **Melvin Calvin** and his colleagues at the University of California. That is why, the dark reactions are also called the Calvin cycle. Calvin was awarded Nobel Prize in 1961 for this work.

Phase I: Carbon Fixation

Carbon fixation refers to the initial incorporation of CO_2 into organic material. An enzyme known as ribulose biphosphate carboxylase (or Rubisco; probably the most abundant protein on Earth) combines three molecules of CO_2 with three molecules of a five-carbon sugar named ribulose biphosphate (RuBP). It results in the formation of six molecules of a three–carbon compound called 3–phosphoglyceric acid (3-PGA) or 3-phosphoglycerate.

Since the product of initial carbon fixation is a three–carbon compound, the Calvin cycle is also known as C-3 pathway.

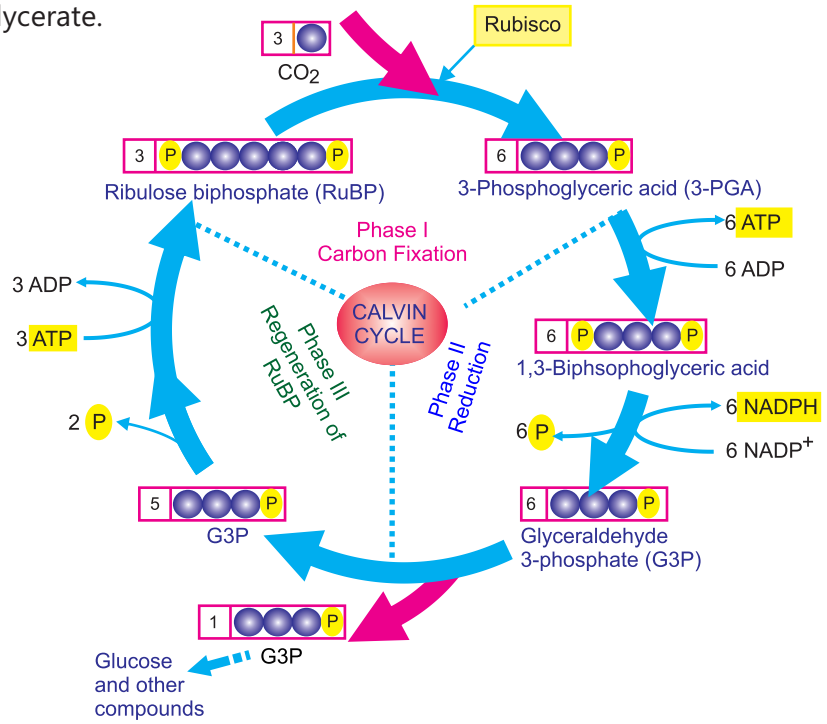


Figure 5.12: The Calvin cycle

Phase II: Reduction

In this phase, six phosphate groups are taken from six ATPs and added to molecules of 3-PGA. In this way, each 3-PGA changes into 1,3-biphsophoglyceric acid. Each 1,3-biphsophoglyceric acid is then reduced to Glyceraldehyde 3-phosphate (G3P). NADPH provides hydrogen for this reduction. During this step, phosphate groups are also detached from 1,3-biphsophoglyceric acid.

G3P is the same three-carbon sugar which is formed in glycolysis (first phase of cellular respiration) by the splitting of glucose.

In this way, six molecules of G3P are produced, out of which one molecule leaves the cycle. It combines with another G3P and makes glucose, which may be then converted to other carbohydrates.

Phase III: Regeneration of RuBp

Through a series of reactions, five molecules of G3P are converted into three molecules of Ribulose phosphate (RuP). One phosphate group is added to each RuP to make three molecules of RuBP by using three ATPs of light reactions. These RuBP receive CO_2 again, and the cycle continues.

5.2. CELLULAR RESPIRATION

Cellular respiration is the universal process by which organisms break down complex carbon containing compounds (e.g., glucose) to get useable energy. Cellular respiration can be summarized as:

$$C_6H_{12}O_6 + 6O_2 \longrightarrow 6CO_2 + 6H_2O + \text{Energy}$$

The exchange of CO_2 and O_2 between the organism and its environment is called external respiration or breathing. Cellular respiration is the process by which energy is made available to cells in a step-by-step oxidation of food in the cells.

You can see that the arrangement of atoms in glucose has more stored energy while there is much less energy in the arrangement of atoms in CO_2 and H_2O. The reason is that there are many C-H bonds in glucose but there are no such bonds in CO_2 and H_2O.

The basic events in cellular respiration in all cells are much similar. Almost all cells in all organisms use glucose as energy source. That is why, glucose is known as respiratory fuel. There are two main types of cellular respiration:

Many of the reactions that occur in your cells also occur in the cells of frog, mice, planaria, mushrooms and radishes.

1. Anaerobic respiration (fermentation) takes place in the absence of oxygen.
2. Aerobic respiration takes place in the presence of oxygen.

In the first step of both these types, glucose is split into two molecules of pyruvic acid ($C_3H_4O_3$) in a process called glycolysis. The next reactions of pyruvic acid are different in anaerobic and aerobic respiration.

Mechanism of Anaerobic Respiration

Anaerobic respiration happens in many microorganisms and in some cells of higher plants. It also happens in the muscle cells of vertebrates. In anaerobic respiration, glucose is not completely oxidized. This type of respiration yields relatively small amount of energy from glucose molecule. As a result of anaerobic respiration, one glucose molecule yields only two ATPs (only about 2% of the energy present in glucose). The energy in two ATPs is equivalent to 14.6 kcal.

Anaerobic respiration consists of glycolysis followed by the reduction of pyruvic acid by NADH to either lactic acid or alcohol and CO_2 i.e., it may again be classified as;

a- Alcoholic Fermentation: In primitive prokaryotic cells (bacteria) and in some eukaryotic cells such as yeast, pyruvic acid is further broken down by alcoholic fermentation into alcohol (C_2H_5OH) and CO_2.

$$2(C_3H_4O_3) \xrightarrow{4H} 2(C_3H_6O_3)$$

Pyruvic acid — Ethyl alcohol

b- Lactic acid Fermentation: In lactic acid fermentation, each pyruvic acid molecule is converted into lactic acid $C_2H_6O_3$ in the absence of oxygen gas.

$$2(C_3H_4O_3) \longrightarrow 2(C_2H_5OH) + 2CO_2$$

Pyruvic acid — Ethyl alcohol

This form of anaerobic respiration occurs in muscle cells of humans and other animals. It happens during extreme physical activities, when oxygen cannot be transported to the cells as rapidly as it is needed. Many bacteria also use lactic acid fermentation to get energy.

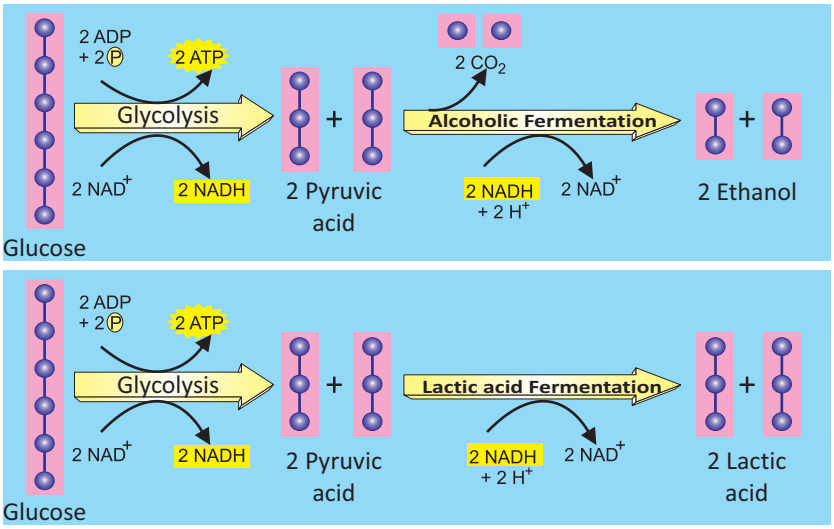


Figure 5.13: Alcoholic fermentation and lactic acid fermentation

Mechanism of Aerobic Respiration

When life evolved on planet Earth free O_2 was not available. So, only anaerobic respiration was possible. But with the evolution of photosynthesis on Earth, molecular oxygen accumulated slowly in the atmosphere. The presence of free oxygen made evolution of aerobic respiration possible.

The complete breakdown of glucose molecule occurs only in aerobic respiration. During aerobic respiration, glucose is broken down to pyruvic acid which is then completely oxidized to CO_2 and water and all the energy stored in its C-H bonds, is released.

Cellular respiration is a continuous process, but for study purposes we can divide it into four main stages.

1- Glycolysis **2-** Pyruvic acid oxidation

3- Krebs cycle or citric acid cycle **4-** Electron transport chain and Chemiosmosis

Glycolysis occurs in the cytosol and oxygen is not essential for this stage. The other three stages occur within mitochondria where the presence of oxygen is essential (Fig 5.14).

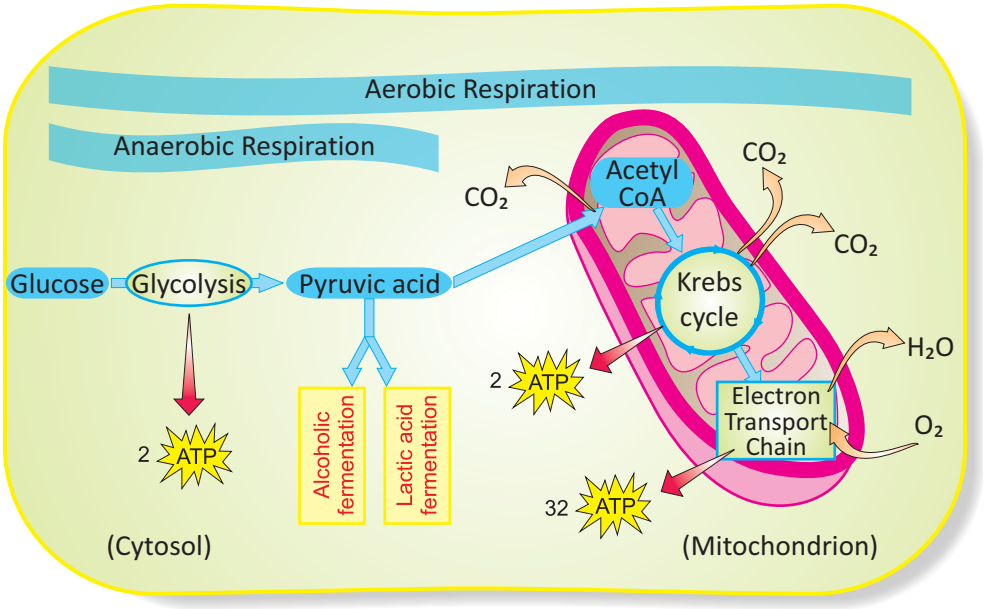


Figure 5.14: Overview of cellular respiration

Stage 1: Glycolysis

Glycolysis is the breakdown of glucose into two molecules of pyruvic acid. Glycolysis takes place in both types of respiration i.e., anaerobic and aerobic. The breakdown of glucose takes place in a series of steps, each catalysed by a specific enzyme (Fig 5.15). All these enzymes are found dissolved in the cytosol. In addition to the enzymes, ATP and coenzyme NAD^+ (nicotinamide adenine dinucleotide) are also essential. Glycolysis involves following reactions.

Preparatory Phase

It involves the expenditure of energy and the breakdown of glucose. It consists of the following steps:

1. A phosphate group is transferred from ATP to glucose. As a result, glucose changes into of glucose 6-phosphate.
2. Glucose 6-phosphate is converted into its isomer called fructose 6-phosphate.
3. Another ATP molecule transfers a second phosphate group to fructose 6-phosphate. So, it becomes fructose 1, 6-biphosphate.
4. Fructose 1, 6-biphosphate is highly reactive and breaks into two molecules of three-carbon intermediates i.e., glyceraldehyde 3-phosphate (G3P) and dihydroxy acetone phosphate (DAP). These are inter-converted and result in two molecules of G3P.

Oxidative Phase

It involves the removal of hydrogen from G3P and packing of released energy in the form of ATP. It consists of the following steps:

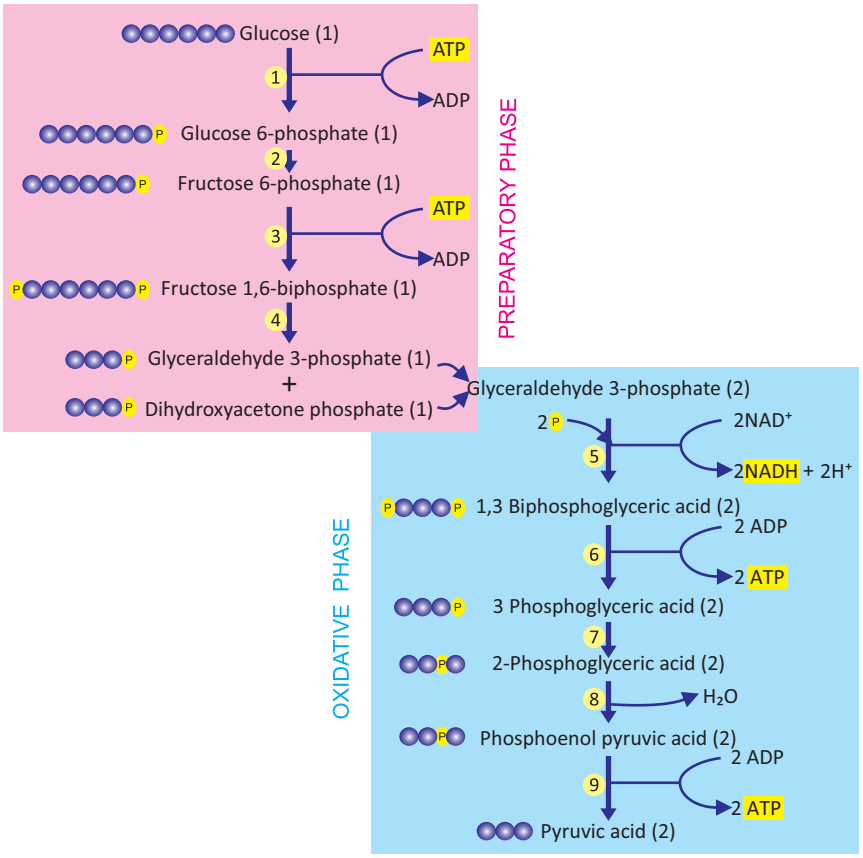


Figure 5.15: Steps in glycolysis

1. Each G3P is oxidized to its acidic form. In this step, two hydrogen atoms (containing two high-energy electrons) are removed from G3P and transferred to NAD^+. At the same time, an inorganic phosphate group is also added to G3P. It results in a molecule of 1, 3-biphosphoglyceric acid (1,3-BPGA).
2. The phosphate group is transferred from 1,3-BPGA to ADP. So, 1,3-BPGA changes into 3-phosphoglyceric acid (3-PGA). A molecule of ATP is also formed in this step.
3. 3-PGA is converted to 2-phosphoglyceric acid (2-PGA).
4. 2-PGA is dehydrated (water removed) into phosphoenol pyruvic acid (PEP).
5. PEP gives up its high energy phosphate to convert a second molecule of ADP to ATP. As a result, PEP is changed into pyruvic acid.

Stage 2: Pyruvic acid Oxidation

Pyruvic acid does not directly participate in Krebs cycle. It has to go through the following changes before entering the Krebs cycle.

Glucose enters cells from the tissue fluid by passive transport using a specific glucose carrier. This carrier can be controlled (gated) by hormones such as insulin.

Pyruvic acid can also be turned back into glucose by reversing glycolysis. This is called gluconeogenesis.

1. A molecule of carbon dioxide is removed from pyruvic acid. So, it changes into acetaldehyde.
2. Acetaldehyde is oxidized (hydrogen is removed) to make acetyl group. A molecule of NAD^+ is reduced to NADH.
3. Acetyl group combines with coenzyme-A (CoA) to form acetyl-CoA (Fig 5.16).

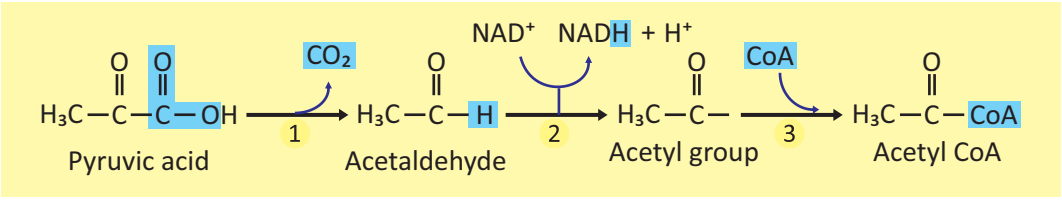


Figure 5.16: Pyruvic acid oxidation

Stage 3: Krebs Cycle

Acetyl-CoA now enters a cyclic series of chemical reactions during which oxidation process is completed (Fig 5.17). Much of this cycle was worked out by a British biochemist, Sir Hans Krebs so it is called the Krebs cycle. It is also called the citric acid cycle, after the six-carbon citric acid molecule formed in its first step. All steps of the citric acid cycle occur in mitochondria. It involves following reactions.

The release of carbon dioxide takes place before oxygen is involved. It is therefore not true to say that respiration turns oxygen into carbon dioxide. It is more correct to say that respiration turns glucose into carbon dioxide, and oxygen into water.

1. Acetyl-CoA splits into CoA and acetyl group. The acetyl group combines with a four-carbon molecule, oxaloacetic acid. As a result, a six-carbon citric acid is formed.
2. Citric acid undergoes an oxidative decarboxylation reaction. It is decarboxylated (releasing a molecule of CO_2) and then oxidized (reducing an NAD^+ to NADH). So, a five-carbon molecule called alpha-ketoglutaric acid is formed.
3. Alpha-ketoglutaric acid undergoes further oxidation and decarboxylation. It results in the formation of a four-carbon molecule i.e., succinic acid. Succinic acid joins with CoA and makes succinyl CoA.

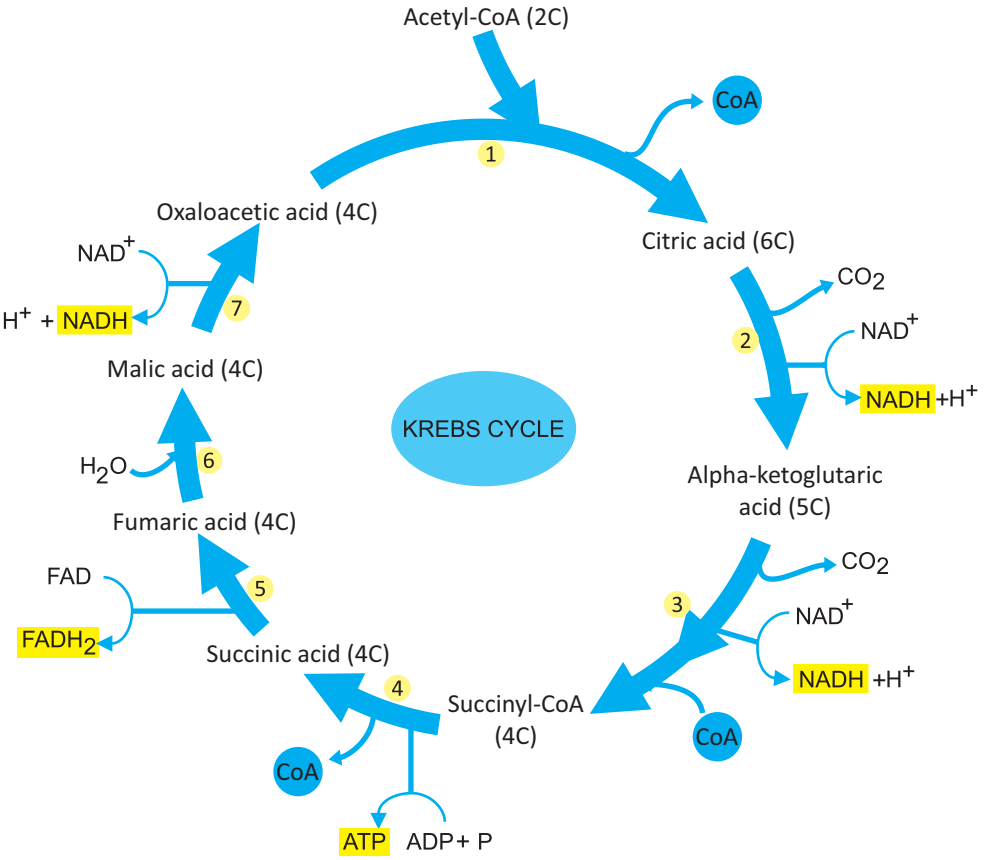


Figure 5.17: Krebs cycle

4. The bond between succinic acid and CoA is a high-energy linkage. It again splits into CoA and succinic acid. The energy released in this reaction, is used in making a molecule of ATP.
5. Succinic acid is oxidized to fumaric acid. When its two hydrogen atoms are removed, the free energy is not enough to reduce NAD+. So, a different

electron acceptor i.e., the coenzyme flavin adenine dinucleotide (FAD) is used and is reduced to FADH2.

6. In order to regenerate oxaloacetic acid, a molecule of water added to fumaric acid and it is changed to malic acid.
7. Malic is oxidized to produce oxaloacetic acid. The hydrogen and electrons released from malic acid convert an NAD+ to NADH. This completes the cycle and oxaloacetic acid is now free to bind another molecule of acetyl CoA to initiate the cycle.

Stage 4: Electron Transport Chain and Chemiosmosis

In electron transport chain the electrons are transferred from the reduced coenzymes i.e., NADH and $FADH_2$ to a series of electron carriers and finally to oxygen. After getting the electrons, the oxygen attaches with hydrogen ions and forms water (Fig. 5.18).

You have seen that in redox reactions electrons and hydrogen ions are removed from substrates and transferred to coenzymes NAD^+ and FAD.

The transfer of electrons to the series of carriers of electron transport chain results in oxidation and reduction reactions i.e., a carrier is oxidized when it loses electrons and next carrier is reduced when it gets electrons. Electrons loose energy during this carrier-to-carrier transport. Chemiosmosis is the mechanism in which membranes are used to couple these redox reactions with the synthesis of ATPs.

Pathway of electrons: The electron transport chain of respiration is built in the inner membrane of the mitochondrion. At the start of electron transport chain, NADH is oxidized and the released electrons are taken up by coenzyme Q. If $FADH_2$ is also to be oxidized, its electrons also move to coenzyme Q. The reduced CoQ transports electrons to cytochrome 'b' which in turn transports them to cytochrome 'c'. Cytochrome 'c' then transports electrons to cytochrome 'a' complex (a complex of two cytochromes). This complex transports electrons to an atom of oxygen that is present at the bottom end of the chain.

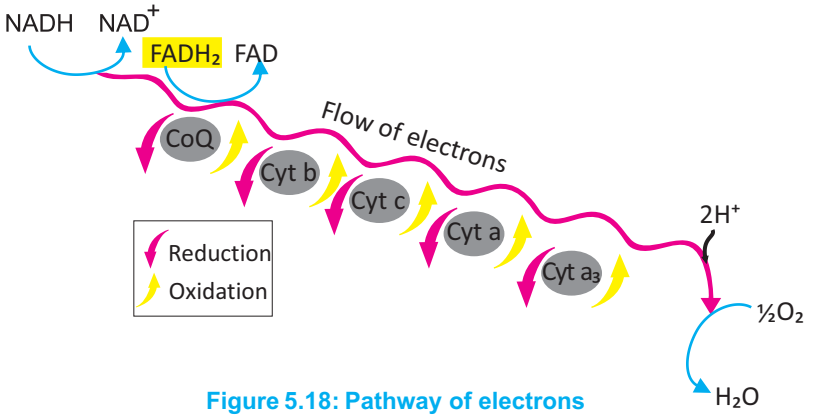


Figure 5.18: Pathway of electrons

Synthesis of ATP: As redox occurs, the energy released from the electrons is used for the active transport of H^+ ions from one side (the matrix of mitochondrion) of the membrane to the other (the inter-membrane space). In this way, many H^+ ions are deposited in the inter-membrane space. The resulting H^+ ion gradient stores potential energy. The H^+ ions diffuse back along their concentration gradient from the inter-membrane space to the matrix (Fig. 5.19).

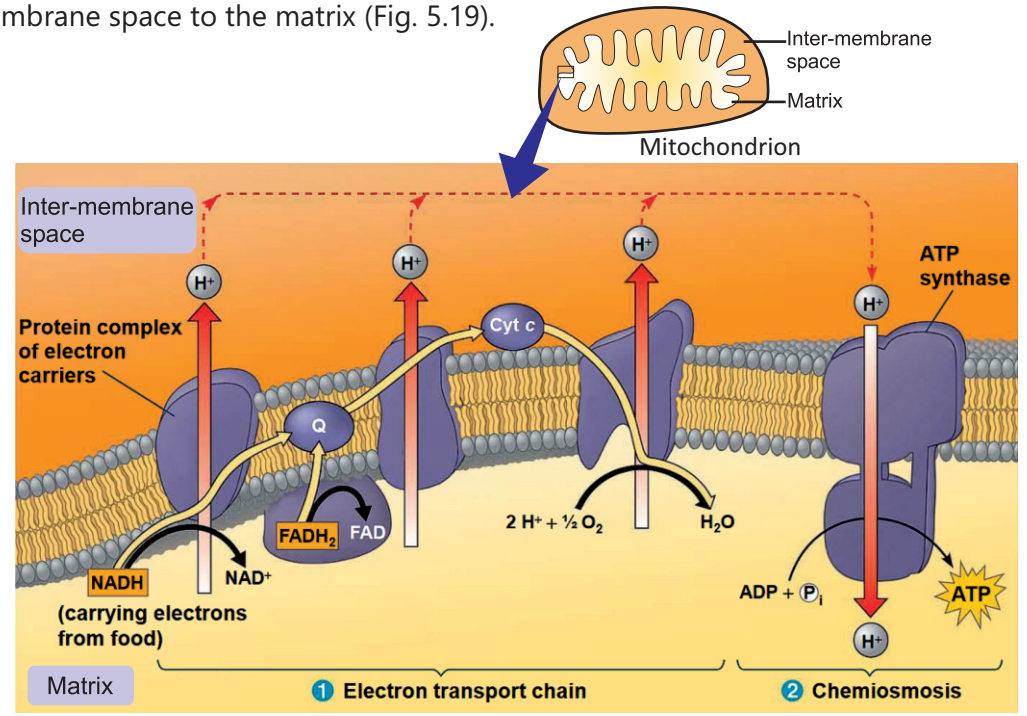


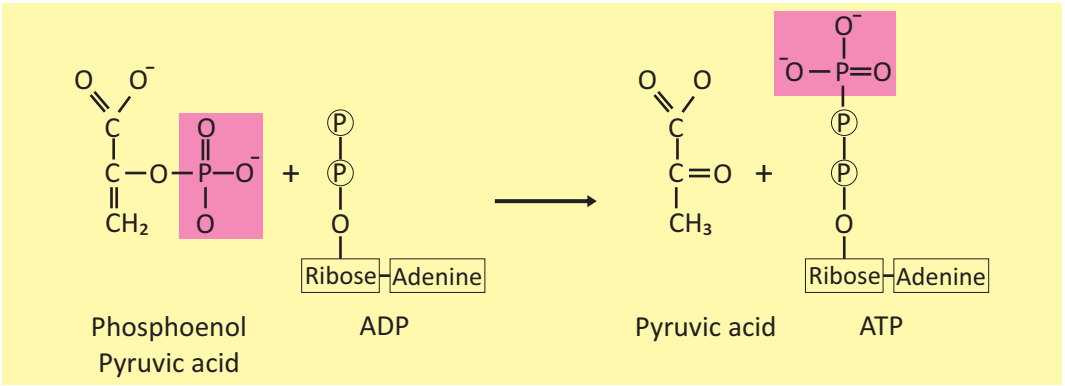
Figure 5.19: Electron transport chain and chemiosmosis in mitochondrion

On their way they pass through a special protein known as ATP synthase. As the H^+ ions move through this protein, their flow drives the synthesis of ATP (Fig 5.19). Oxidation of one molecule of NADH in electron transport chain produces three ATP. While oxidation of one $FADH_2$ produces two ATP. At the end, the two hydrogen ions are taken by the oxygen atom which has also taken two electrons to form water.

Substrate-level Phosphorylation

Cells generate ATP by phosphorylation i.e. adding a phosphate group to ADP. A cell has two ways to do this: chemiosmotic phosphorylation (chemiosmosis) and substrate-level phosphorylation. Substrate-level phosphorylation is much simpler than chemiosmosis. It does not involve any membrane or electron transport chain. In this process, an enzyme transfers a phosphate group from an organic substrate molecule to ADP. The products are a new organic molecule and a molecule of ATP. For example; during the last step of glycolysis, an enzyme transfers phosphate group from

phosphoenol pyruvic (PEP) acid to ADP. As a result, ADP becomes ATP and PEP is changed into pyruvic acid. Substrate–level phosphorylation accounts for only a small percentage of the ATP that a cell generates. This reaction can be shown as:



Overview of the energy extracted from the Oxidation of Glucose

The NADH and $FADH_2$ produced during glycolysis and Krebs cycle pass on their energy-rich electrons to the electron transport chain and ATPs are produced.

- The NADH molecule generated in the Krebs cycle causes the production of three ATP molecules, during chemiosmosis.

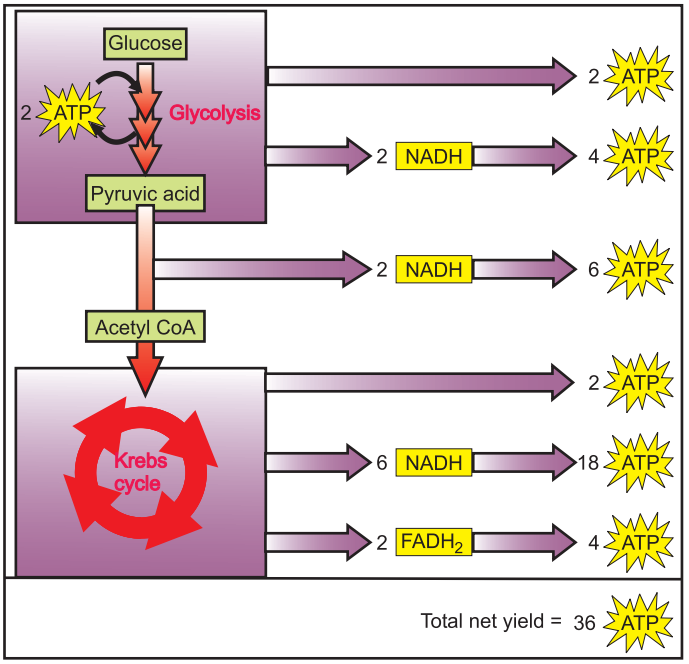


Figure 5.20: An overview of the energy extracted from the aerobic oxidation of glucose

- Glycolysis takes place in cytoplasm and the NADH, produced during glycolysis, have to be transported across the mitochondrial membrane. It costs one ATP molecule

per NADH. Thus, each NADH of glycolysis produces two ATP molecules in the final balance sheet instead of three.

- Each $FADH_2$ molecule leads to the production of two ATP molecules.

In this way, aerobic oxidation of glucose yields a net profit of 36 ATP molecules. While during the glycolysis of anaerobic oxidation only 2 ATP molecules are generated. Thus, aerobic oxidation is 18 times more efficient than anaerobic (Fig 5.20).

Other Organic Molecules as fuel for Cellular Respiration

Free glucose molecules are not common in our diet. Rather, we consume sucrose and other disaccharides, starch, and fats and proteins. Proteins may also be used as fuel but they must be digested to their constituent amino acids. Typically, a cell uses most of the amino acids to make its own proteins. Some amino acids are de-aminated (amino group detached) and then are converted to other organic compounds. These compounds are usually converted to pyruvic acid, acetyl CoA, or the organic acids in the Krebs cycle, and their energy is converted to ATP.

Lipids are excellent cellular fuel because they contain many carbon-hydrogen bonds. They are first hydrolysed into glycerol and fatty acids. Glycerol is converted to glyceraldehyde 3-phosphate, an intermediate in glycolysis, while the fatty acids are changed into acetyl CoA. In this way both the fatty acids and the glycerol enter cellular respiration.

5.3- PHOTORESPIRATION

The respiratory activity that occurs in green cells in the presence of light resulting in release of carbon dioxide is termed as photorespiration. It needs oxygen and produce CO_2 and H_2O like aerobic respiration. However, ATP is not produced during photorespiration.

Recalling:
During carbon fixation, rubisco combines three molecules of CO_2 with three molecules of RuBP and makes six molecules of 3–phosphoglyceric acid (3-PGA).

Mechanism of Photorespiration

We know that RuBP carboxylase (rubisco) catalyses the addition of CO_2 to RuBP to make phosphoglyceric acid (phosphoglycerate), which is further reduced to form glucose. However, when the relative concentration of CO_2 decreases and there is more oxygen in leaf cells, rubisco adds O_2 in RuBP instead of CO_2. It results in the breakdown of RuBP into two molecules i.e., one phosphoglycerate and one phosphoglycolate (a two-carbon molecule).

Phosphoglycolate is converted into glycolate, which moves from chloroplast to peroxisome. Here, it is metabolized to glyoxylate by using O_2. This reaction also produces toxic hydrogen peroxide (H_2O_2). Glyoxylate is then converted to glycine, which is transported to mitochondrion. Here, two molecules of glycine form a molecule

of serine. Serine is then transported to peroxisome. Here, it is converted to glycerate. From peroxisome, glycerate moves to chloroplast, where it is changed to phosphoglycerate which can re-enter Calvin cycle.

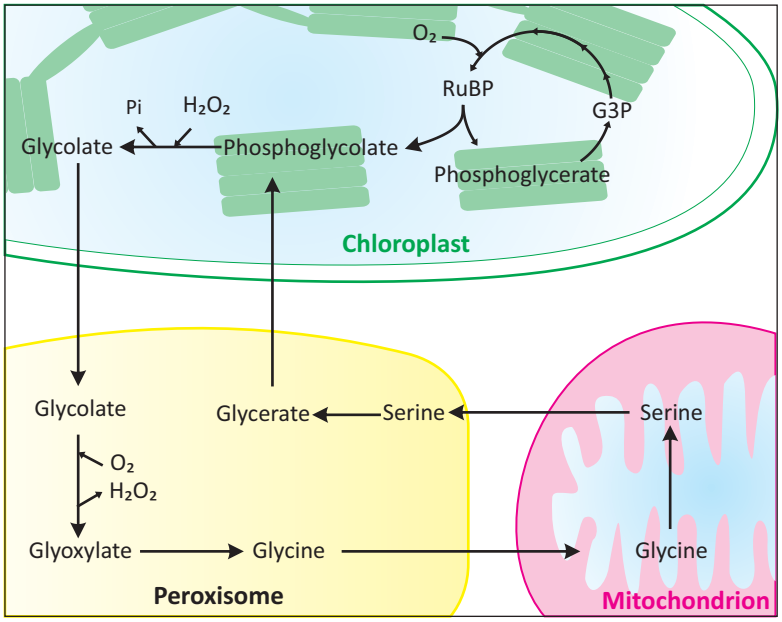


Figure 5.21: Reactions of photorespiration

Disadvantages of Photorespiration

Plants that use Calvin cycle to fix carbon are called C-3 plants. When photorespiration occurs in these plants, they lose between a 25% to 50% of their fixed carbon. It results in reduction in their yields. The rate of photorespiration also depends on temperature. At higher temperatures the oxidative activity of rubisco increases than its carbon fixing activity. In tropical climates, especially those in which the temperature is often above 28 °C, the problem is a severe and it has a major negative impact on agricultural yields.

When photosynthesis first evolved, there was little oxygen in the atmosphere. So, there was little or no photorespiration. After millions of years, free O_2 accumulated in the atmosphere and competition started between CO_2 and O_2 for the same active site of rubisco. It led to the problem that photorespiration now poses.

Adaptations to the problems of Photorespiration

Plants of warmer climates evolved the following two ways to deal with the problem of photorespiration.

C-4 plants carry out C-4 as well as C-3 photosynthesis.

i. C-4 Photosynthesis

Some plants including grasses (corn, sugarcane and sorghum) and about two dozen other plant groups run a special pathway called C-4 photosynthesis in addition

to the normal Calvin cycle. In their leaves, the mesophyll cells have less air spaces. The enzymes of Calvin cycle are more deposited in specialized cells called bundle-sheath cells, which are impermeable to CO_2.

In C-4 photosynthesis, the energy cost for making a glucose molecule is almost double. However, in hot climates, in which photorespiration would otherwise remove more than half of the carbon fixed, it is best compromise available.

During C-4 photosynthesis (Fig 5.22) in mesophyll cells, CO_2, is attached with a 3-carbon molecule called phosphoenol pyruvic acid. It results in the formation of a four-carbon molecule oxaloacetic acid. Due to this first 4-C product, this process is called C-4 photosynthesis and the plants are called C-4 plants. Oxaloacetic acid is then converted to malic acid, by using NADH. Malic acid is transported to an adjacent bundle-sheath cell. Here, malic acid is broken down to pyruvic acid and CO_2. These cells can hold CO_2 in them. So, concentration of CO_2 increases in these cells and they run Calvin cycle instead of photorespiration. Pyruvic acid produced in bundle sheath cells returns to mesophyll cell and is converted again to phosphoenol pyruvic acid b using an ATP.

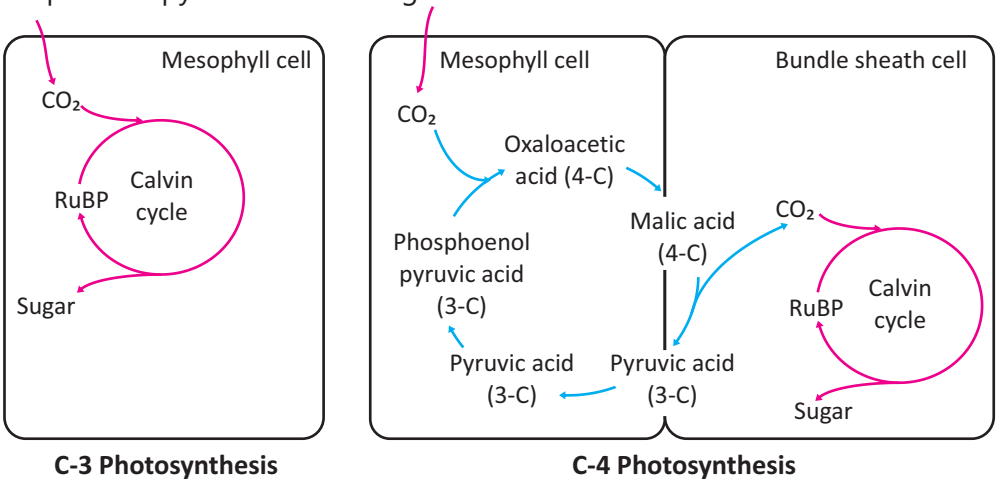
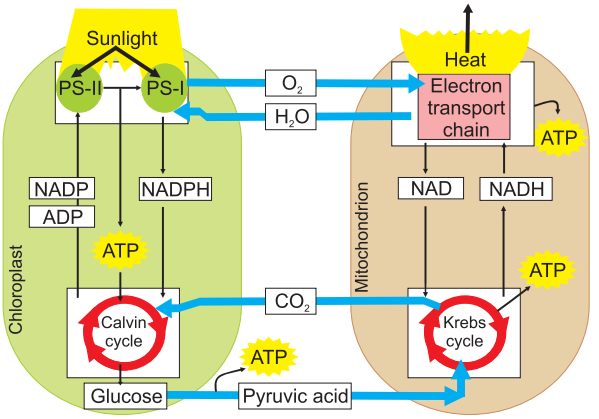


Figure 5.22: C-3 photosynthesis andC-4 photosynthesis

CAM Metabolism

In hot climates, many succulent plants such as *Cacti*, pineapples and some other plant groups perform Crassulaceal acid metabolism or CAM (after the plant family Crassulaceae in which it was first discovered). In these plants, the stomata open during the night and close during the day. Closing stomata during the day prevents water loss and removal of CO_2. So, rate of photorespiration is reduced due to high concentration of carbon dioxide. The carbon dioxide necessary for producing sugar is provided from organic molecules made the night before. Like C-4 plants, these plants use both C-4 and C-3 pathways.

From the given flowchart, build a paragraph that can describe a comparison between photosynthesis and respiration in terms of reactants and products of major steps.



EXERCISE

SECTION 1: MULTIPLE CHOICE QUESTIONS

1- What main process occurs during the dark reaction of photosynthesis?

(a) Release of oxygen (b) Energy absorption by chlorophyll

(c) Adding of hydrogen to CO_2 (d) Formation of ATP

2- What is TRUE about glycolysis?

(a) It produces no ATP

(b) It takes place only in aerobic respiration

(c) It takes place in the mitochondrion

(d) It reduces 2 molecules of NAD+ for every glucose molecule processed

3- Which of the following are produced by the reactions that occur in the thylakoid and consumed by the reactions that occur in the stroma?

(a) CO2 and H_2O (b) Glucose and O_2

(c) NADP+ and ADP (d) ATP and NADPH

4- When deprived of oxygen, yeast cells obtain energy by fermentation, producing CO2, ATP and;

(a) Acetyl CoA (b) Ethyl alcohol (c) Lactic acid (d) Pyruvic acid

5- Conversion of Glucose 6-phosphate into Fructose 6-phosphate is;

(a) Isomerization (b) Polymerization

(c) Condensation (d) Phosphorylation

6- In which of the following conversions, ATP is produced?

(a) Alpha ketoglutaric acid into succinyl CoA

(b) Succinyl CoA into succinic acid

(c) Succinic acid into fumaric acid

(d) Fumaric acid into malic acid

7- In electron transport chain, FADH:H produces how many ATPs?

(a) One (b) Two (c) Three (d) Four

8- Which of these is CO_2 acceptor during photosynthesis?

(a) Malic acid (b) Ribulose biphosphate

(c) Oxaloacetic acid (d) Phosphoglyceric acid

9- Which of the following takes the electrons lost by Photosystem I on absorption of light energy?

(a) Ferredoxin (b) Cytochrome (c) Cytochrome a-3 (d) Plastocyanin

10- Photosystem-II makes up the electrons lost due to light excitation by taking up the electrons released from,

(a) Ferredoxin (b) $NADPH:H^+$

(c) Plastocyanin (d) Photolysis of water

SECTION 2:SHORT QUESTIONS

1- Differentiate between action spectrum and absorption spectrum.
2- How is photosynthesis a redox reaction?
3- Which molecule contributes Oxygen in glucose? Water or carbon dioxide!
4- State the role of CO_2 in photosynthesis.
5- Define electron transport chain.
6- What do you mean by glycolysis?
7- What is the main structural difference between chlorophyll-a and chlorophyll-b?
8- How can a cell synthesize ATP through substrate-level phosphorylation?
9- Can pyruvic acid enter Krebs cycle as such? If not, what changes are made to it before Krebs cycle?
10- Differentiate between C-3 and C-4 photosynthesis.

SECTION 3: LONG QUESTIONS

1- What are photosynthetic pigments and what role they play in the absorption and conversion of light energy?
2- How are the absorption spectra of chlorophyll 'a' and 'b' different?
3- Describe and illustrate how photosynthetic pigments are organized in thylakoid membrane?
4- Describe how the role of water in photosynthesis can be explained through experiment.
5- What are the events that capture light and convert it into chemical energy during light dependent reactions?
6- Illustrate the cyclic photophosphorylation.
7- Describe light independent reactions of photosynthesis in terms of paragraph and illustrate in terms of Calvin cycle.

8- What happens with glucose in anaerobic respiration and how different organisms modify the end products?
9- How is glucose broken down to pyruvic acid in glycolysis?
10- Describe how Krebs cycle is the completion of the oxidation of glycolytic products.
11- Explain the passage of electron through electron transport chain.
12- Define chemiosmosis. How would you relate it with electron transport chain?
13- Through which ways proteins and fats enter cellular respiration?
14- Define photorespiration and present it in proving that "photosynthesis is not perfect".
15- What are the effects of temperature on the oxidative activity of Rubisco?
16- How is the process of C4 photosynthesis an adaptation to deal with the problem of photorespiration?

INQUISITIVE QUESTIONS

1. Why does cellular respiration release energy more efficiently than fermentation?
2. Why is the conversion of glucose into ATP during cellular respiration considered a more efficient use of energy than burning glucose directly?
3. Why might a disruption in either photosynthesis or respiration processes affect global carbon and oxygen cycles?

STUDENTS'LEARNING OUTCOMES

After studying this chapter, the students will be able to:

- Define structural biology.
- Explain that structure determination of biomolecules are important.
- Describe how X-ray crystallography works.
- Outline the online databases where biomolecule structures are available.
- Describe computational biology.
- Define sequence homology.
- Define structural homology.

Structural biology deals with the study of three dimensional (3D) structures of macromolecules (including proteins and nucleic acids) at atomic levels. It provides the detailed information about the structure of biomolecule, its functions, dynamics and interaction with ligands and other macromolecules.

7.1- APPLICATIONS OF STRUCTURAL BIOLOGY

Structural biology has a wide range of applications especially in the field of medical research. Some of these are discussed here:

1- Determining the Active sites and Domains

Structural biologists can determine the three-dimensional (3D) structures of macromolecules such as proteins and nucleic acids. The 3D structures reveal the exact location, shape, and environment of the active sites and different domains (distinct structural units with independent functions) of macromolecules. For example, structural studies of the enzyme HIV-1 reverse transcriptase have identified its polymerase domain (which synthesizes DNA) and RNase H domain (which breaks down the RNA strand of RNA-DNA hybrids). Knowing the location and structure of these domains has helped in the design of antiviral drugs that specifically target them. Similarly, the structure of serine proteases reveals its well-defined active site, which is responsible for breaking down peptide bonds.

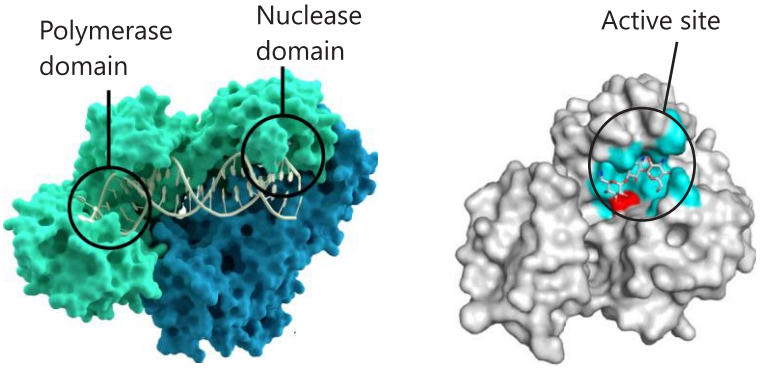


Figure 7.1: (a) 3D structure of HIV-1 reverse transcriptase (b) 3D structure of serine protease

2- Identifying Drug Targets

Structural biology helps scientists find the right place on a disease-causing molecule where a drug can work. These places are usually proteins and are called drug targets. By studying the 3D shape of these proteins, scientists can find specific spots where a drug can attach and stop the protein from working. For example, in COVID-19, scientists used structural biology to study the spike protein of the coronavirus (SARS-CoV-2). This protein helps the virus to enter human cells. By knowing its 3D structure, scientists identified it as a drug target. Thus, they designed vaccines and medicines that block the spike protein, preventing the virus from infecting more cells.

3- Identifying Host–Pathogen Interactions

Structural biology also helps in understanding how pathogens (like viruses or bacteria) interact with the host's body cells. This is called host–pathogen interaction. By studying the 3D structures of both the pathogen and the host cell proteins, scientists can see how the pathogen attaches to and enters the host cell, and which molecules are involved in the process. For example, structural biologists studied the spike protein of coronavirus, which sticks out from the surface of the virus. They also looked at a protein on human cells that acts as receptor of virus spike protein. So, the scientists discovered exactly how the virus enters human cells. This information was vital in developing the drugs that can bind with receptor proteins. Such drug inhibits the interaction of the virus with the receptor and consequently blocks the entry of virus into the host cells.

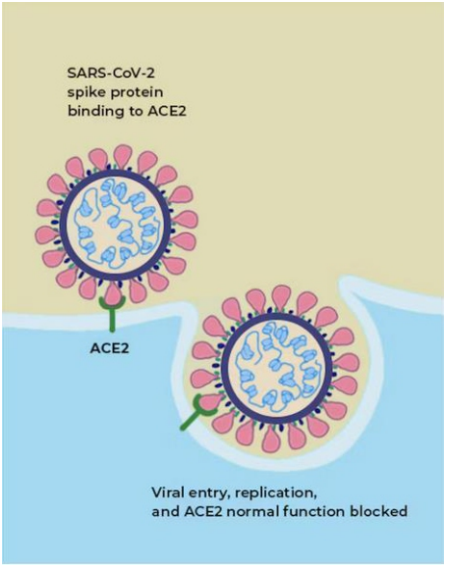


Figure 7.2: Mechanism of corona virus binding with receptorof human cell.

4- Identifying Protein Misfolding

The functionality of proteins depends on the correct folding into three dimensional shapes. Several diseases (including cyctic fibrosis, Parkinsons, Alziemer's) originate due to incorrect folding of proteins. Structural biology provides understanding of intricate folding pathways and how misfolding leads to the diseases.

7.2- X-Ray Crystallography

X-ray crystallography was developed in 1912 by William Henry Bragg and William Lawrence Bragg. They were awarded 1915 Nobel Prize in Physics for their work. Since then it has been used to analyze the diverse substances including minerals, salts, metals, proteins, carbohydrates, nucleic acids and vitamins. In this technique, x-rays beam strikes a crystals and atoms and molecules in the crystals diffract the x-rays beam in specific directions. From the angles and intensities of diffracted beams, a 3D picture of electron density within the crystals are produced. The electron density is exploited to create 3D structure of the molecule.

In order to understand the working of X-ray crystallography, let us take the example of protein structure determination. The method can be divided into following steps:

(i) **Protein crystallization:** Protein crystallization means turning a purified protein into a solid crystal form. Crystals are needed because they arrange protein molecules in a regular, repeating pattern, which is important for getting a clear image during the X-ray process. To make crystals, scientists slowly mix the protein with special solutions that cause the protein molecules to stick together in an orderly way. This process can take hours, days, or even weeks. It often

requires careful control of temperature, pH, and salt concentration. Once a clear and stable protein crystal is formed, it can be used in the next steps.

(ii) **Production of a diffraction pattern:** Once a good quality crystal is formed, it is mounted on the x-ray machine. The x-rays beam is bombarded at the crystal at various angles. The atoms in the crystal diffract the x-rays beam and a diffraction pattern (which is a series of spots) is created on the detectors.

(iii) **Creating density map:** The angles and intensities of these spots contain information about the arrangement of atoms in the crystal. Diffraction pattern is used to make a density map.

(iv) **Determination of protein structure:** Then the data is analyzed mathematically by using computational programs. These calculations transform data into the 3D structure of protein.

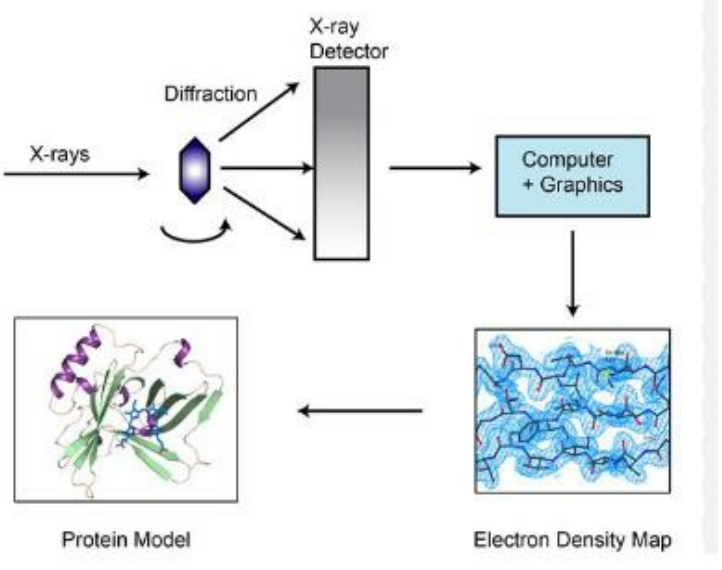


Figure 7.3: Schematic representation of X-ray crystallography

7.3- COMPUTATIONAL BIOLOGY

Computational biology is an interdisciplinary field that uses computational techniques and tools to solve biological problems. It integrates knowledge from biology, computer science, mathematics, and statistics to analyze and interpret biological data. The importance of computational biology lies in its ability to handle large datasets, uncover hidden patterns, and generate predictive models that can lead to new biological insights and applications. Major areas in the computational biology include:

(i) Genomics i.e., the study of genomes, which are the complete set of DNA within a single cell of an organism. Genomics involves sequencing, assembling, and

analyzing the function and structure of genomes. It helps in understanding genetic variations, gene function, and evolutionary relationships.

(ii) **Proteomics** i.e., the large-scale study of proteins, including their structures and functions. Proteins are essential molecules that perform many functions within organisms. Proteomics aims to map the entire set of proteins (the proteome) produced by an organism and understand their interactions and roles in cellular processes.

(iii) **Bioinformatics** i.e., the application of computer technology to manage and analyze biological data. Bioinformatics tools and techniques are used to store, retrieve, and analyze DNA, RNA, and protein sequences.

Applications of Computational Biology

Though computation biology has vast application, some of these are discussed here.

(i) **Drug Discovery:** Computational biology helps in identifying potential drug targets and simulating the effects of drugs on biological systems. It accelerates the drug discovery process by predicting how drugs interact with proteins and other molecules.

(ii) **Genetic Research:** By analyzing DNA sequences, computational biology helps identify genetic variations associated with diseases. It aids in understanding the genetic basis of diseases and can lead to the development of personalized medicine.

(iii) **Evolutionary Biology:** Computational tools are used to compare genetic information across different species, helping to reconstruct evolutionary relationships and understand the process of evolution.

Key Databases: Here are some of the key databases used to analyze nucleic acid and proteins. **GenBank:** https://www.ncbi.nlm.nih.gov/nuccore/

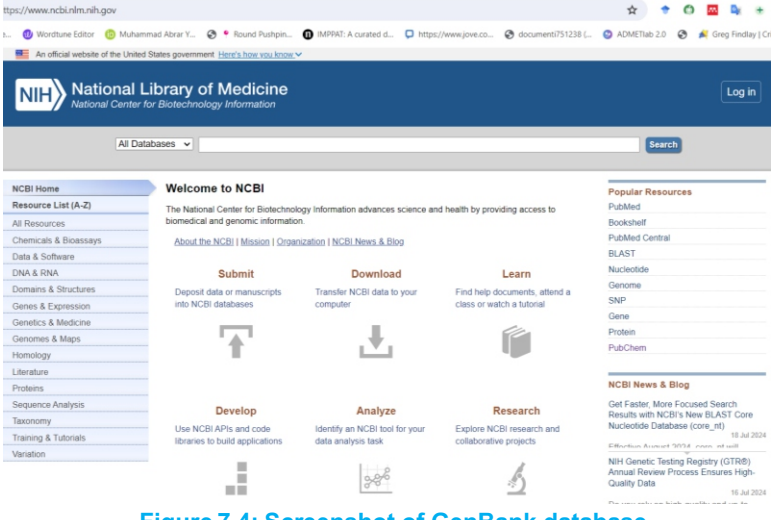


Figure 7.4: Screenshot of GenBank database

It is a comprehensive public database of nucleotide sequences and supporting bibliographic and biological annotations. It provides access to a vast repository of DNA sequences from various organisms, facilitating genetic research and comparative genomics.

Protein Data Bank (PDB)

This database provides 3D structural data of large biological molecules, such as proteins and nucleic acids. It is important for studying the structures of macromolecules, understanding their functions, and designing drugs that target specific protein structures.

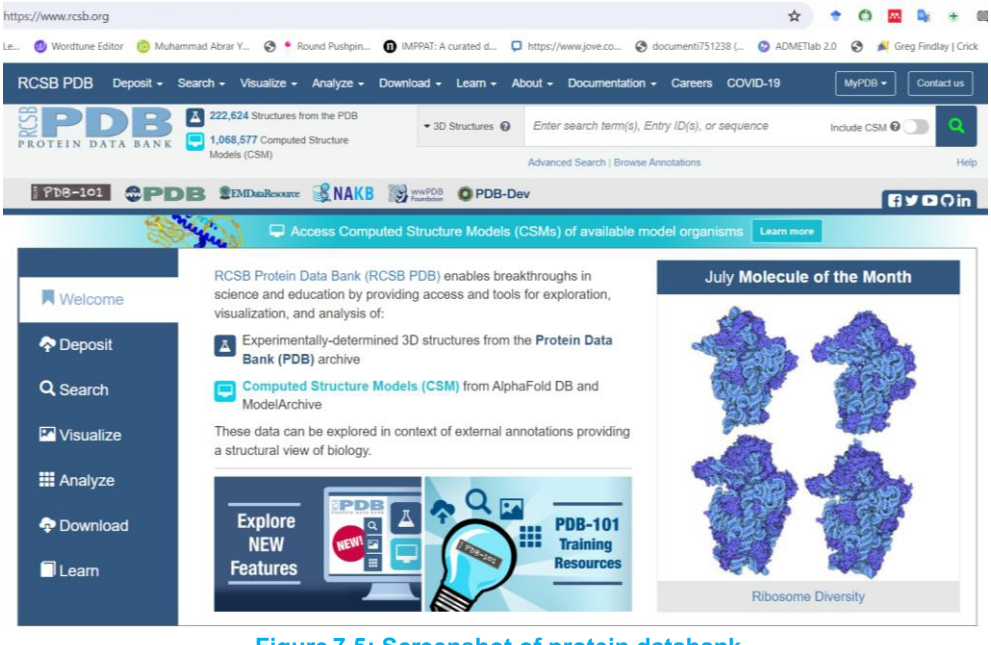


Figure 7.5: Screenshot of protein databank

Ensembl

It is a genome browser providing information on genome sequences, gene models, and comparative genomics for various species. Ensembl helps to access and visualize genomic data, supporting studies in genomics and evolutionary biology.

Key Algorithms

In addition to above mentioned databases, some algorithms being used in data analysis are discussed below.

BLAST (Basic Local Alignment Search Tool) It is used for comparing primary biological sequence information, such as the amino-acid sequences of proteins or the nucleotides of DNA sequences. It helps identify homologous sequences, predict functions of unknown genes, and study evolutionary relationships.

FASTA: It is a sequence alignment tool that compares a query sequence to a database of sequences to find regions of similarity. It is used for searching protein

and nucleotide databases, identifying sequence homology, and analyzing sequence alignments.

7.4- SEQUENCE HOMOLOGY

Sequence homology refers to the similarity between DNA, RNA, or protein sequences due to shared ancestry. Homologous sequences have evolved from a common ancestral sequence and can be categorized into two main types: (i) **Orthologs:** Sequences in different species that originated from a common ancestral gene during speciation. Orthologs often retain the same function across species. (ii) **Paralogs:** Sequences within the same species that originated from gene duplication. Paralogs can evolve new functions even if they originally arise from the same ancestral gene.

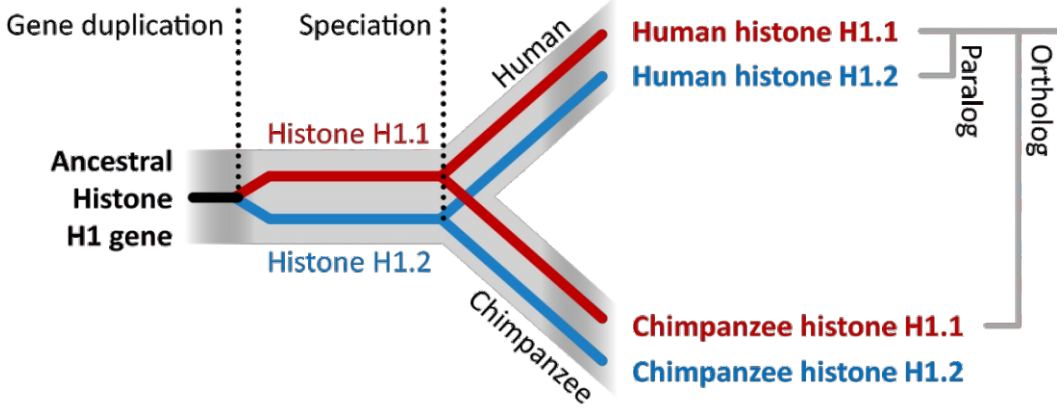


Figure 7.6. Types of Homologous Sequences

Sequence homology provides an insight into the evolutionary relationships between organisms. By comparing homologous sequences, scientists can infer the evolutionary history and divergence of species. Furthermore sequence homology provides a clue about the function of an unknown gene or protein. If an unknown gene/protein is homologous to a gene/protein with a known function, it is likely to have a similar function. Additionally, Identifying homologous genes involved in diseases across different species helps in understanding disease mechanisms and developing treatments. Homologous genes in model organisms can be studied to gain insights into human diseases.

Structural Homology

Structural homology refers to the similarity in the three-dimensional structures of proteins or other macromolecules due to shared ancestry. Proteins with similar structures often perform similar functions, even if their sequences are not highly similar. The three-dimensional structure of a protein provides critical information about its function. Understanding structural homology helps in predicting the function of newly discovered proteins. Furthermore, structural homology is crucial in

drug design, as drugs are often designed to interact with specific protein structures. Understanding the structural relationships between proteins can help in designing more effective drugs. Also studying the structural homology of proteins helps in understanding the evolutionary processes that shape protein functions and interactions.

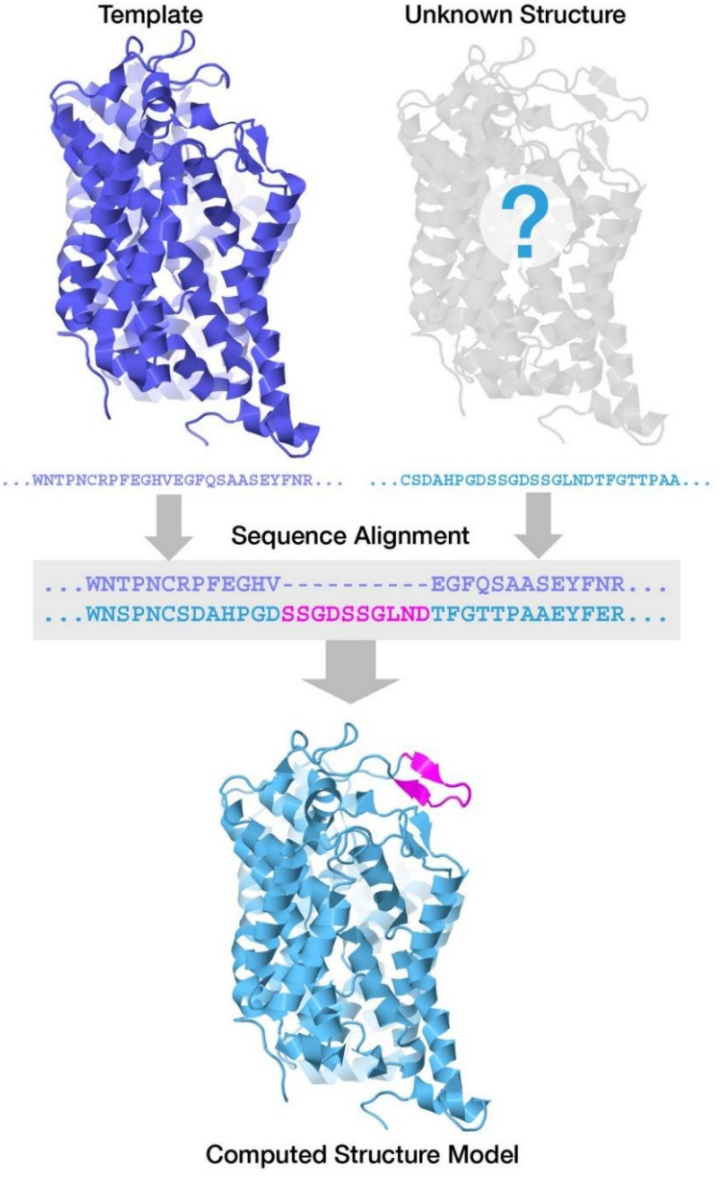


Figure 7.7: Structural homology of protein

EXERCISE

SECTION 1: MULTIPLE CHOICE QUESTIONS

1. Generally, the function of a protein depends on its:
   (a) One-dimensional structure (b) Two-dimensional structure
   (c) Three-dimensional structure (d) Four-dimensional structure
2. The protein domains are:
   (a) Functional and structural units within protein
   (b) Secondary structural elements
   (c) Linear sequences of amino acids
   (d) Specific regions for post-translational modification
3. The first step in x-ray crystallography experiment is:
   (a) Compute an electron density (b) Build a model of your molecule
   (c) Measure a diffraction pattern (d) Grow a crystal
4. What is primary role of computational biology?
   (a) Using computer algorithms to analyze data
   (b) Identifying genetic mutations
   (c) Studying protein functions
   (d) Analyzing the expression patterns
5. Which computational approach is used to predict protein structure based on amino acid sequence?
   (a) Multiple sequence alignment (b) Homology modelling
   (c) Clustering analysis (d) BLAST searches

SECTION 2:SHORT QUESTIONS

1. Define domains of the protein.
2. How corona virus enters the host cells?
3. Define genomics.
4. Differentiate between genomics and proteomics.
5. What is GenBank. Describe it briefly.
6. Write a short note on protein data bank.

SECTION 3: LONG QUESTIONS

1. Describe the applications of structural biology.
2. Write a note on principle and working of x-ray crystallography.
3. Briefly describe key databases of computational biology.

INQUISITIVE QUESTIONS

1. Consider there is a pandemic of a new unknown disease, and the causative agent is a virus. You also know that virus belongs to X family. How structural biology can be helpful in preventing the disease?
2. Suppose you find an unknown protein and determine amino acid sequence by Edman degradation/mass spectrometry. How you can exploit the computational biology to predict the structure and function of the protein.
3. Homology models of macromolecules differ from experimentally determined structures of the macromolecules. Please comment.
4. Draw a flow chart to describe the steps involved in drug development till its prescription.

Chapter 8

PLANT PHYSIOLOGY

STUDENTS'LEARNING OUTCOMES

After studying this chapter, the students will be able to:

- List the macro and micronutrients of plants highlighting the role of each nutrient.
- State the examples of carnivorous plants.
- Explain the role of stomata and palisade tissue in the exchange of gases in plants.
- Relate transpiration with gas exchange in plants.
- Describe the structure of xylem vessel elements, sieve tube elements, companion cells, tracheids and relate their structures with functions.
- Describe the movement of water between plant cells, and between the cells and their environment in terms of water potential.
- Describe the movement of water through roots in terms of symplast, apoplast and vacuolar pathways.
- Explain the movement of water in xylem through TACT mechanism.
- Describe the mechanisms involved in the opening and closing of stomata.
- Explain the movement of sugars within plants.
- State movement of water into or out of the cell in isotonic, hypotonic, and hypertonic conditions.
- Explain the osmotic adjustments in hydrophytic (marine and freshwater), xerophytic and mesophytic plants and plants in saline soil.
- List the adaptations in plants to cope with low and high temperatures.
- Explain the turgor pressure and its significance in providing support to herbaceous plants.
- Describe the structure of supporting tissues in plants.
- Explain primary and secondary growth in plants.
- Justify the formation of annual rings.
- Explain influence of apical meristem on the growth of lateral shoots.
- Outline the role of important plant growth regulators.
- Explain the types of movement in plants in response to light, force of gravity, touch and chemicals.
- Define photoperiodism.
- Classify plants with examples on the basis of photoperiodism.
- Describe the mechanism of photoperiodism with reference to the mode of action of phytochrome.
- Explain the role of low temperature treatment on flower production especially to biennials and perennials.

8.1- NUTRITION IN PLANTS

Organisms require nutrition for their survival and maintenance. A **nutrient** is a substance that provides the body with essential ingredients required for metabolism. Specific nutrients, such as carbohydrates, lipids, and proteins, serve as sources of energy. Other nutrients, including water, electrolytes, minerals, and vitamins, are necessary for the metabolic process. **Nutrition** refers to the collective processes involved in the intake and utilization of nutrients for growth, repair, and maintenance of activities in an organism.

Macronutrients and Micronutrients

All autotrophic organisms need carbon dioxide and water, which supply carbon, oxygen and hydrogen. These are the predominant elements which serve as nutrients and are required by plants for the synthesis of organic molecules. There are many other nutrients that plants get from environment. The nutrients of plants can be divided into two groups.

Macronutrients are needed in relatively larger amounts. There are nine macronutrients i.e., carbon, hydrogen, oxygen, nitrogen, potassium, calcium, phosphorus, magnesium and sulphur.

- **Carbon, oxygen and hydrogen** are required for making organic compounds.
- **Nitrogen** is necessary for plant growth as it plays an essential role in energy metabolism and the production of proteins. A deficiency of nitrogen results in leaf loss and stunted growth.
- **Phosphorus** is a part of ATP. It also plays a role in promoting root growth and favours flowering in the aerial zone. A deficiency of phosphorus leads to delayed flowering, as well as the browning and wrinkling of the leaves.
- **Potassium** is involved in water regulation and the transportation of the plant's reserve substances. It enhances the ability of plants to carry out photosynthesis, reinforces cellular tissue, and stimulates the uptake of nitrates. Dark patches are formed on the leaves when there is shortage of potassium.
- **Calcium** provides stability to the cell wall and promotes the development of the cell wall. It also plays a role in cellular proliferation and maturation, and aiding in the development of seeds. Insufficient calcium leads to the development of yellow and brown patches on the leaves.
- **Magnesium** constitutes the core of the chlorophyll molecule and is therefore essential for photosynthesis. It promotes the absorption and transportation of phosphorus and also contributes to the storage of sugars within the plant. Magnesium deficiencies result in weak stalks, loss of greenness in the oldest leaves, and the appearance of yellow and brown spots.
- **Sulfur** is a fundamental element in the metabolism of nitrogen. If there is a shortage of sulfur, the plant becomes lighter in colour.

Micronutrients are needed in very smaller amounts. There are seven micronutrients i.e., iron, manganese, zinc, molybdenum, copper, chlorine, and boron.

Fertilizers are added to the soil to provide macro and micronutrients to the crops.

- **Iron** is essential for the synthesis of chlorophyll. It acts as a cofactor for several enzymes which are involved in energy

Manganese is important for the activity of antioxidant enzymes, such as superoxide dismutase (SOD), which help mitigate

transfer and nitrogen metabolism. Its deficiency results in interveinal chlorosis.

oxidative stress in plants under adverse environmental conditions.

- **Manganese** is involved in the processes of photosynthesis, nitrogen metabolism, carbohydrate metabolism and activation of enzymes. Its deficiency results in the premature falling of the leaf and delayed maturity.
- **Zinc** facilitates chlorophyll synthesis, root development and uptake of nutrients. Deficiency of zinc can lead to stunted growth.
- **Molybdenum** is critical for nitrogen fixation, nitrogen reduction, sulfur metabolism, phosphorus metabolism and iron utilization. Its deficiency can result in chlorosis of older leaves and stunted growth.
- **Copper** is necessary for lignin synthesis providing strength and rigidity to cell wall. It is involved in nitrogen metabolism, reproductive development and also acts as a cofactor for enzymes. Its deficiency can result in chlorosis, twisted leaves and stunted growth.
- **Chlorine** is involved in stomatal regulation, osmotic adjustment and transport of nutrients. Its deficiency can affect the health and growth of plants.

Nutrition in Insectivorous Plants

Some plants supplement organic molecules into their food in addition to inorganic nutrients. These organic chemicals are acquired through the process of capturing and breaking down insects and tiny animals. All insectivorous plants are true autotrophs. However, their development accelerates when they capture prey. Apparently, nitrogenous compounds of animal body are of benefit to these plants. The captured insects are broken down by enzymes that are released by the leaves. Pitcher plant, Venus fly trap and sundew are some of the known insectivorous plants.

Pitcher plant has leaves modified into a sac or a pitcher, partly filled with water **(Fig.8.1).** The leaf's terminal portion is altered to create a hood, which partially covers the exposed opening of the pitcher. It has numerous stiff hairs that prevent little insects from crawling out once they fall inside it.

Figure 8.1: Pitcher plant, insects are entrapped within the leaf.

Venus-fly trap has a "trap" consisting of two lobes that are hinged at the end of each leaf. The inner surfaces of the lobes contain **trichomes**, which are hair-like projections that trigger the lobes to close rapidly upon contact with prey **(Fig.8.2)**. The hinged traps are lined with fine bristles that interlock upon closure, preventing

the prey from escaping. The trapped insect is then digested by the enzymes secreted from the glands on the leaf surface and the products are then absorbed.


Figure 8.2: Venus-fly trap, prey is trapped between the lobes of a leaf.

Sundew catches its prey with shiny drops of "dew," where the plant's common name comes from **(Fig. 8.3)**. The leaves are covered with tiny hairs that look like tentacles. Each leaf has gland and has a single drop of dew at the tip. The insects, attracted by plant's odour are trapped by tentacles. The trapped insects are digested by enzymes and products are absorbed.

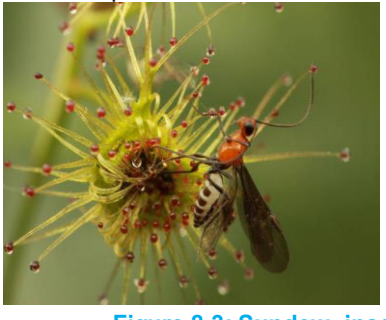
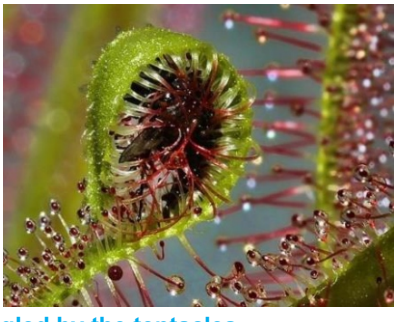



Figure.8.3: Sundew, insects are entangled by the tentacles.

8.2- Gas Exchange In Plants

Stomata (singular = stoma) are the tiny openings or pores present within the plant tissues which are necessary for gaseous exchange. These are typically found in leaves but can even be present in some stems. The stomata are surrounded by specialized cells or the guard cells that facilitate the opening and closing of the stomatal pores. Guard cells are bean-shaped and contain chloroplasts. Guard cells can open and close depending on environmental conditions. The opening and closing of stomata control the **transpiration rate** in plants.

Figure 8.4: Scanning electron micrograph (SEM) of open and closed stomata on a lavender leaf

During daylight, stomata open to allow CO_2 to enter the plant for photosynthesis. The opening of stomata is primarily regulated by guard cells. At night, when photosynthesis ceases due to lack of light, stomata typically close to conserve water. However, plants still respire, taking in O_2 and releasing CO_2. The closure of stomata at night helps minimize water loss through transpiration.

Opening and Closing of Stomata

The guard cells function as multisensory hydraulic valves **(Fig.7.4).** The two hypotheses which may explain the opening and closing of stomata are starch sugar hypothesis and influx of k^+ ion.

Starch sugar hypothesis

In 1856, German botanist H. Van Mohl proposed that guard cells in leaf epidermis are solely responsible for photosynthesis, producing sugars during the day. As sugar concentration increases in guard cells, the water potential drops. Water moves into guard cells causing them to become turgid and open the stomata. At night, photosynthesis ceases, and sugars are converted to insoluble starch or used for respiration, leading to a decline in free sugars. Consequently, water moves out of guard cells and they lose turgor pressure. So, they become flaccid and close the stomata. However, this mechanism does not fully explain the rapid turgor changes in guard cells during stomatal movements.

Influx of K^+ ion

The opening of stomata in plants is facilitated by the active transport of potassium ions (K^+) into guard cells, which reduces their osmotic potential. This influx of K^+ leads to water entering the guard cells through osmosis, causing them to become turgid and open the stomata. Blue light enhances this process by acidifying the surrounding environment, promoting K^+ uptake and subsequent water absorption. At night, K^+ passively diffuses out of the guard cells, resulting in water loss and causing the guard cells to become flaccid, thereby closing the stomata.

Palisade tissue is primarily located just beneath the upper epidermis of the leaf. It consists of elongated, tightly packed cells that are rich in. The arrangement of these cells is organized to maximize light absorption and allowing plants to efficiently convert light energy into chemical energy.

Hormones are involved in stomatal movement in plants. At high temperature when leaf cells start wilting, a hormone called abscisic acid, is released by mesophyll cells. This hormone stops the active transport of K^+ into guard cells, overriding the effect of light and CO2 concentration. So, K^+ pumping stops and stomata close.

Carbon dioxide from the atmosphere diffuses into the leaf through the stomata. Once inside, the gas travels through air spaces within the spongy mesophyll and then into the palisade mesophyll cells, where it is used in photosynthesis. Oxygen produced during photosynthesis diffuses out of

the palisade cells back through the spongy mesophyll and exits the leaf through the stomata.

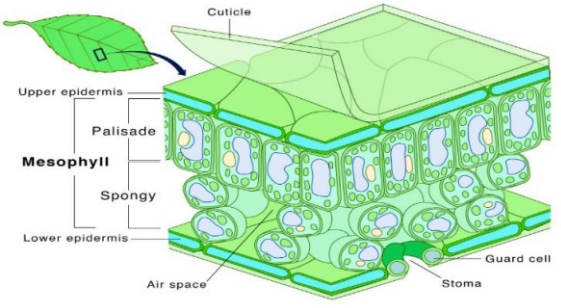


Figure 8.5: Structure of a leaf showing cuticle, epidermis, palisade mesophyll, spongy mesophyll, guard cells and stoma.

8.3- SUPPORT IN PLANTS

Supporting tissues play an important role in maintaining the structural integrity, support and flexibility of plants. These tissues consist of parenchyma, collenchyma, sclerenchyma, xylem and phloem.

1. Parenchyma

The parenchyma tissue provides support to herbaceous plants and parts of larger plants. The parenchyma cells of the epidermis, cortex, and pith absorb water. This water creates an internal hydrostatic pressure known as **turgor pressure** that maintains the rigidity of cells.

Turgor pressure arises from the elevated osmotic pressure within the cell vacuole. The membrane that surrounds the vacuole is called the **tonoplast**. It has many active transport mechanisms that move ions into the vacuole, even when the concentration within is higher than that of the surrounding fluid. Due to the elevated ionic concentration, water is drawn into the vacuole, resulting in turgidity and providing mechanical support to the plant's soft tissues.

2. Collenchyma

Collenchyma cells are specialized cells that are grouped in the form of strands or cylinders. They are found beneath the epidermis of young stems, leaf stalks and along veins in leaves. Collenchyma cells lack secondary walls. Their primary walls are thickened at the corners, due to extra deposition of cellulose. They elongate when stem or leaf grows lengthwise. They provide support to the young parts of plant in which secondary growth has not taken place.

3. Sclerenchyma

This tissue also provides structural support to the plants. Typically, the cells of sclerenchyma tissue possess thick secondary cell walls. These walls are saturated with lignin, an organic compound that confers strength and rigidity to the walls. The

majority of sclerenchyma cells are non-living. The main function of this tissue is to provide support to the various components of the plant. There are three types of sclerenchyma cells which are fibres, sclereids and vessels.

Fibers (Tracheids) are elongated and cylindrical in shape. They can be found either as compact bundles inside the xylem or as bundle caps. **Sclereids** are smaller in size as compared to fibers and are present in the seed coats and shells of nuts. Their function is to offer protection. **Vessels (Tracheae)** are long tubular structures that are joined end to end to form a long water conducting pipe in xylem.

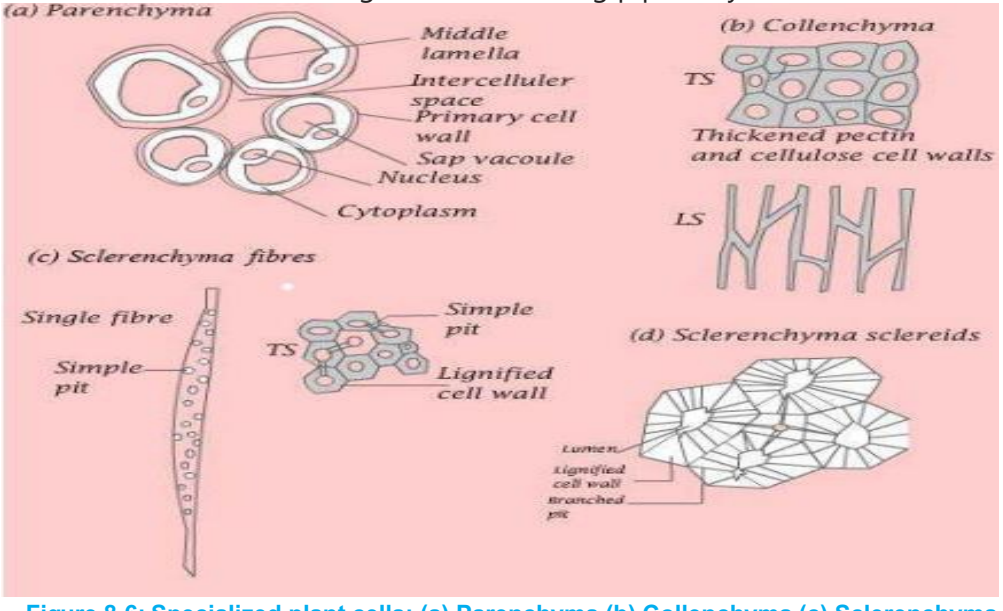


Figure.8.6: Specialized plant cells; (a) Parenchyma (b) Collenchyma (c) Sclerenchyma

8.4- WATER POTENTIAL

Water molecules possess kinetic energy which means that in liquid or gaseous form they move about rapidly and randomly from one place to another. So, greater the concentration of the water molecules in a system the greater is the total kinetic energy of water molecules. This is called water potential (symbolized by Greek letter psi = Ψ_w). In plant cells, two factors determine water potential i.e., Solute potential (Ψ_s) and Pressure potential (ΨP).

Pure water has maximum water potential which by definition is zero. Water moves from a region of higher Ψ_w to lower Ψ_w. All solutions have lower Ψ_w than pure water and so have negative value of Ψ_w (at atmospheric pressure and at a defined temperature). So, the **osmosis** can be defined as the movement of water molecules from a region of higher water potential to a region of lower water potential through a partially permeable membrane.

Solute Potential (Ψs)

The solute potential or osmotic potential is a measure of the change in water potential (Ψ_w) of a system due to the presence of solute molecules. Ψ_s is always a negative value, so if more solute molecules are present, lower (more negative) is the Ψ_s.

Pressure Potential (ΨP)

It is the part of water potential which is due to the pressure exerted by water. If pressure greater than atmospheric pressure is applied to pure water or a solution, its water potential increases. When water enters plant cells by osmosis, pressure may be built up inside the cell making the cell turgid and increasing the pressure potential.

Thus, the total water potential (Ψ_W) is sum of solute potential (Ψ_s) and pressure potential (Ψ_P):

$$\Psi_W = \Psi_S + \Psi_P$$

If we use the term water potential, the tendency for water to move between any two systems can be measured; not just from cell to cell in a plant but also from soil to root, from leaf to air and from soil to air. The steeper the potential gradient the faster is the flow of water along it.

8.5- TRANSPORT OF WATER IN PLANTS

Uptake of Water by Roots

Roots of plants provide large surface area for absorption by their extensive branching systems. You know that roots have tiny root hairs, which are actually extensions of epidermal cells of roots. Most of the uptake of water and minerals in roots takes place through root hairs.

From soil, water and minerals enter the root epidermal cells by active and passive transport. From root epidermis, they move to cortex, and then into the xylem tissue in the centre of root. Inside roots, water and minerals move in three different pathways to reach the xylem.

1. The Apoplast Pathway

It is a continuous pathway that involves a system of adjacent cell walls in the plant roots. The apoplast pathway becomes discontinuous in the endodermis in the roots due to the presence of Casparian segments.

2. The Symplast Pathway

In symplast pathway, water and minerals move through interconnected protoplasts of root cells. The protoplasts of neighbouring cells are interconnected through **plasmodesmata**, which are cytoplasmic strands that extend through pores in adjacent cell walls. The symplast pathway is less important, except for minerals in the region of endodermis.

3. The Vacuolar Pathway

In vacuolar pathway, water and minerals move through cell membranes, cytoplasm and tonoplast (membranes of vacuoles) and vacuoles. They move from vacuole to vacuole and bypass the symplast and apoplast pathways. Movement in vacuolar pathway is negligible.

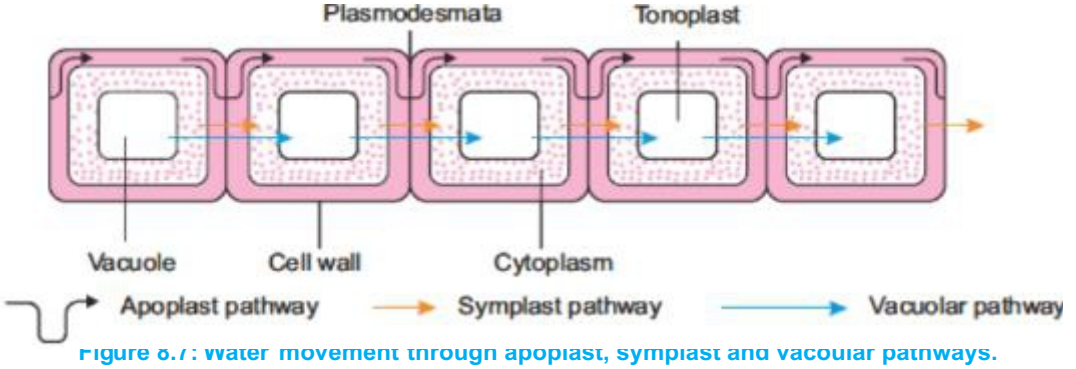


Figure 8.7: Water movement through apoplast, symplast and vacuolar pathways.

Structure of Xylem Tissue

Xylem is the vascular tissue in plants that carries water and dissolved minerals from the roots to the stem and leaves. It is also a key structural component which provides mechanical support to the plant body.

Xylem comprises of tracheids, vessels, xylem fibres and xylem parenchyma **(Fig. 8.7).**

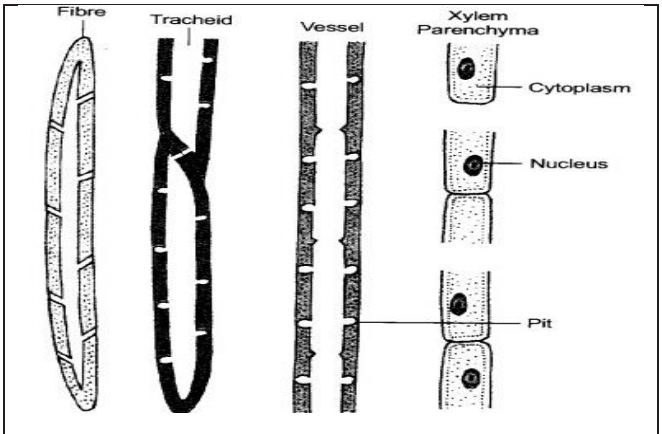


Figure 8.8: Different components of xylem tissue

Tracheids are elongate and thin cells that have thick walls made of lignin. The ends of the cells are tapered and they are linked to each other by bordered pits, which enable the lateral movement of water between cells. **Vessels** are shorter and broader compared to tracheids. They are arranged in a linear fashion, forming continuous channels. Perforation plates are present at the outer edges of these structures, enabling efficient movement of water. **Xylem fibres** are elongated cells with thickened lignified walls. At maturity, they are dead and enhance the structural integrity of the xylem. They offer additional structural support to the plant. **Xylem parenchyma** are living cells with thin walls that have the ability to retain and hold nutrients and water. Xylem parenchyma cells participate in the lateral translocation of water and nutrients and can also contribute to the healing and regeneration of xylem tissue.

The Movement of Water through Xylem

The movement of water within plants, from roots to leaves, occurs primarily through specialized vascular tissue known as xylem. The TACT (Transpiration, Adhesion, Cohesion, Tension) mechanism is a widely accepted model explaining how water moves against gravity through the xylem to reach all parts of the plant. This mechanism depends on both physical and chemical properties of water and the plant's interaction with its environment.

Transpiration is the process by which water evaporates from the surface of plant leaves, specifically through stomata. As water vapour exits the leaf, a **negative pressure** is generated within the leaf tissue. This negative pressure creates a pulling force, drawing water upward from the roots through the stem and toward the leaves. Transpiration, therefore, act as the primary driving force behind water transport in the xylem.

Adhesion is the attraction between water molecules and the walls of the xylem vessels. Due to this attraction, water molecules stick to the walls of xylem vessels as they move upward. This property prevents any break in the water column within xylem. Adhesion thus play a crucial role in maintaining the continuity of the water column, especially in tall plants where gravity exerts a significant downward force on the water column.

Cohesion refers to the attractive force between water molecules themselves, caused by hydrogen bonding. Water molecules within the xylem stick together, forming an unbroken column from the roots to the leaves. This cohesive property of water ensures that the **"pull"** initiated by transpiration at the leaf level extends down through the entire water column.

Tension is the negative pressure created by the pulling force of the transpiration at the leaf level. As water evaporates from the leaf surface, it creates a low-pressure area that extends through the xylem. This tension pulls the cohesive water column upwards. Tension is therefore vital for the continuous ascent of water within the xylem.

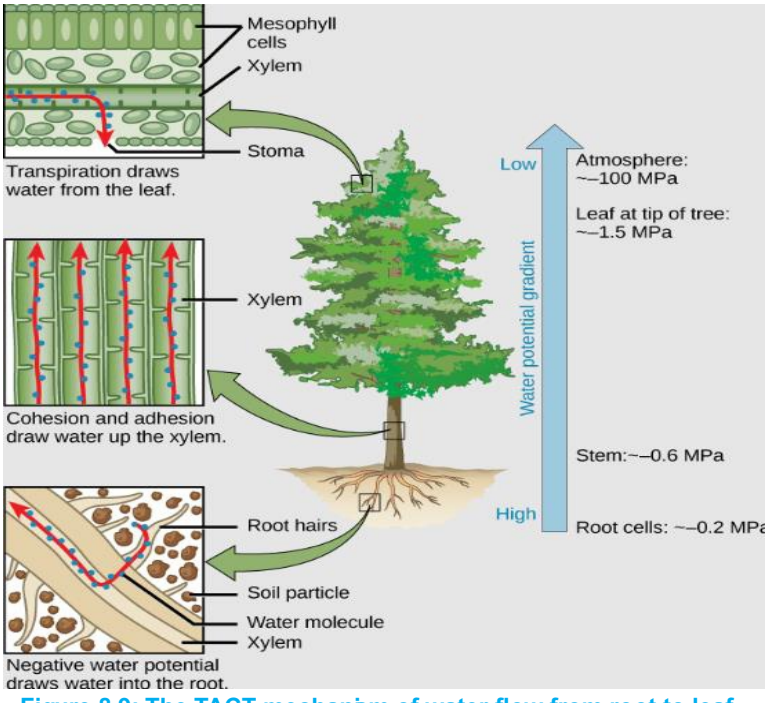


Figure 8.9: The TACT mechanism of water flow from root to leaf.

8.6- TRANSLOCATION OF FOOD IN PLANTS

Structure of Phloem

Phloem is a vascular tissue in plants responsible for the transport of organic nutrients, particularly the products of photosynthesis, from the leaves to other parts of the plant where they are needed or stored. The phloem is generally found on the outer side of both primary and secondary vascular tissue in plants with secondary growth. The phloem constitutes the inner bark.

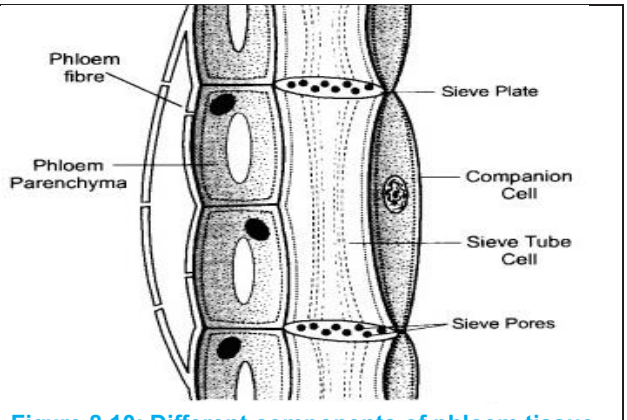


Figure 8.10: Different components of phloem tissue.

Phloem comprises of sieve elements, companion cells, phloem fibres and phloem parenchyma **(Fig. 8.10).**

The cells of phloem that transport sugars and other organic material throughout the plant are called **sieve tube elements or cells**. Sieve tube elements have **'sieve areas'**, which are the portions of the cell wall where pores interconnect

the sieve tube elements. Some of the sieve areas are generally formed in end walls of sieve tube elements where the individual cells are joined together to form a longitudinal series called a **sieve tubes**. Each sieve tube element is associated with one or more companion cells. Sieve tube elements and companion cells are in communication with each other by plasmodesmata. Companion cells supply ATP and proteins to sieve tube elements. **Phloem parenchyma** stores substances, such as sugars, resins, latex, and mucilage, which are important for plant defence and moisture retention.

Mechanism of Translocation

The transport of sugars in plants takes place through phloem tissue. Passive theories of phloem transport include:

Diffusion is far too slow, to account for the velocities of sugar movement in phloem, which on the average is 1 meter per hour, while the rate of diffusion is 1 meter per eight years.

Pressure flow theory: The pressure-flow theory, also known as the mass-flow hypothesis, is the most widely accepted explanation for the transport of sugars in plants through the phloem. This process of translocation moves sugar from the **source** (where they are synthesized) to the **sink** (where they are consumed or stored). This theory was proposed by **Ernst Munch** in 1930. This theory relies on the principle of osmotic pressure differences between source and sink regions. Following steps explain the pressure-flow theory.

1. The glucose formed during photosynthesis in mesophyll cells, is used in respiration. The excess of glucose is converted into non-reducing sugar i.e., sucrose.
2. Sucrose is actively transported from mesophyll cells to the companion cells of phloem. From here, sucrose diffuses to sieve tubes, through plasmodesmata. So, the concentration of sucrose in sieve tubes increases.
3. Due to higher sucrose (solute) concentration in sieve tubes, water moves into them by osmosis from the nearby xylem of leaf. It results in an increase in the water potential at the source end of sieve tubes.
4. At the sink end, sugar is actively unloaded from sieve tubes and water also follows by osmosis. The exit of water lowers the water potential at the sink end. So, there is a higher water potential at the source end while a lower water potential at the sink end.
5. The difference in water potential causes water to flow from source to sink. Since sucrose is dissolved in water, it is carried along from source to sink along with water.

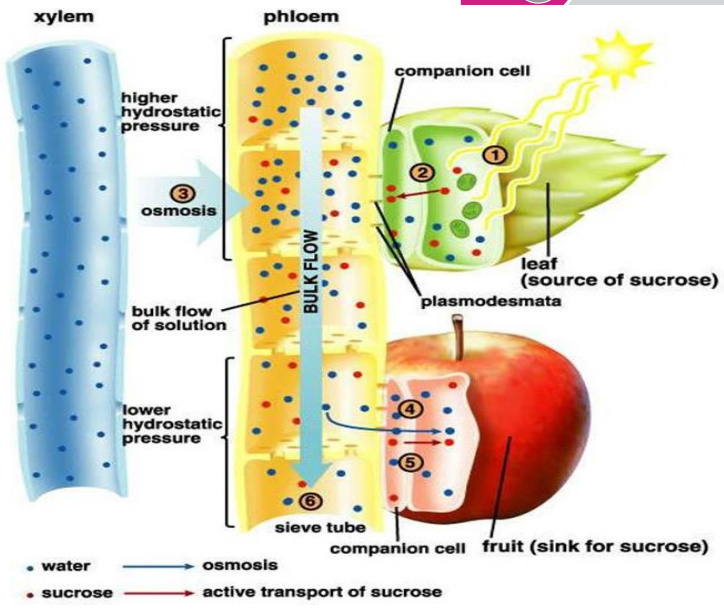


Figure 8.11: The pressure-flow theory

8.7- GROWTH IN PLANTS

Growth in plants refers to a permanent increase in size, which can occur in various dimensions such as height, width, and mass. Throughout life, the plant adds organs such as branches, leaves, and roots. Its organs increase in size from the tips but the rate of growth is not uniform throughout the body. In lower plants, the entire plant body is capable of growing, but in higher plants, growth is limited to certain regions known as **growing points**. These growing points consist of groups of cells, called **meristems**, that are capable of continuous cell division.

Types of Meristems

There are three types of meristems in plants i.e., apical meristems, intercalary meristems and lateral meristems **(Fig.7.13)**.

Apical meristems are found at the tips of roots and shoots. They are primarily responsible for the extension of the plant body. These are perpetual growth zones found and are responsible for the increase in the number of cells at the tips of roots and stems. They play an important role in primary growth.

Intercalary Meristems are separated from the apex by permanent tissues. They are situated at the bases of internodes in many plants such as grasses and play an important role in the production of leaves and flower. These are temporary.

Lateral meristems are cylinders of dividing cells present along the peripheral regions. They are responsible for growth in thickness of stems and roots. They are found in woody plants and are crucial for secondary growth. There are two main forms of lateral meristems; vascular cambium and cork cambium. **Vascular cambium** is

located between the xylem and phloem and is responsible for production of secondary xylem and secondary phloem. **Cork cambium** is formed in the outer layer of stems and roots. This tissue produces cork cells which replace the epidermis and forms the outer protective bark.

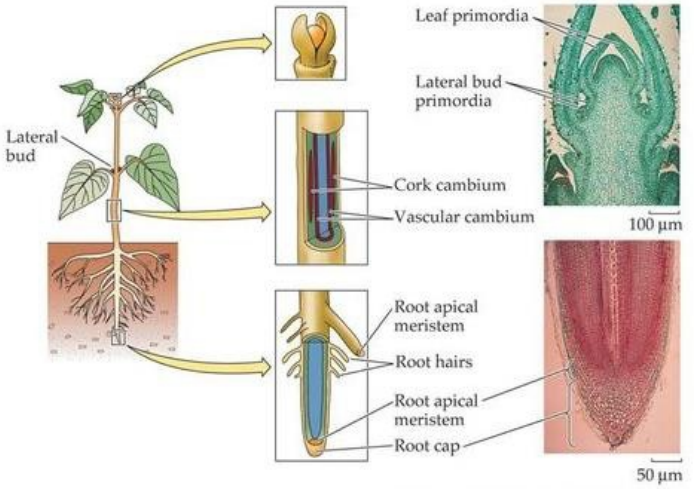


Figure 8.12: Apical meristem produces the primary plant body and lateral meristem produces the secondary plant body.

Types of Growth

In plants, there are two types of growth i.e., primary growth and secondary growth **(Fig.7.14)**.

Primary Growth

Primary growth is responsible for an increase in the length of the plants. It is facilitated by the activity of apical meristems. Herbaceous plants generally display primary growth with little secondary growth as compared to woody plants.

The process of primary growth in plants occurs in three phases.

1. **Cell Division:** The cells of apical meristems undergo divisions and the number of cells is increased. It happens at the tips of apical meristems of root and shoot. The area of apical meristem where cell division occurs, is called **zone of cell division** In this zone, cells are non-vacuolated and small. These cells have spherical nuclei in the centre of cytoplasm.
2. **Cell Elongation:** After the formation of new cells, their volume increases due to uptake of water. Plasticity of cell wall increases and wall pressure is reduced. It happens at a little distance from the tips of apical meristems. The area where cell elongation occurs, is called **zone of cell elongation**. In this zone, cells are vacuolated and large. They have nuclei in the peripheries of cytoplasm. During this phase, different cells elongate in different dimensions and the final size of cells is attained. For example, the cells which are determined to develop into pith, cortex

etc. do not elongate much length-wise while the cells which are determined to develop into xylem tissue elongate more length-wise.

3. **Cell Differentiation:** After the cells have got their final size and shape, elongation stops and cells are specialized to perform specific functions. Their cell walls become thicker and many new structural features develop. It happens in the area next to the zone of elongation. This area is called zone of cell differentiation. In this zone, cells are fully differentiated and each type of cell performs specific function.

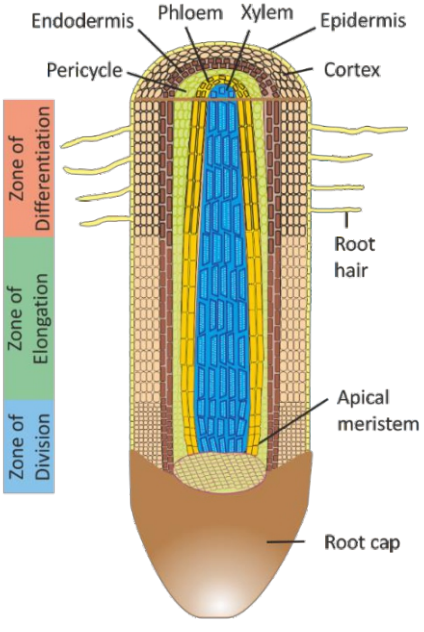


Figure 8.13: Primary growth in a root

Secondary Growth

Secondary growth refers to the increase in thickness or girth of stems and roots. It is due to the activity of lateral meristems, specifically the vascular cambium and cork cambium. It is more prominent in woody perennial plants, while herbaceous plants show only primary growth.

The cells of vascular cambium divide and produce new cells on both of its outer and inner margins. Cells produced on outer margins of vascular cambium make secondary phloem while the cells produced on its inner margins make secondary xylem. Secondary tissues (particularly secondary xylem) cause increase in plant's thickness. Division in cork cambium produces cells on both outer and inner sides. These cells make new cork. The region of mature stem outside of the vascular cambium, which contains secondary phloem, cork cambium and cork, is collectively called bark.

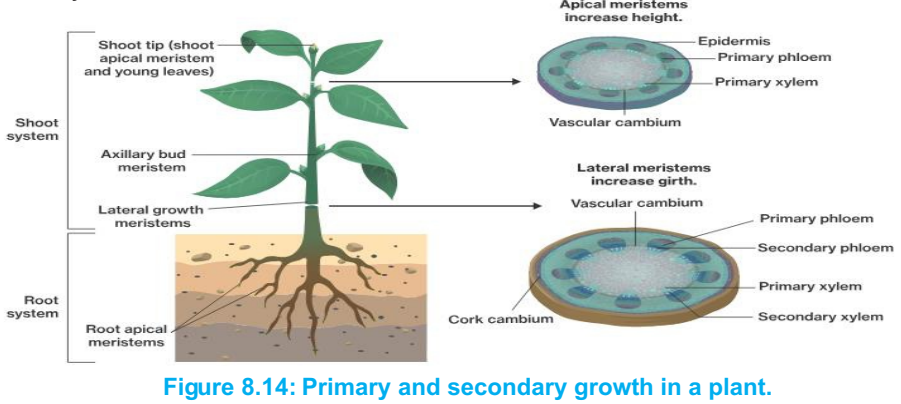


Figure 8.14: Primary and secondary growth in a plant.

Annual rings are formed due to the seasonal activity of the cambium layer in trees. This process is influenced by environmental factors and results in the production of two distinct types of wood each year: **spring wood** (early wood) and **autumn wood** (late wood). These rings provide valuable information about the age of the tree and the environmental conditions experienced during each growing season.

Dendrochronology is the scientific method of dating and studying tree rings to analyse past climate conditions and events.

The cambium is a meristematic tissue that generates new vascular tissues i.e., xylem and phloem. In spring, when conditions are favourable, the cambium is highly active, producing a large volume of xylem with wider vessels, resulting in lighter-coloured spring wood. As the season changes to autumn, the cambium's activity decreases. It produces fewer xylem elements, which are narrower and denser, leading to the formation of darker autumn wood. The combination of spring wood and autumn wood forms a complete annual ring. Each year, a new ring is added, allowing for the determination of a tree's age through dendrochronology.

The transition between these two types of wood is gradual from spring to autumn, but the shift from autumn back to spring in the following year is abrupt, marking a clear distinction between the growth periods. This data is valuable for studying long-term climate variability and changes.

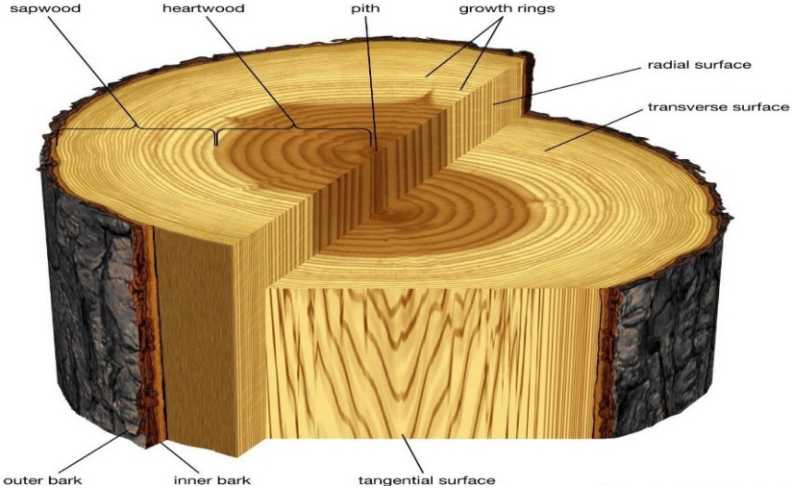


Figure 8.15: Anatomy of a tree trunk showing annual rings

Plant Growth Regulators

Plants regulate the rates of growth and the rate of metabolism in their cells. Special chemical messengers, called plant growth regulators or **plant hormones** regulate their growth. There are five major groups of plant growth regulators i.e., auxins, cytokinins, gibberellins, abscisic acid, and ethylene.

Auxins

These are indole acetie acid (IAA) or its variants. These regulate following activities:

- In stem, promote cell enlargement in region behind apex.
- Promote cell division in cambium.
- In root, promote growth at very low concentrations. Inhibit growth at higher concentrations, e.g., geotropism. Promote growth of roots from cuttings and calluses.
- Promote bud initiation in shoots but sometimes antagonistic to cytokinins and is inhibitory.
- Promote apical dominance and fruit growth. They can sometimes induce parthenocarpy.
- Cause delay in leaf senescence (aging) in a few species.
- Inhibit abscission.

Gibberellin

Gibberellins are produced in the apical portions of roots and shots, and transported to other parts. Gibberellins contain Gibberellic acid and there are more than 110 different gibberellins. They preform following activities:

- Promote cell enlargement in the presence of auxins. Also promote cell division in apical meristem and cambium.
- Promote 'bolting' of some rosette plants.
- Promote bud initiation in shoots of chrysanthemum callus.
- Promote leaf growth and fruit growth. May induce parthenocarpy.
- In apical dominance, enhance action of auxins.
- Break bud and seed dormancy.
- Sometimes may substitute for red light. Therefore, promote flowering in long-day plants, while inhibit in short-day plants.
- Cause delay in leaf senescence in a few species.

Cytokinins

They are usually produced in roots, young fruits, and in seeds. Cytokinins promote cytokinesis during cell division. They increase the rate of DNA replication and the rate of RNA and protein synthesis. They perform the following:

- Promote stem growth by cell division in apical meristem and cambium.
- Inhibit primary root growth.
- Promote lateral root growth.
- Promote bud initiation and leaf growth.
- Promote fruit growth but can rarely induce parthenocarpy.
- Promote lateral bud growth, also break bud dormancy.
- Cause delay in leaf senescence.

- Promote stomatal opening.

Abscisic acid

Abscisic acid (ABA) is synthesized mainly in mature green leaves, fruits, and root caps. It performs the following functions:

- Inhibits stem and root growth notably during physiological stress, e.g., drought, and waterlogging.
- Promotes bud and seed dormancy.
- Promotes flowering in short day plants, and inhibits in long day plants (antagonistic to gibberellins).
- Sometimes promotes leaf senescence.
- Promotes abscission.
- Promotes closing of stomata under conditions of water stress (wilting).

Ethylene

It is a natural product of the metabolism of plants. Inhibits stem growth, notably during physiological stress.

- Inhibits root growth.
- Breaks dormancy of bud.
- Promotes flowering in pineapple.
- Promotes fruit ripening.

8.8- OSMOREGULATIONIN PLANTS

Osmoregulation refers to the process by which an organism maintains a stable internal equilibrium of water and dissolved substances, irrespective of the surrounding environmental conditions. Many marine organisms undergo osmosis without the requirement for regulatory systems since their cells have the same osmotic pressure as that of the sea. However, some organisms must actively acquire, retain, or eliminate water or salts in order to regulate their internal water and mineral balance.

Types of Solutions

Hypotonic solution: A solution having reduced solute concentration relative to the intracellular environment of a cell. As a result, water enters the cell by osmosis resulting in the swelling.

Hypertonic solution: A solution having high solute concentration relative to the intracellular environment of a cell. As a result, water moves out of the cell which causes the cell to shrink due to loss of water, a condition called **plasmolysis**

Isotonic solution: A solution whose solute concentration resembles to the intracellular environment of the cell. Net movement of water between the cell and its environment is zero in this case.

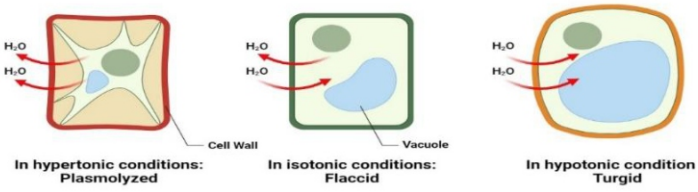


Figure 8.16: Effect of Hypertonic, Hypotonic and isotonic solution to plant cell.

Osmotic Adjustments in Plants

Plants are distributed in different habitats of aquatic, moderate, severely dry terrestrial and saline nature, thus termed as hydrophytes, mesophytes, xerophytes and halophytes, respectively.

Hydrophytes are adapted to aquatic environments, including marine and freshwater ecosystems, through specialized osmotic adjustment mechanisms. **Marine hydrophytes** thrive in saline (hypertonic) conditions, where water tends to leave their cells. They excrete excess salts using specialized salt glands and synthesize organic solutes like proline, glycine betaine, and sugars to retain water by increasing their internal osmotic potential. They have thick cuticles which further reduce water loss, and they exhibit halophytic traits to tolerate high salinity. **Freshwater hydrophytes** grow in hypotonic environments, where water continuously enters their cells. These plants expel excess water through structures like hydathodes or vacuoles to avoid overhydration. They actively absorb essential ions, such as potassium and calcium, to maintain osmotic balance and compensate for the dilute surroundings. With thin or absent cuticles, these plants facilitate water exchange and often have reduced root systems, relying on direct nutrient and water absorption from their environment. Examples of hydrophytes are water lilies, lotus, seaweeds and tape grass **(Fig. 8.17).**

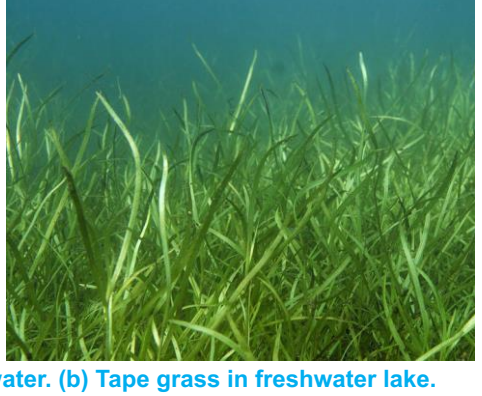


Figure 8.17: (a) Waterlily floating in freshwater. (b) Tape grass in freshwater lake.

Mesophytes live in moderate environments that are neither too dry nor too wet. They prefer soil that is not waterlogged and has a moderate salt content and humidity. Mesophytes have well-developed roots and shoots with a fully formed vascular system. They do not require any special adaptations to survive. Their leaves

are flat, broad, and green with stomata on the surface. Examples of mesophytes include rose, tomatoes, and daisies **(Fig.8.18)**.

Figure 8.18: Examples of mesophytes, left (rose) and right (daisy).

Xerophytes are plants that are adapted to survive in dry conditions. They have special adaptations to minimize water loss and store water. Plants that store water are known as **succulents** They possess fleshy stems that can store water and used when needed. Other adaptations in xerophytes include waxy coatings on leaves to reduce water loss, leaf dropping during dry periods, and leaf folding or repositioning to absorb sunlight efficiently. Examples of xerophytes include thorn trees, desert marigold, and blue agave **(Fig. 8.19)**.

Figure 8.19: A xerophytic plant

Halophytes inhabit saline soil with high concentrations of salts like NaCl, $MgCl_2$, $MgSO_4$, or saline water. On such a substratum, only such plants can grow which can tolerate a relatively high concentration of these salts. These plants have succulent leaves and sometimes the stem is also succulent. In certain cases, leaves are modified into spines. Examples of halophytes are sea arrowgrass and sea lavender.

Figure 8.20: Sea Arrowgrass

Halophytes growing in marshy places near seashore form a special vegetation known as the mangrove or tidal woodland. These are also called Helophilous halophytes.

7.9- THERMOREGULATION IN PLANTS

Thermoregulation is a homeostasis in which organisms maintain their body temperature despite variations in environmental temperature. **High temperature** denatures the enzymes and damages the metabolism. Plants use evaporative cooling to cope with high temperature. Hot and dry weather, however, causes water deficiency resulting in closing of stomata, thus plants suffer in such conditions. Most plants have adapted to survive in heat stress as the plants of temperate regions face the stress of 40°C and higher temperature. The cells of these plants synthesize large quantities of special proteins called **heat-shock proteins** These proteins embrace enzymes and other proteins thus help to prevent their denaturation.

Low temperature, on the other hand alters the fluidity of the cell membrane, because lipids of the membrane become locked into crystalline structures, which affects the transport of the solutes. The structure of the membrane proteins is also affected. Plants respond to cold stress by increasing proportion of unsaturated fatty acids, which help membrane to maintain structure at low temperature by preventing crystal formation. This adaptation requires time. Because of this reason, rapid chilling of plants is more stressful than gradual drop in air temperature. Freezing temperature causes **ice crystal formation**. The confinement of ice formation around cell wall does not affect as badly and plants survive. However, formation of ice crystals within protoplasm perforates membranes and organelles hence killing the cells. The plants native to cold region such as oaks, maples, roses and other plants have adapted to bring changes in solutes composition of the cells, which causes cytosol to super cool without ice formation, although ice crystals may form in the cell walls.

7.10- MOVEMENTS IN PLANTS

Organisms react to both external and internal stimuli. Animals may exhibit locomotion in reaction to stimuli but the plants are fixed, hence they can only alter their growth pattern.

Tropic movements: The growth movements in plants that are triggered by a stimulus, are collectively called tropic movements or tropisms. Such movements occur as a curvature of whole organ towards or away from stimuli such as light, touch, chemical, water and gravity. Following are the major types of tropic movements in plants:

1. **Phototropism**: It is the movement of part of plant, in response to stimulus of light and is caused by the differential growth of part of a plant like stem or root. The tips of shoots usually show positive phototropism while roots show negative phototropism.
2. **Geotropism**: It is the movement of plant parts in response to gravity. Roots display positive geotropism and shoots negative geotropism.
3. **Thigmotropism**: It is the movement in response to stimulus of touch, for example climbing vines. When they come in contact with some solid object, the growth on the opposite side of contact increases and the tendril coils around the support.
4. **Chemotropism**: The movement in response to some chemicals is called chemotropism. The hyphae of fungi are chemotropic.

7.11 - PHOTOPERIODISM

The response to changes in day length that enables plants to adapt to seasonal changes in their environment is termed as **photoperiodism**. Simply, it is response of plants to the length of day and night.

Effect of photoperiodism was first studied in 1920 by Garner and Allard. They studied that tobacco plant flowers only after exposure to a series of short days. Tobacco plant naturally flowers under same conditions, in autumn, but flowering could be induced by artificially exposing to short days. With further studies they were able to classify flowering plants into **long-day plants**, which require long days for flowering, **short-day plants**, which require short days for flowering and **day-neutral plants** which flower without being influenced by photoperiod. Later on, further studies indicated that it is really the length of the dark period which is critical. Thus, short-day plants are really long-night plants. If they are grown in short days, but the long night is interrupted by a short light period, flowering is prevented. Long-day plants will flower in short days if the long night period is interrupted.

Mechanism of Flower Induction

Phytochrome, a photoreceptor protein exists in two forms i.e., P_{660} and P_{730}. P_{660} is a quiescent form. It absorbs red light at a wavelength of 660 nm and is converted to active P_{730} which absorbs far red light at 730 nm and is converted to P_{660}. In nature, the P_{660} to P_{730} conversion takes place in day light and P_{730} to P_{660} conversion occurs in the dark. The rate at which P_{730} is converted to P_{660} provides the plant with a **"clock"** for measuring the duration of darkness.

It has been found that red light inhibits flowering in short-day plants but promotes flowering in long-day plants, under conditions during which flowering normally takes place. This observation led to the hypothesis that the P_{730}-P_{660} interconversion might be the plant time-regulator for flowering. According to this hypothesis, P_{730}, converted from P_{660} by the absorption of red light, would inhibit flowering in short day plants but promote flowering in long day plants. Because P_{730} accumulates in the day and diminishes at night, short day plants could flower only if the night were long enough, during which a great amount of P_{730} would not be completely inactivated, so that enough P_{730} would remain at the end of night to promote flowering. But now it is generally agreed that the time measuring phenomenon of flowering is not totally controlled by the interconversion of P_{660} to P_{730}. Other factors, like presence or absence of light and length of dark or light period also play an important role in flowering. The biological clock once stimulated causes production of **florigen** hormone in leaves, which travels through phloem to the floral buds, initiating flowering.

Table7.2: Classification of plants according to photoperiodic requirements for flowering

Short-day plants (SDPs)	Long-day plants (LDPs)	Day-neutral plants (DNPs)
Flowering induced by dark periods longer than a critical length, e.g., cocklebur 8.5 h; tobacco 10-11h.	Flowering induced by dark periods shorter than a critical length, e.g., henbane 13h.	Flowering independent of photoperiod.
Examples include cocklebur (Xanthium), chrysanthemum, soyabean, tobacco, strawberry.	Examples include henbane (Hyoscyamus niger), snapdragon, cabbage, spring wheat, spring barley	Examples include cucumber, tomato, garden pea, maize, cotton.

7.12- VERNALISATION

Biennial and perennial plants are stimulated to flowering by exposure to low temperature. This is called **vernalisation**. The low temperature stimulus is received by the shoot apex of a mature stem or embryo of the seed but not by the leaves as in photoperiodism.

For some plants, vernalisation is an absolute requirement while in some cases it simply assists in inducing flowering. The duration of low temperature (chilling) treatment required varies from four days to three months. Temperature around 4°C is found to be very effective in this regard. It stimulates the production of a hormone "**vernalin**" which induces vernalisation. Photoperiodism and vernalisation serve to synchronise the reproductive behaviour of plants with their environment, ensuring reproduction at favourable times of year. They also ensure that members of the same species flower at the same time, encouraging cross pollination for genetic variability.

EXERCISE

SECTION 1: MULTIPLE CHOICE QUESTIONS

1. Process by which water evaporates from surface of leaf primarily through stomata:
   (a) Transpiration (b) Guttation (c) Imbibition (d) Cohesion
2. Through which structure does most of transpiration occurs?
   (a) Root hairs (b) Phloem (c) Xylem (d) Stomata
3. The TACT theory primarily explains
   (a) The movement of nutrients in the plants
   (b) The transport of water in plants
   (c) The absorption of minerals
   (d) The process of photosynthesis
4. Which of the following is not a function of xylem?
   (a) Transport of water (b) Transport of minerals
   (c) Transport of food (d) Mechanical support
5. Which of the following has a perforated cell wall?
   (a) Vessel (b) Fibre (c) Tracheid (d) Sclereid
6. Exposure to low temperature stimulates the process of flowering in biennial or perennial plants:
   (a) Dormancy (b) Photoperiodism (c) Vernalization (d) All of above
7. Plants that are adapted to survive in dry conditions:
   (a) Xerophhytes (b) Hydrophytes (c) Mesophytes (d) Halophytes
8. When sugar content in a cell increases the concentration of solute increases, what happens to the water potential?
   (a) Raises (b) Drops (c) Unchanged (d) None of these
9. In higher plant, transport of food materials occurs through;
   (a) Companion cells (b) Sieve tubes
   (c) Vessel elements (d) Tracheids
10. The plant hormone which inhibits the stem and root growth is
    (a) Auxin (b) Ethylene (c) Cytokinin (d) Gibberellin
11. The leaves of some hydrophyte float on the surface of water. In such a leaf, stomata are found in;
    (a) Lower epidermis (b) Upper epidermis
    (c) Sides of leaf (d) Deep depressions in leaf

12. Mesophytes are adapted to survive in:

(a) Moderate environments (b) Dry conditions

(c) Water environments (d) All of above

SECTION 2:SHORT QUESTIONS

1. Differentiate between macronutrients and micronutrients?
2. What is water potential?
3. What are the main three pathways for the movement of water between plant cells?
4. Differentiate between hypertonic and hypotonic solution?
5. What are halophytes?
6. Differentiate between long day plants and short day plants?
7. Write down the phases of plant growth?
8. Differentiate between Vernalin and Florigen.
9. Differentiate between Thigmotropism and Geotropism.
10. How intercalary meristem is different from apical meristem?

SECTION 3: LONG QUESTIONS

1. Describe osmoregulation in Hydrophytes and Halophytes?
2. Describe the Physiological adaptation of plants to extreme conditions. How do plants adjust their cell membrane composition and protein structures to survive high and low temperatures?
3. What is the role of meristem in the growth of plants?
4. Describe the mechanism of opening and closing of stomata?
5. Explain the concept of photoperiodism and its influence on plant flowering. How do short-day, long-day and day-neutral plants differ in their flowering responses, and what role does phytochrome plays in this process?

INQUISITIVE QUESTIONS

1. Can you explain the hypothesis regarding the opening and closing of stomata?
2. What mechanisms enable carnivorous plants to supplement their nutrient uptake despite being autotrophs?
3. How can you say that parenchyma and schlerenchyma provide support to plants?
4. How do the annual rings depict climatic variability?
5. How does Pressure Flow Theory explain the movement of sugars through a plant?
6. What strategies would you adopt to induce flowering in a plant?

Chapter 9

HUMAN DIGESTIVE SYSTEM

STUDENTS'LEARNING OUTCOMES

After studying this chapter, the students will be able to:

- Describe the mechanical and chemical digestion in the oral cavity
- Explain swallowing and peristalsis.
- Illustrate with a diagram the structure of the stomach and relate each component with the mechanical and chemical digestion in the stomach.
- Identify the role of the nervous system and gastrin hormone on the secretion of gastric juice.
- Describe the major actions carried out on food in the three regions of the small intestine.
- Trace the absorption of digested products from the small intestine lumen to the blood capillaries and lacteals of the villi.
- Describe the component parts of large intestine with their respective roles.
- Correlate the involuntary reflex for egestion in infants and the voluntary control in adults.
- Explain the storage and metabolic role of the liver.
- Describe composition of bile and relate the constituents with respective roles.
- Outline the structure of pancreas and explain its function as an exocrine gland.
- Relate the secretion of bile and pancreatic juice with the secretin hormone.

Digestion is the process by which the body breaks down food into smaller, absorbable components. Digestion is crucial for converting food into energy and raw materials required for growth, repair and maintenance of body functions. It supports the immune system, provides essential nutrients and ensures overall health. Efficient digestion prevents nutrient deficiencies, supports metabolism and maintains energy levels, making it vital for sustaining life.

9.1- ANATOMY & PHYSIOLOGYOF DIGESTIVE SYSTEM

The human digestive system is composed of the **gastrointestinal** (GI) tract and accessory digestive organs. The GI tract is a continuous tube that extends from mouth to anus. It includes oral cavity, pharynx, oesophagus, stomach, small intestine and large intestine. The accessory digestive organs include the salivary glands, liver, gallbladder and pancreas.

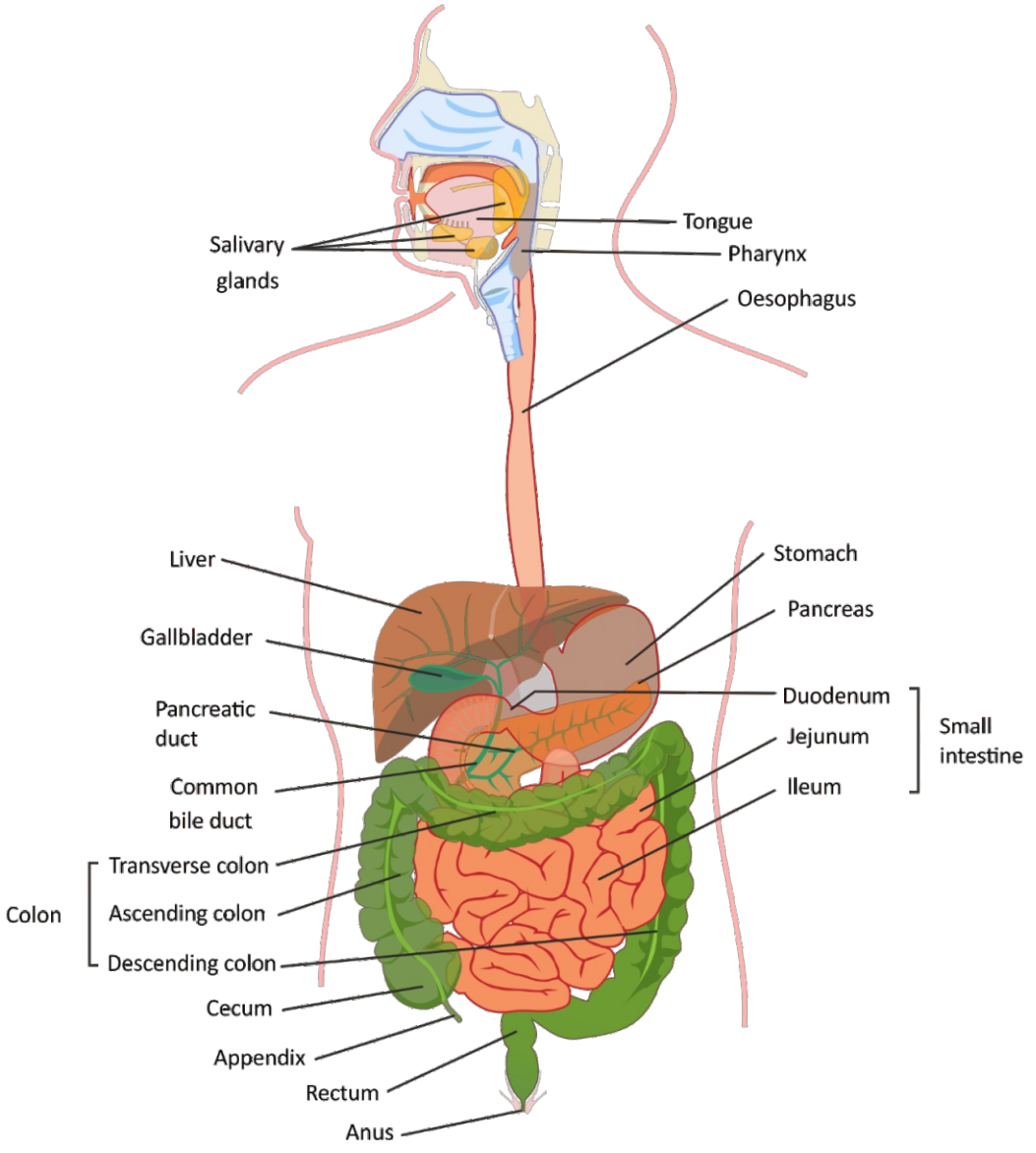


Figure 9.1: Human digestive system

Oral Cavity

It is a cavity immediately after the opening of mouth. **Lips** are made of highly vascularized, skeletal muscle tissue with many sensory nerve endings. Lips help to retain food as it is being chewed. They also play a role in phonation (the modification of sound). The important functions performed by oral cavity are as follows:

Selection of food: The muscular tongue is plays role in the selection of food through its taste buds. When food enters the oral cavity, it is tasted and physically felt. If the

taste or smell is unpleasant or if hard objects like bone or dirt are present in the food, it is rejected. The senses of smell and sight also play role in the selection of food.

Mechanical digestion of food: The ingested food is physically broken down by the teeth through a process called **mastication** (chewing). Chewing reduces food into smaller and more manageable pieces, increasing the surface area for enzymatic action.

Chemical digestion of food: As the chewing of food goes on, the salivary glands pour their secretion, **saliva**, into oral cavity. Palate, tongue and cheeks help in the mixing of chewed food with saliva. There are three pairs of salivary glands which pour saliva into oral cavity. These three pairs are; **sublingual** glands situated below tongue, **submaxillary** glands located behind jaws, and **parotid** glands located in front of ears.

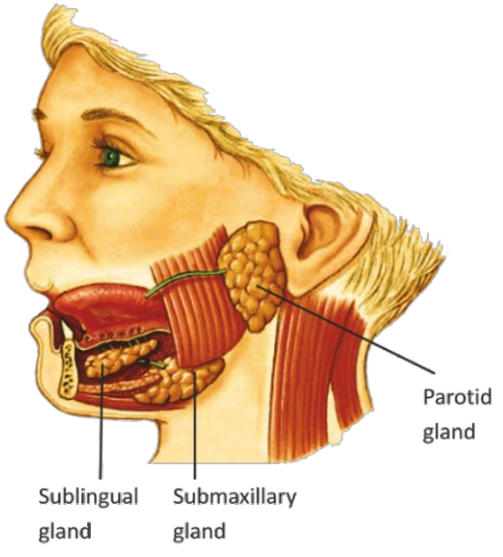


Figure 9.2: Location of salivary glands

Saliva contains water and mucus that moisten and lubricate the food. Saliva also contains bicarbonate ions, which buffer chemicals in the oral cavity, and thiocyanate ions, which kill microorganisms. Fresh saliva is alkaline (pH: 8) but it quickly loses CO_2 and gets pH 6. Saliva also contains an enzyme, **salivary amylase** It partially digests the polysaccharides (starch and glycogen) to disaccharides (maltose). After the mechanical and chemical digestive processes in the oral cavity, food mass is in the form of a small moist mass called a **bolus**.

Pharynx

The pharynx is a cavity behind the mouth. It is the common passageway for both the digestive and respiratory tracts. The bolus is pushed to the back of the mouth and is swallowed through the pharynx.

Swallowing of food: During swallowing, the tongue moves upwards and backwards against the roof of the mouth. Due to it, the bolus is forced to the back of oral cavity. The soft palate is also raised against the back wall of pharynx. These movements close the passage between nasal cavity and pharynx. At the same time, the larynx moves upward and it lowers the **epiglottis** (a flap of cartilage) and closes the opening of trachea. In this way, the bolus passes over the trachea and enters oesophagus.

The beginning of the swallowing action is voluntary, but once the food reaches the back of the mouth, swallowing becomes automatic.

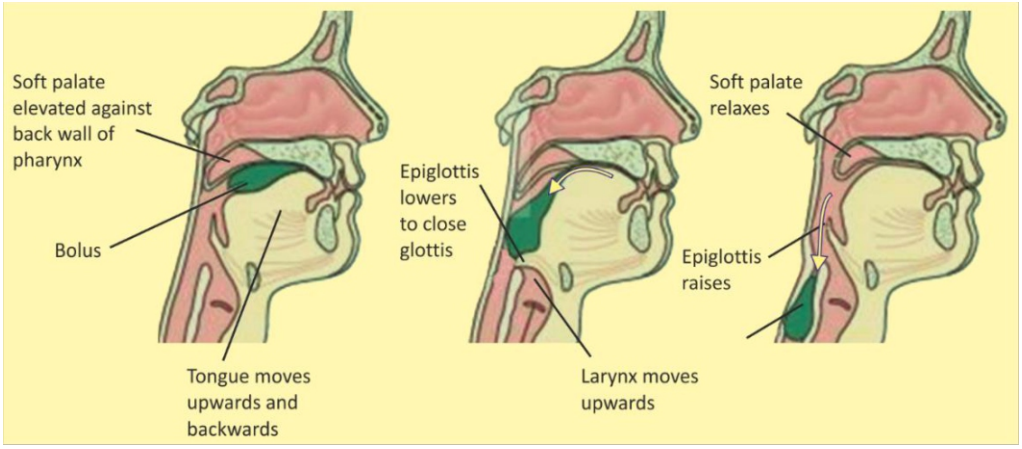


Figure 9.3: Swallowing of food

Oesophagus

After being swallowed, the food enters the tube called oesophagus. It connects the pharynx to the stomach. The previous digestive actions of saliva continue in oesophagus. In adult human, the oesophagus is about 25 cm long and its lower end opens in stomach. Food moves down through the oesophagus to the stomach by **peristalsis** The exit of food from the oesophagus to the stomach is controlled by the **lower oesophageal sphincter** or **cardiac sphincter**, which opens in response to the pressure exerted by food. It also prevents the backflow of stomach contents into the oesophagus.

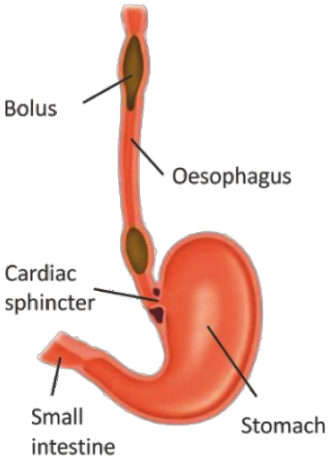


Figure 9.4: Oesophagusand its connections

Motility of Alimentary Canal

The following two types of movements occur in alimentary canal.

Peristalsis: It is the rhythmic sequence of waves of contraction in the smooth-muscles of the walls of alimentary canal. Peristalsis squeezes the food down along oesophagus and other parts of the alimentary canal.

Segmentation: The small and large intestines also have rings of smooth-muscles, which contract and relax repeatedly. These contractions and relaxations create a back-and-forth movement in the same place, called segmentation. This movement mixes the food with digestive secretions and increases the efficiency of absorption.

Antiperistalsis

Occasionally, the peristaltic movements may reverse in a process called **antiperistalsis**, pushing food from the intestines back into the stomach and oral cavity, leading to **vomiting**. In contrast, **hunger contractions** are peristaltic movements triggered by low blood glucose levels, creating the uncomfortable sensation known as **hunger pangs**.

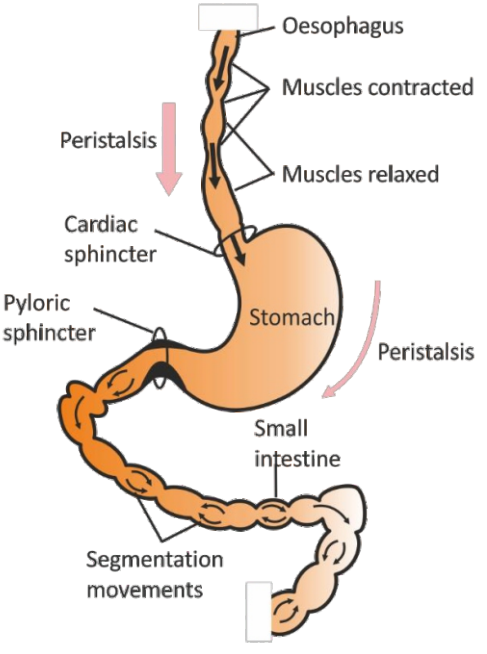


Figure 9.5: Peristalsis and Segmentation

The Stomach

The stomach is an elastic muscular bag (J-shaped) situated after oesophagus and before duodenum. It is located in the left side in abdominal cavity, right below the diaphragm. Its has three portions. The **cardiac portion** is present immediately after oesophagus. **Fundus portion** is present on a side of the cardiac portion. **Pyloric portion** is located beneath the cardiac portion. The cardiac sphincter opens when a wave of peristaltic contractions coming down the oesophagus reaches it and allows food to enter the stomach.

Mechanical digestion of food: The stomach wall is made of the same layers, as the other parts of alimentary canals. The outermost layer is **serosa**, the middle layer is made of **smooth muscles** In stomach, there are three layers of muscles i.e., outer longitudinal muscles, middle circular muscles and the inner oblique muscles. The inner two layers are **submucosa** and **mucosa** The muscular walls of stomach contract and vigorously and help in churning of food (mechanical digestion) and mixing the food with stomach secretions. These contractions also generate enough heat that melts the solid fats.

Sometimes there is a back flush of acidic chyme from stomach into the oesophagus. It causes a painful burning sensation in the chest and this condition is known as **pyrosis** or **heartburn**.

Chemical digestion of food: The mucosa of stomach possesses numerous tubular **gastric glands** These glands open in the mucosa wall through deep depressions, called **gastric pits**. Each gastric gland contains epithelial cells and three secretory cells:

i. The **mucous cells** which secrete mucous – a

In infants, the gastric juice contains large amounts of **rennin** enzyme. This enzyme coagulates milk proteins and delays the passage of milk into the small intestine. The delay enables other enzymes to digest the milk proteins.

thick secretion that covers the inside of the stomach and protects it from HCl and digestive enzymes.

ii. The **parietal (oxyntic) cells** which secrete Hydrochloric acid. It adjusts the pH of stomach contents to about 2-3. HCl also softens the food, activates the pepsinogen and kills microorganisms.

iii. The **chief cells** which secrete enzyme, pepsinogen.

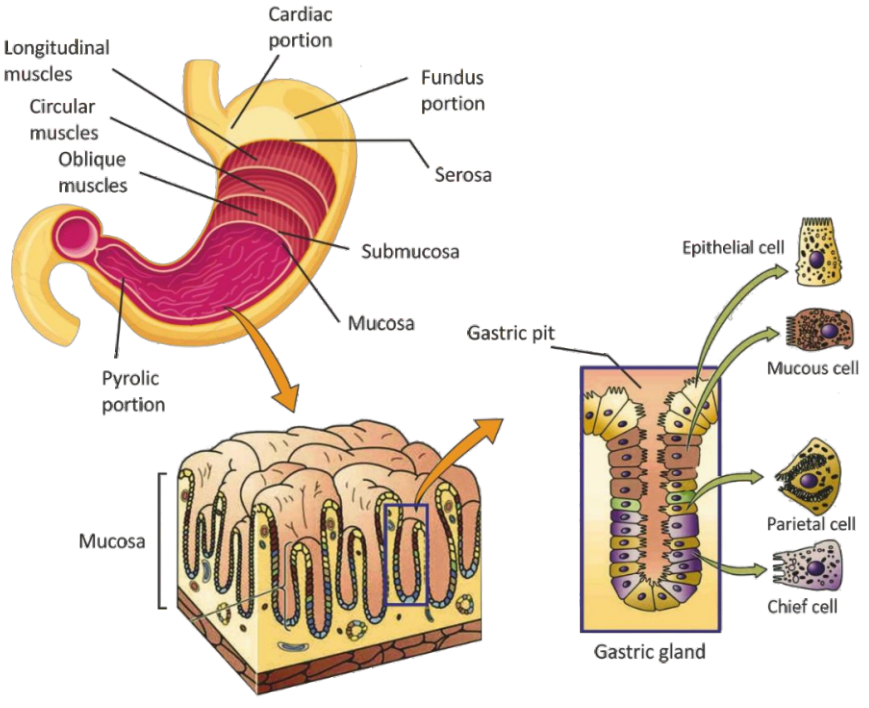


Figure 9.6: Stomach; external and internal structure

All the secretions of gastric glands are collectively called **gastric juice** When the bolus enters the stomach, the gastric glands secrete gastric juice. The H^+ ions of the HCl activate pepsinogen into pepsin. Pepsin catalyses the breakdown of proteins to yield polypeptides and peptides. About three to four hours after a meal, the stomach contents have been sufficiently mixed and are semi-liquid acidic mass called **chyme**. The **pyloric sphincter** regulates the release of the chyme into the small intestine.

Regulation of Secretion of Gastric Juice

The secretion of gastric juice is regulated by both the nervous system and hormonal mechanisms. In reaction to the smell, sight, or thought of food, the medulla of brain sends message to the gastric glands

The mucosa of stomach is susceptible to damage from acid and pepsin if it had no protection. Protection of the mucosa is provided in two ways; viscous mucous and bicarbonate, which neutralizes acid.

to secrete small amounts of gastric juice. When food arrives in stomach, the distension of stomach and decrease in the pH of the gastric contents stimulate more secretion and powerful contractions.

The presence of proteins in food stimulate special endocrine cells present in the mucosa of stomach to release a hormone called **gastrin**. Gastrin is carried by blood to the gastric glands where it stimulates them to produce and secrete more gastric juice. When food moves from stomach to small intestine, a hormone called **somatostatin** stops the release of hydrochloric acid.

The Small Intestine

It is the longest part of alimentary canal. It starts after the stomach and ends at the large intestine. In adult man it is about 2-3 cm in diameter and 6 m in length. Small intestine is responsible not only for the final digestion of all kinds of food but also for the absorption of digested food into blood and lymph. Small intestine consists of three parts i.e., duodenum, jejunum and ileum.

Duodenum

The first 20 – 25 cm long portion is the duodenum. It is concerned with the digestion of food. It also contains glands, which produce an alkaline secretion containing bicarbonate. Two main secretions are poured into duodenum.

a- Pancreatic juice It is the secretion of pancreas and is poured into duodenum. It is slightly alkaline (pH: 8) due to the presence of bicarbonate. It neutralizes the acidity of chyme. The important enzymes in pancreatic juice are:

i. **Pancreatic amylase,** which digests polysaccharides into maltose and even glucose)
ii. **Trypsinogen,** which is in inactive form. Another enzyme **enterokinase** (secreted by the walls of duodenum) activates trypsinogen into trypsin, which digests proteins into polypeptides.
iii. **Chymotrypsin and carboxypeptidase,** which digest proteins into smaller peptides and then into amino acids.
iv. **Pancreatic lipase,** which digests lipids to glycerol and fatty acids.
v. **Pancreatic nucleases,** which digest DNA and RNA into nucleotides.

Fats are insoluble in water. So, they cannot be attacked readily by lipase enzymes of pancreatic juice. Bile salts act as detergent molecules. They break fats into droplets and keep them separate from one another.

b- Bile: It is the secretion of liver. Before its release, it is stored in gallbladder. It contains salts which emulsify fats and break them into small droplets (emulsion). These droplets provide large surface areas for effective action of lipids-digesting enzymes.

If bile pigments are prevented from leaving digestive tract, they may accumulate in blood, causing a condition known as jaundice.

Jejunum and Ileum

Jejunum is 2.4 meters long part, next to duodenum. Ileum is the last three fifth i.e., about 3.5 metres long part of small intestine. These parts carry out the rest of digestion and absorption of food. The walls of jejunum and ileum contain glands which secrete intestinal juice. It contains various enzymes; for example, aminopeptidase digests polypeptides into dipeptides, erypsin digests dipeptides into amino acids, lipase digests fats into fatty acids and glycerol, maltase digests maltose into glucose, sucrase digests sucrose into glucose and fructose, and lactase digests lactose into glucose and galactose. After the action of enzymes of intestinal juice, the chyme is converted into an alkaline emulsion, called **chyle**.

Absorption of Digested Food and Water

The absorption of digested food, water, and dissolved minerals occurs in jejunum and ileum. The inner wall of jejunum and ileum contains large circular folds. These folds have numerous finger-like projections called **villi**

Each villus is richly supplied with blood capillaries and a vessel of lymphatic system, called **lacteal**. The blood capillaries and lacteal are covered by a single-cell thick epithelium. The epithelial cells of villi have countless cytoplasmic projections, called **microvilli**. The total surface area of absorption becomes extraordinarily large due to villi and microvilli.

Due to the presence of folds and numerous villi, the internal surface of jejunum and ileum appears velvety.

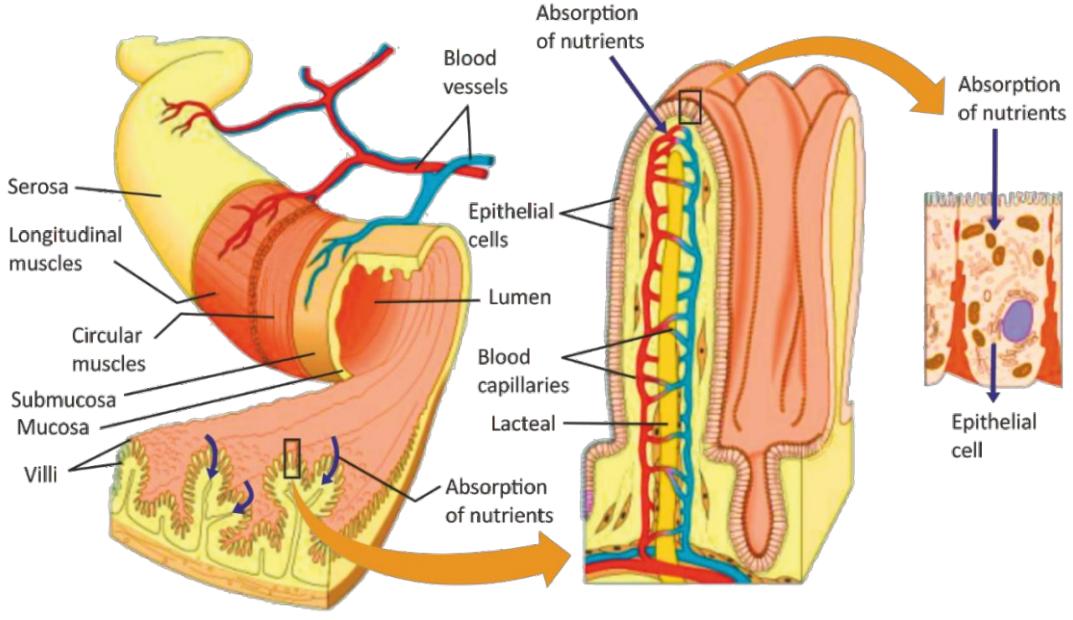


Figure 9.7: Intestinal wall and detailed structure of villi

Absorption of simple sugars and amino acids Simple sugars (e.g., glucose) and amino acids are absorbed by diffusion or active transport into the epithelial cells of villi. From here, these molecules enter the blood capillaries of villi. Blood capillaries of villi join to form **hepatic portal vein** which carries sugars and amino acids to liver. Liver stores extra glucose and amino acids in the form glycogen and proteins respectively. From liver, the required amounts of these products pass to heart via hepatic vein.

Absorption of Fatty acids and glycerol: The products of fat digestion i.e., fatty acids and glycerol are absorbed by passive transport into the epithelial cells of villi. Inside villi, they combine to form triglycerides. The triglycerides are coated with proteins. In this way small droplets, called **chylomicrons** are formed. The chylomicrons enter the lacteals of villi. From the lacteals, the chylomicrons move into thoracic lymphatic duct, from where they enter in bloodstream. Blood plasma has enzymes which hydrolyse chylomicrons back into fats and proteins. Fats are ultimately hydrolysed into fatty acids and glycerol and enter body cells.

The Large Intestine

It is the last part of the alimentary canal. It is much shorter than small intestine, occupying about the last metre of the intestinal tract. It is involved in the absorption of water and salts and vitamin 'K' from the lumen of intestine into the blood. The large intestine is not convoluted and its inner surface area does not possess villi. It consists of three parts.

Cecum

It is a blind sac that projects from the area of large intestine between ileum and colon. From the blind end of caecum there arises a finger-like process called vermiform appendix. In human digestive system, appendix performs no function so is vestigial.

Appendicitis is the inflammation of the appendix. It is usually due to bacterial infection. The infected appendix must be removed surgically otherwise it may burst and the inflammation may spread in the entire lining of the abdomen. The surgical removal of appendix is called **appendicectomy**.

Colon

Next to cecum is the colon. It has an ascending, a transverse and a descending limb. Its main function is to absorb water from the alimentary canal. As the water is absorbed, the remaining material becomes more solid. These wastes products, called faeces, consist of a large number of bacteria, indigestible plant fibres (e.g., cellulose), other undigested food stuff, sloughed off mucosal cells, bile pigments and water.

Rectum

It is the last part of large intestine where faeces are temporarily stored. At its distal end, the rectum opens out through anus. Anus is surrounded by two sphincters; the internal sphincter is made of smooth muscles and the outer is made of striated

muscles. Under normal conditions when the rectum is filled up with faeces, it gives rise to a defecation reflex. The defecation reflex is consciously inhibited in adults but in infants it is controlled involuntarily. During growth, the child learns to bring this reflex under voluntary control.

Many bacteria, for example E. coli, live and actively divide within colon. During their metabolism, they produce amino acids and vitamin K. Vitamin K is necessary for man for the coagulation of blood. It is absorbed from the large intestine into the blood.

Control of Egestion

The involuntary reflex for **egestion** in infants and the voluntary control in adults represent two stages of neurological and muscular development. In infants, egestion is an involuntary reflex mediated by the spinal cord, where rectal distension triggers automatic relaxation of the internal anal sphincter and expulsion of waste. This occurs because the higher brain centres responsible for voluntary control are not yet fully developed. In adults, egestion becomes voluntary as the **cerebral cortex** matures, allowing conscious regulation of the external anal sphincter to delay or initiate defecation. This transition reflects the integration of reflex pathways with cognitive control, adapting to social and environmental demands.

Accessory Digestive Organs

1. Liver and Gallbladder

The liver plays a vital role in digestion by producing **bile**, which is essential for fat digestion. Bile emulsifies fats, making them easier to digest. Liver also processes nutrients absorbed from the small intestine, detoxifies harmful substances, synthesizes proteins and stores glycogen for energy.

Cholesterol, secreted by the liver, may precipitate in the gall bladder to produce gall stones, which may block release of bile.

The gallbladder stores and concentrates bile produced by the liver. When food enters the small intestine, the gallbladder releases bile through the bile duct.

2. Pancreas

Pancreas is a large gland situated just ventral to the stomach. It has exocrine and endocrine portions. The **exocrine** (ducted) portion secretes its secretion i.e., pancreatic juice into pancreatic duct. The pancreatic duct joins with the common bile duct from the liver and enters the duodenum. Pancreatic juice contains enzymes for the digestion of all groups of food. Its major enzymes include trypsin, chymotrypsin, lipases, amylases, nucleases etc. The **endocrine** (ductless) portion of pancreas secretes its secretion i.e., insulin and glucagon hormones into extracellular fluid from where they diffuse into nearby capillaries.

Hormonal Control of the Secretions of Pancreas and Liver

We have studied the regulation of gastric secretions through nervous system and hormones. The release of secretions from pancreas and liver is also controlled by hormones. When chyme enters duodenum from stomach, its acidity stimulates duodenal walls to release a hormone, **secretin** Similarly, the partially digested proteins and fats present in chyme stimulate the duodenal walls to secrete another hormone, **cholecystokinin**(CCK). Both these hormones stimulate pancreas to release pancreatic juice, and gallbladder to release bile.

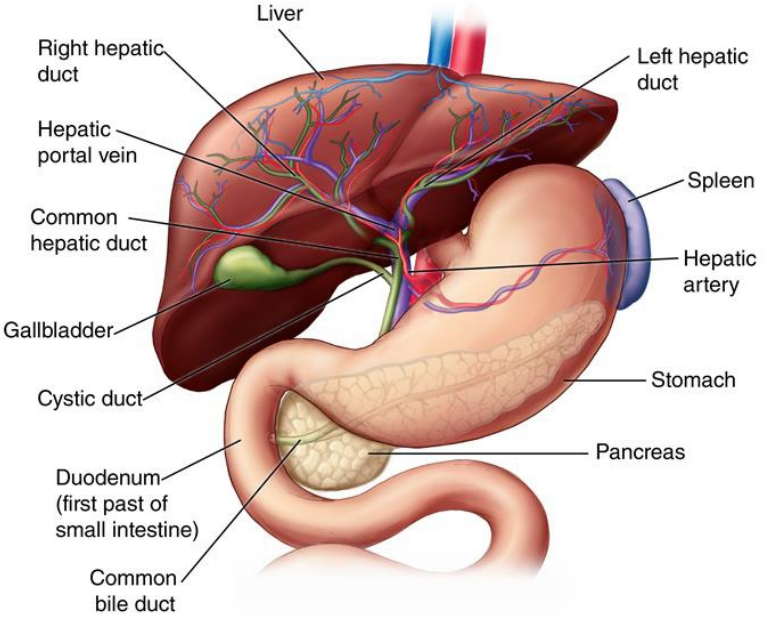


Figure 9.8: Accessory Digestive Organs

Storage and Metabolic Role of the Liver

The liver performs many important functions, especially in storing nutrients and regulating metabolism. It stores excess nutrients from the food and releases them when the body needs energy or building materials. These nutrients stored in the liver include glucose (stored as glycogen), vitamins (like A, D, B12, and K), minerals (e.g., iron and copper), and fats and fat-soluble substances. It also plays a central role in metabolism. It helps in breaking down, building up, and converting substances in the body. For example, it converts excess glucose into glycogen and back when needed, It also breaks down fats to produce energy and forms cholesterol and lipoproteins. It converts amino acids and removes harmful ammonia by turning it into urea, which is excreted in urine. It breaks down and removes toxins, drugs, and alcohol from the blood. The liver also helps in breaking down and regulating hormones

EXERCISE

SECTION 1: MULTIPLE CHOICE QUESTIONS

1. Where does chemical digestion of carbohydrates begin?
   (a) Stomach (b) Oesophagus (c) Small intestine (d) Mouth
2. Which enzyme in saliva starts breaking down starch?
   (a) Lipase (b) Amylase (Ptyalin) (c) Trypsin (d) Pepsin
3. What prevents food from entering the trachea during swallowing?
   (a) Epiglottis (b) Oesophageal sphincter
   (c) Uvula (d) Tongue
4. Why does the enzyme activity drops in the stomach when pH rises?
   (a) Acid blocks food entry (b) Enzymes denature in low pH
   (c) Enzymes need acidic pH to work (d) Saliva dilutes gastric juice
5. Which change would most affect protein digestion?
   (a) Blocking bile release (b) Inhibiting salivary glands
   (c) Inhibiting pepsin production (d) Slowing peristalsis
6. Why is lipase not active in the stomach?
   (a) It is destroyed by acid (b) It needs alkaline pH to work
   (c) It is secreted by the liver (d) It digests only proteins
7. Which stomach secretion activates pepsin and kills bacteria?
   (a) Bile (b) Hydrochloric acid (HCl)
   (c) Sodium bicarbonate (d) Mucus
8. Why is segmentation important in the small intestine?
   (a) It absorbs bile (b) It breaks down enzymes
   (c) It mixes food with digestive juices (d) It pushes food to the rectum
9. What is the function of villi and microvilli in the small intestine?
   (a) Produce enzymes (b) Increase surface area for absorption
   (c) Store bile (d) Neutralize stomach acid
10. Which best explains the liver's role in digestion?
    (a) It produces insulin (b) It stores undigested food
    (c) It produces bile for fat digestion (d) It secretes enzymes into the colon

SECTION 2: SHORT QUESTIONS

1. What is the main function of the digestive system?
2. What is the mode of action of saliva in mouth?
3. What is role of tongue in the mouth?
4. What role does the epiglottis play during swallowing?
5. What is the composition of gastric juice?
6. Why is hydrochloric acid (HCl) important in the stomach?
7. What is the difference between bolus and chyme?

8. Which organ produces bile, and what is its function?
9. Differentiate between physical and chemical digestion.
10. What do you understand by emulsification of fats?
11. What is role of the role of the pyloric sphincter in digestion?
12. How do villi and microvilli help in nutrient absorption?
13. What are the main functions of the large intestine?
14. What causes jaundice in the digestive system?
15. How does stress negatively impact digestion?

SECTION 3: LONG QUESTIONS

1. Explain the complete process of digestion, starting from ingestion in the mouth to egestion in the large intestine. Include the roles of mechanical and chemical digestion at each stage.
2. Describe the structure and function of the stomach in digestion.
3. Compare and contrast the roles of the small intestine and large intestine in digestion.
4. Explain the absorption of food from the small intestine?
5. Discuss accessory organs (liver, gallbladder and pancreas) and their contributions in digestion.
6. Describe the hormonal and nervous regulation of gastric acid secretion.

INQUISITIVE QUESTIONS

1. Why does the small intestine need both peristalsis and segmentation?
2. How does the liver help digestion without using enzymes?
3. Why do we need bile if we already have enzymes for fat digestion?
4. How does the pancreas “know” when to release its enzymes?
5. Why are pancreatic secretions alkaline, not acidic?

Chapter 10 HUMAN RESPIRATORY SYSTEM

STUDENTS'LEARNING OUTCOMES

After studying this chapter, the students will be able to:

- Define the respiratory surface and list its properties
- Describe the main structural features and functions of the components of human respiratory system.
- Explain the ventilation mechanism in humans.
- Describe the transport of oxygen and carbon dioxide through blood.
- Outline the role of respiratory pigments.
- State the causes, symptoms and treatment of upper Respiratory Tract Infections (sinusitis, otitis media) and lower Respiratory Tract Infections (pneumonia, pulmonary tuberculosis).
- Describe the disorders of lungs (emphysema and COPD).

Recalling

Our cells obtain oxygen from the blood. The blood obtains this oxygen from air present in our lungs. Oxygen diffuses across the wet membranes of the lungs, which are filled with air in the process of breathing.

You have studied in your previous class how organisms get energy out of food molecules. For this purpose, organisms carry out catabolic processes in their cells, collectively called cellular respiration (glycolysis, Krebs cycle, and electron transport chain). These processes use oxygen and produce carbon dioxide. The term **external respiration** is used for the uptake of oxygen from the environment and the disposal of carbon dioxide into the environment at the body system level. It involves breathing and the exchange of oxygen and carbon dioxide in the capillaries. The organs which carry out these processes constitute the respiratory system. The theme of this chapter is to explain the respiratory system of humans and important respiratory disorders.

10.1- RESPIRATORY SYSTEM OF MAN

It consists of the organs that carry out external respiration (uptake of oxygen and disposal of carbon dioxide) at the body system level. The main organs of respiratory systems are the lungs which provide suitable respiratory surface for this gaseous exchange.

Properties of the Respiratory Surface

Respiratory surface means the area where actual gas exchange occurs between the environment and the blood. This gaseous exchange occurs through diffusion. In humans and other vertebrates which breathe in air, oxygen from the air diffuses into the blood and carbon dioxide diffuse from the blood to air. The following properties enable respiratory surfaces for effective diffusion of gases across them.

1. It is moist and permeable – so that gases may pass through it.
2. It is thin – so that gases have to travel minimum distance.
3. It has a blood supply – so that gases can diffuse in and out of blood.
4. It has structural support– so that it remains open and does not collapse.
5. It is located internally – so that its moist surface does not lose water to the atmosphere.
6. Air ventilates over it i.e., moves towards and away from it.
7. Air reaches to it after passing a branched tubular way – so that air becomes saturated with water vapour before reaching it.

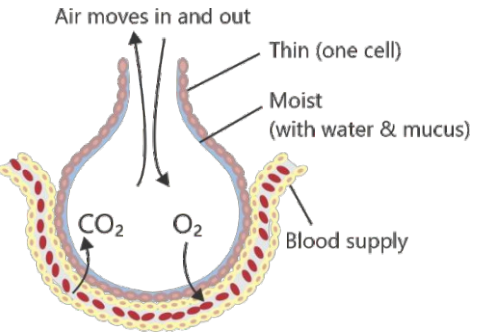


Figure 10.1: Some properties of respiratory surface

Components of Human Respiratory System

The organs of the respiratory system form a continuous system of passages, called the **respiratory tract**, through which air flows into and out of the body. The respiratory tract has two major divisions: the upper respiratory tract and the lower respiratory tract.

Upper Respiratory Track

It consists of nasal cavity, pharynx and larynx. These organs are involved in the movement of air into and out of the body. They also clean, humidify, and warm the incoming air. No gas exchange occurs in these organs.

1- Nasal cavity

The external openings of nose, called **nostrils**, lead to a **nasal cavity**. It is a large, air-filled space behind the nose and partitioned by a **nasal septum** (a part of the nasal bone). As inhaled air flows through the nasal cavity, it is warmed and humidified by blood vessels present very close to its surface. Hairs in the nose and mucous produced by mucous membranes trap larger foreign particles in the air before they go deeper into the respiratory tract. In addition to its respiratory functions, the nasal cavity also contains chemoreceptors needed for sense of smell, and contribution to the sense of taste.

2- Pharynx

It is a tube-like structure that connects the nasal cavity and oral cavity to larynx and oesophagus. Both air and food pass through it. So, it is part of both the respiratory and the digestive systems. Air passes from the nasal cavity through the pharynx to the larynx (as well as in the opposite direction). Food passes from the mouth through the pharynx to the esophagus.

3- Larynx

The larynx connects the pharynx and trachea. It is composed of muscles and cartilages. It is also called the voice box, because it contains two bands of smooth muscles called **vocal cords** The vocal cords vibrate when air flows over them and so produce sound.

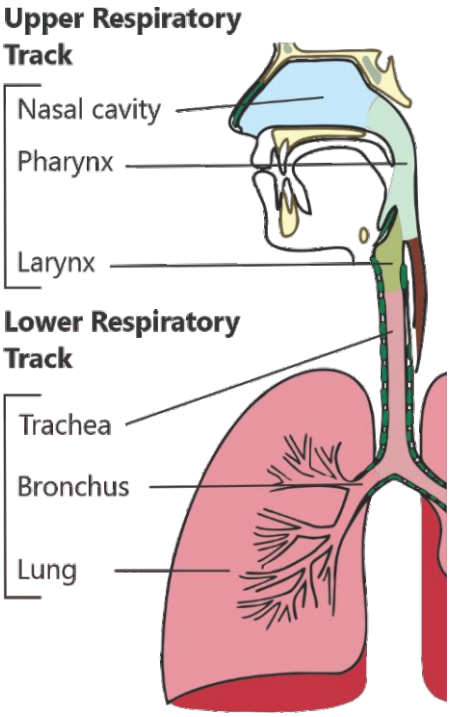
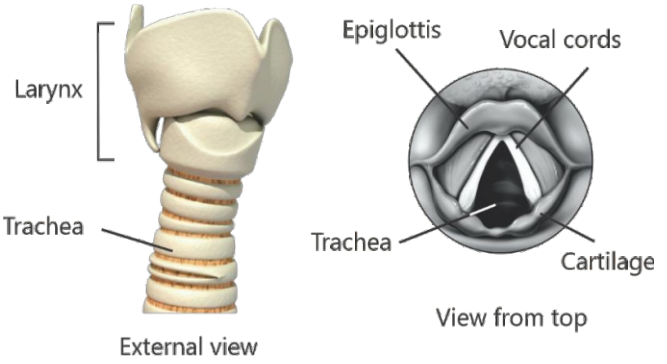


Figure 10.2: Respiratory track

Epiglottis is a cartilaginous flap that extends in front and above the opening of larynx called glottis. When air enters the larynx, the epiglottis keeps standing upwards to give way to air. When we swallow something, the backward motion of the tongue raises the larynx. Due to it, the epiglottis is forced downwards to close the glottis. It prevents swallowed material from entering the larynx.

Muscles in the larynx move the vocal cords apart to allow breathing. Other muscles in the larynx move the vocal cords together to allow the production of vocal sounds. The latter muscles also control the pitch of sounds and help control their volume.



If swallowed material does start to enter the larynx, it irritates the larynx and stimulates a strong cough reflex. This generally expels the material out of the larynx, and into the throat.

Figure 10.3: Larynx and Trachea

Lower Respiratory Track

The trachea and other passages of the lower respiratory tract conduct air between the upper respiratory tract and the lungs. These passages make a tree-like shape, with repeated branching. There are an astonishing 2,414 kilometres of airways conducting air through the human respiratory tract! It is only in the lungs, however, that gas exchange occurs between the air and blood.

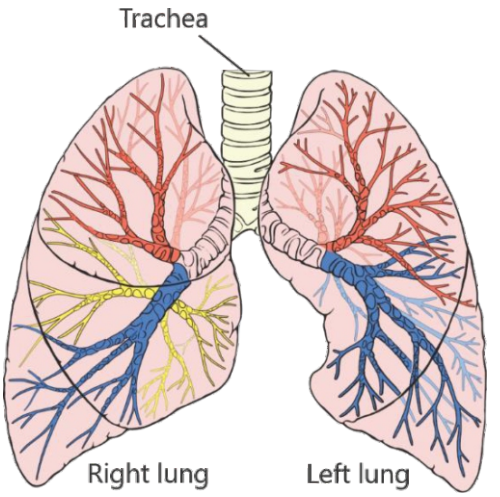


Figure 10.4: Tree-like branching of the lower respiratory tract

1- Trachea

The trachea, or windpipe, connects the larynx to the lungs for the passage of air. It is the widest passageway in the respiratory tract. It is about 1 inch wide and 4–6 inches long. Its walls are made of smooth muscles and C-shaped rings of cartilage. The trachea is lined with mucus and cilia. The cilia propel foreign particles trapped in the mucus toward the pharynx. The C-shaped cartilage provides strength and support to the trachea to keep the passage open. The trachea branches at the bottom to form two bronchi.

2- Bronchi, Bronchioles, and Alveoli

There are two primary bronchi (singular, bronchus). The right and left bronchi enter the lungs and branch into smaller, **secondary bronchi** There are two secondary bronchi in left lung while three in right lung. In secondary bronchi, the C-shaped cartilages are replaced with cartilage plates. The secondary bronchi branch into still smaller **tertiary bronchi**, which branch further into very small **bronchioles**. The bronchioles do not have cartilage plates. They divide many times and make **terminal bronchioles**. The terminal bronchioles end in **alveolar ducts**, which terminate in clusters of tiny air sacs, called **alveoli** (singular, alveolus), in the lungs.

3- Lungs

The lungs are the largest organs of the respiratory tract. The outside of each lung is covered by two membranes. First membrane, **visceral pleura,** lines the lungs while the second membrane, **parietal pleura,** lines the inner wall of thoracic cavity. The small space between these two membranes, called **pleural cavity**, is filled with fluid. This fluid allows the lungs to expand and contract freely during breathing. Each lung is divided into **lobes**. The right lung is larger and contains three lobes. The left

lung is smaller and contains two lobes. The smaller left lung allows room for the heart, which is just left of the centre of the chest.

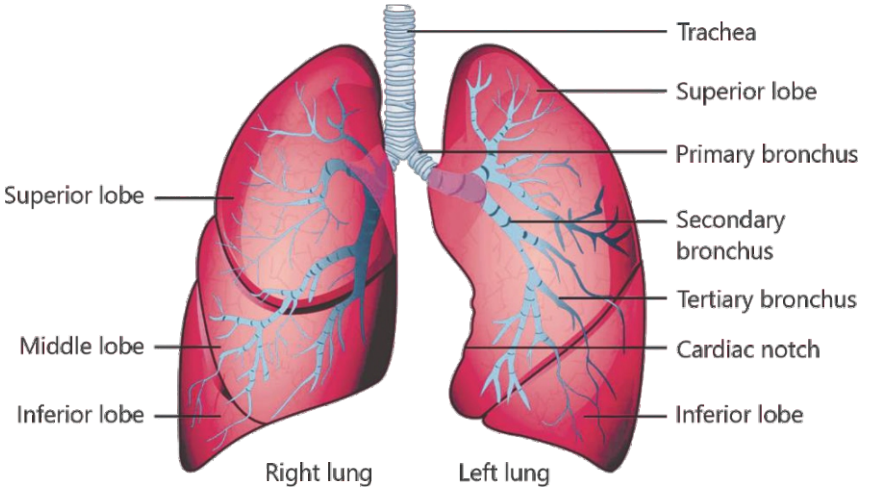


Figure 10.5: Right and left lungs

As mentioned previously, the terminal bronchi end in alveolar ducts. Each alveolar duct opens in a cluster of alveoli. These clusters make the bulk of the lung and are surrounded by blood capillaries. Each cluster contains 20-30 alveoli. An alveolus is made of moist epithelial tissue (only 0.1 micrometre thick). So, they provide the respiratory surface where gas exchange takes place between the air and blood.

Some epithelial cells of alveoli secrete a liquid called surfactant, which lines the inside of alveoli. It prevents the alveoli from collapsing and sticking together when air moves out of them. In healthy lungs, surfactant is constantly secreted and reabsorbed.

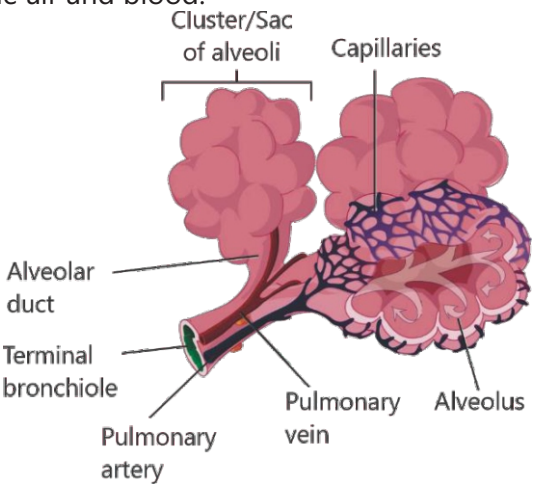


Figure 10.6: Clusters of alveoli

Recalling

You have studied that pulmonary arteries carry deoxygenated blood to the lungs. This blood absorbs oxygen in the lungs and pulmonary veins carry the oxygenated blood back to the heart to be pumped throughout the body. The lungs also receive oxygenated blood from the heart that provides oxygen to the cells of the lungs for cellular respiration.

The alveoli are the functional units of the lungs where gas exchange takes place. The two lungs may contain as many as 700 million alveoli. They provide a huge total surface area for gas exchange. When we breathe in, the alveoli fill with air, making the lungs expand. Oxygen in the air inside the alveoli is absorbed by the blood via diffusion in the network of tiny capillaries that surround them. The blood in these capillaries also releases carbon dioxide (also by diffusion) into the air inside the alveoli. When we breathe out, air leaves the alveoli and rushes into the outside atmosphere, carrying carbon dioxide with it.

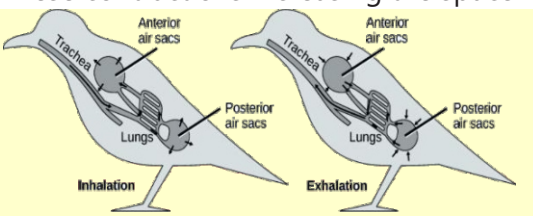
Mechanism of Breathing or Ventilation

The movement of the air in and out of the body is called breathing or ventilation. Our lungs do not draw in air or push it out. Rather, it is done by creating negative and positive pressures in the lungs. This role is played by two sets of muscles i.e., (i) **diaphragm** (dome-like large skeletal muscle that separates thoracic cavity and abdomen) and (ii) the **intercostal muscles** (present between each pair of ribs).

Atmospheric pressure is lower at high altitudes. It means a greater increase in thorax is required to make the pressure in lungs lower than the atmospheric pressure. That is why it is harder to breathe at high altitudes. The body adapts mechanisms to improve oxygen uptake under these conditions, which is why athletes often undertake high altitude training prior to competitions.

Inspiration: Taking in of air is called inspiration or inhalation. For this purpose, the diaphragm contracts. It causes the diaphragm to lower and take a more flattened shape. At the same time, the intercostal muscles contract.

It raises the ribs and expands the rib cage. These contractions increasing the space in the thorax. As a result, lungs expand because of the adherence of the visceral and parietal pleural membranes. The expansion of lungs lowers the air pressure inside them. The pressure in lungs becomes lower than the atmospheric pressure and the air enters the lungs.



Birds have lungs as well as air sacs in their body. Air flows in one direction. It flows from outside to posterior air sacs. For here, the air goes to the lungs, then to anterior air sacs, and then outside. The flow of air is in the opposite direction from blood flow. So, gas exchange takes place much more efficiently. This type of breathing enables birds to obtain the required oxygen, even at high altitudes where oxygen concentration is low.

Expiration: Moving the air out of lungs is called expiration or exhalation. Expansion of the thorax and lungs during inspiration places these structures under elastic tension. This elastic tension is relieved by the relaxation of the intercostal muscles and diaphragm. When diaphragm relaxes, it assumes its dome-like shape. Similarly, when intercostal muscles relax, the ribs lower

and rib cage moves inward. These movements decrease the space in thorax and allow the lungs to recoil. So, the pressure inside lungs becomes more than the atmospheric pressure and the air moves out of the lungs.

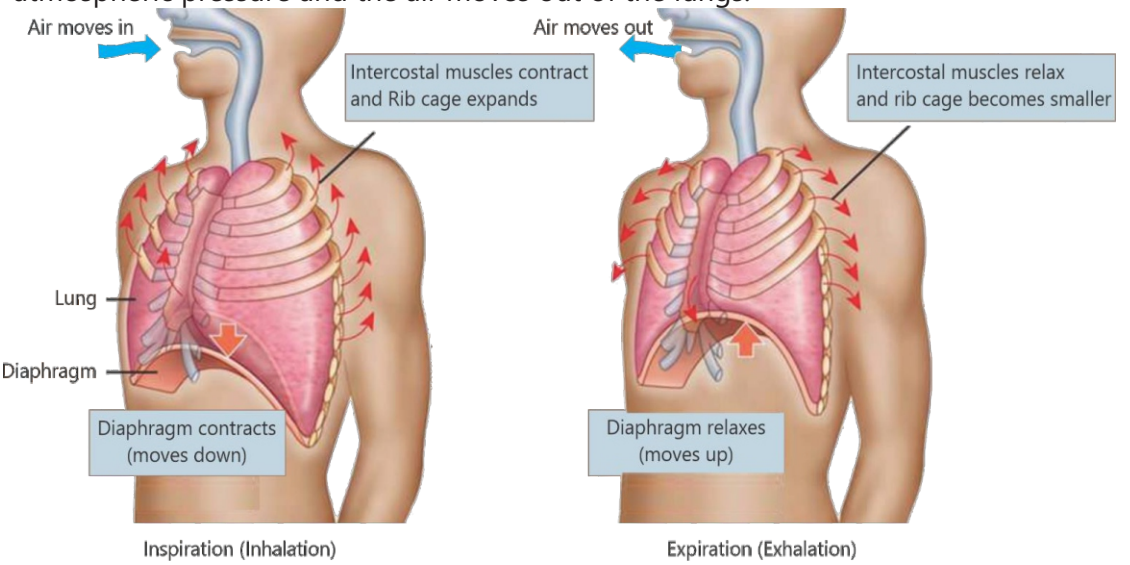


Figure 10.7: Mechanism of breathing

Control of Breathing

Each breath is initiated by neurons in a respiratory centre located in the medulla oblongata i.e., a part of the brain stem. These neurons send impulses to the diaphragm and intercostal muscles, stimulating them to contract., causing inspiration. When these neurons stop producing impulses, the diaphragm and intercostal muscles relax and expiration occurs.

10.2- TRANSPORT OF GASES

The process known as gas transport is an essential component of respiration. Oxygen is transported from lungs to all tissues and, at the same time, carbon dioxide is transported from tissue to the lungs. The following is a brief description of the mechanisms by which gases are transported in human body.

Transport of Oxygen

The partial pressure of oxygen in alveoli allows to diffuse through alveoli into pulmonary capillaries. Inside the blood, small amount of oxygen dissolves in the blood plasma. Blood plasma can dissolve a maximum of only about 3 mL O_2 per litre. Yet whole blood carries almost 200 mL O_2 per litre! The reason is that most of the oxygen is not dissolved in blood plasms but is bound to molecules of haemoglobin inside the RBCs.

Oxyhaemoglobin is bright red while deoxyhaemoglobin is dark red. But deoxyhaemoglobin imparts a bluish tinge to tissues. Because of these colour changes, vessels that carry oxygenated blood are always shown with a red colour, and vessels that carry oxygen-depleted blood are indicated with a blue colour.

The partial pressure of oxygen in alveoli (at sea level) is approximately 105 mm Hg, which is less than the partial pressure of oxygen in the atmosphere. So, about 97% of the haemoglobin within RBCs combines with oxygen and becomes **oxyhaemoglobin**. This molecule has a bright red, tomato juice colour. As the blood travels through the blood capillaries, some of the oxyhaemoglobin releases oxygen and becomes a dark red coloured **deoxyhaemoglobin**. Consequently, when blood leaves the tissue in the veins, it has a low partial pressure of oxygen (40 mm Hg). Here, 75% of haemoglobin is saturated in the form of oxyhaemoglobin. It means that 22% (97% minus 75%) of the oxyhaemoglobin has released its oxygen to the tissues, leaving 78% oxyhaemoglobin in the blood as a reserve. This large reserve of oxygen enables the blood to fulfil the body's oxygen needs during exercise as well as at rest.

Factors affecting Oxygen Transport

During exercise, the muscles use more oxygen from the capillary blood. It decreases the venous blood partial pressure of oxygen to 20 mm Hg. In this case, the percent saturation of haemoglobin drops from 75% to 35%. Because arterial blood still contains 97% oxyhaemoglobin, the amount of oxygen unloaded is now 62% (97% minus 35%), instead of the 22% at rest.

The oxygen reserve also ensures that the blood contains enough oxygen to maintain life for four to five minutes if breathing is interrupted or if the heart stops pumping.

The CO_2 produced by tissues lowers the pH of blood. This lowered pH reduces haemoglobin's affinity for oxygen and thus causes it to release oxygen more readily. The effect of pH on haemoglobin's affinity for oxygen is known as the Bohr effect. Increasing temperature has a similar effect on haemoglobin's affinity for oxygen. During exercise, skeletal muscles produce more heat, haemoglobin unloads a higher percentage of the oxygen.

Transport of Carbon dioxide

Blood capillaries deliver oxygen to the tissues and remove carbon dioxide from tissues. The partial pressure of CO_2 is higher in tissues than in blood. It causes the carbon dioxide to enter from tissues into blood. While, the process reverses in lungs where the partial pressure of CO_2 is lower in alveoli than in blood. Blood transports carbon dioxide from tissues to lugs in three ways.

1- As bicarbonate ions

Approximately 72% of carbon dioxide is carried in the blood as bicarbonate ions. CO_2 enters the RBCs and combines with water to form carbonic acid (H_2CO_3) in the presence of enzyme carbonic anhydrase. Carbonic acid

The formation of carbonic acid is important in maintaining the acid-base balance of the blood, because bicarbonate serves as the major buffer of the blood plasma.

(H_2CO_3) disassociates to form hydrogen ions (H^+) and bicarbonate ions (HCO_3^-). The hydrogen ion readily associates with oxyhaemoglobin and oxygen of oxyhaemoglobin is released to the tissue. While the bicarbonate ions (HCO_3^-) moves out from RBCs into plasma. The movement of bicarbonate ions (HCO_3^-) is facilitated by a transporter that exchanges one chloride ion (Cl^-) for a bicarbonate ion (this is called the "chloride shift" or "Hamburger phenomenon").

2- As Carboxyhaemoglobin

About 20% of CO_2 is carried as carboxyhaemoglobin. When partial pressure of CO_2 is higher in blood than tissues, CO_2 combines with the globin chains of haemoglobin and forms carboxyhaemoglobin.

CO_2 binds to the protein portion of haemoglobin while O_2 binds to the haem irons. So, both do not compete for attachment to haemoglobin.

3- As dissolved CO_2 in Plasma

When CO_2 enters blood, a little amount dissolves in the water of blood plasma. About 8% of CO_2 is carried this way.

The blood carries CO_2 in these three forms to the lungs. The lower PCO_2 of the air inside the alveoli causes the conversion of H_2CO_3 into H_2O and CO_2. The CO_2 diffuses out of blood into the alveoli, so that it can leave the body in the next exhalation.

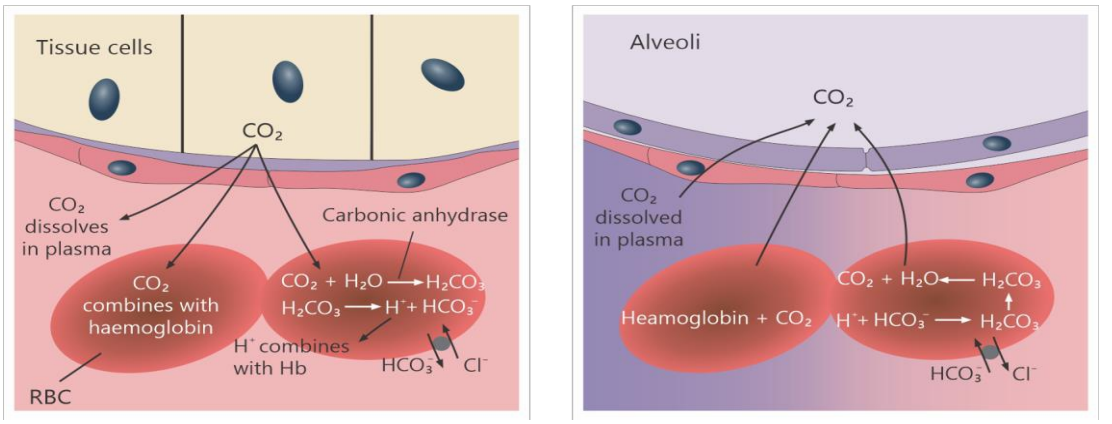


Figure 10.8: Transport of Carbon dioxide by blood

Carbon Monoxide Poisoning

Incomplete combustion of fuels such as wood, gasoline, propane, or natural gas produces CO gas. If gas heaters are left burning overnight in closed environments, CO accumulates in the room. It enters the body through inhalation and binds to haemoglobin with a much higher affinity than oxygen. This binding reduces the amount of haemoglobin available to transport oxygen to the body's tissues, leading to tissue hypoxia (oxygen deprivation). It leads to CO poisoning. Symptoms of CO poisoning may include headache, dizziness, weakness, nausea, confusion, shortness of breath, chest pain, and loss of consciousness. In severe cases, it can cause permanent brain damage, and even death.

10.3- RESPIRATORY PIGMENTS

Respiratory pigments are special proteins in blood or tissues and are involved in transporting oxygen throughout body. They also serve other purposes e.g., O_2 storage, CO_2 transport, and transport of substances other than respiratory gases. The two well-known respiratory pigments are haemoglobin and myoglobin.

Haemoglobin

Haemoglobin is a protein present in RBCs. A haemoglobin molecule is composed of four globin (globular) polypeptide chains (two α chains and two β) and four haem groups. There are 141 and 146 amino acids in the α and β chains, respectively. Each polypeptide chain is folded in such a way that it contains a pocket where the heme group binds. So, each chain is associated with a haem group. A haem group consists of an iron ion held in a porphyrin ring. The iron ion is attached with four nitrogen atoms of the polypeptide chain. Under higher partial pressure of oxygen, iron ion attaches a molecule of O_2. In this way, one haemoglobin molecule can carry up to four O_2molecules.

The four polypeptide chains of haemoglobin are bound to each other by salt bridges, hydrogen bonds, and hydrophobic effect.

Myoglobin

Myoglobin is the oxygen-binding protein in skeletal and cardiac muscle cells of vertebrates. It gives a distinct red or dark gray colour to muscles. It is a monomer, composing of a single polynucleotide chain (made of 153 amino acids) and contains a single haem group. Therefore, it is capable of binding with a single O_2 molecule. The binding affinity of myoglobin is high as compared to that of haemoglobin. As a result, myoglobin serves as the oxygen-storing protein in muscles. It releases oxygen when the partial pressure of oxygen is below 20 mm Hg. In this way, myoglobin provides oxygen to the muscles when they need.

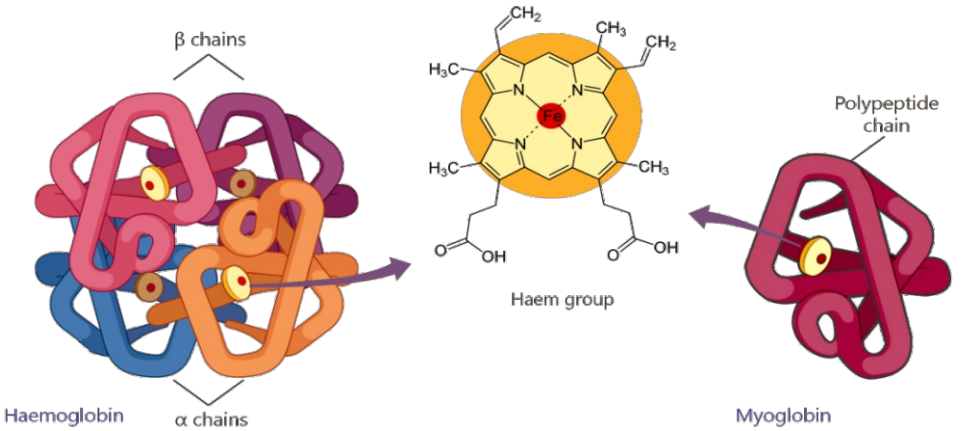


Figure 10.9: Structure of haemoglobin and myoglobin

Table10.1: Differences between Haemoglobin and Myoglobin		
	Haemoglobin	**Myoglobin**
1	Consists of four polypeptide chains.	Consists of one polypeptide chain.
2	Possesses four haem groups.	Possesses one haem group.
3	Found in blood (RBCs).	Found in skeletal and cardiac muscles.
4	Can attach four O_2 molecules.	Can attach one O_2 molecule.
5	Transports oxygen.	Stores oxygen.
6	Has less affinity with oxygen.	Has more affinity with oxygen.
7	Loses oxygen at PO_2 60 mm Hg.	Loses oxygen at PO_2 20 mm Hg.

10.4- Respiratory Disorders

A range of disorders can affect the respiratory system and interfere with respiration. These respiratory disorders can range from mild and self-limiting conditions such as the common cold to more severe diseases such as sinusitis, otitis media, pneumonia, pulmonary tuberculosis, emphysema and COPD.

Upper Respiratory Tract Infections

Upper Respiratory-tract Infections (URIs) affect the nose, throat, sinuses, and larynx and can be easily transmitted from person to person through respiratory droplets.

1. Sinusitis

It is the inflammation of the lining of the sinuses (four paired air-filled spaces that surround the nasal cavity i.e., under the eyes; above the eyes; between the eyes and behind the eyes). It may be acute (lasts for 7 to 10 days) or chronic (lasts longer than 12 week). Most case of sinusitis are due to viral infections; some may be due to bacterial infections and rare cases may also involve fungal infections.

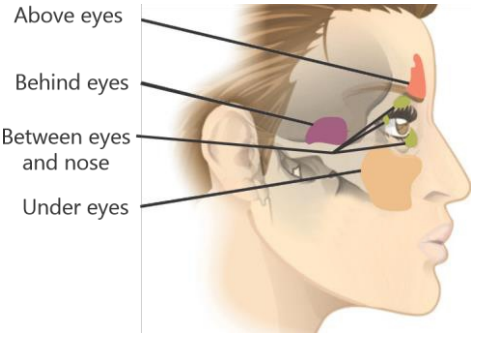


Figure 10.10: Sinuses

Symptoms of sinusitis include fever, plugged nose, pus-like nasal discharge, loss of sense of smell, facial pain, a feeling that phlegm is falling from the back of nose into throat, and headache that is sometimes aggravated by bending over.

Treatment: Most cases are caused by viruses and resolve without antibiotics. If it is due to a bacterial infection, antibiotics or sulpha drugs are usually prescribed. Beside it, the physician may also prescribe nebulization which can be useful in reducing inflammation in the sinuses and nose and to accelerate recovery. For chronic or recurring sinusitis, treatment may include nasal surgery in which the pathogens and mucous are removed.

2. Otitis media

It is the inflammation of the middle ear. Otitis may be acute (rapid onset) or chronic (lasts more than six weeks). The common cause of otitis media accumulation of fluid in Eustachian tube, which cannot be drained from the middle ear. When this fluid is not drained, it allows the growth of bacteria and viruses in the middle ear that lead to otitis media.

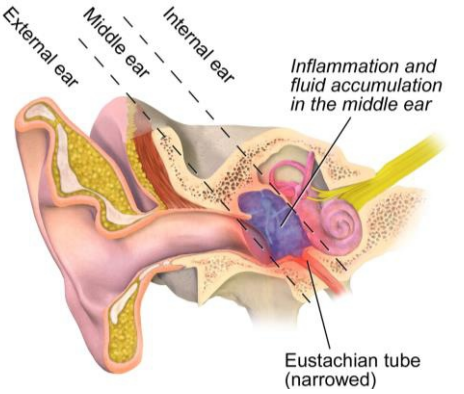


Figure 10.11: Otitis media

Symptoms of otitis media include severe ear pain, pulling at one or both ears, fever, fluid draining from ear(s), loss of balance, and hearing difficulties.

Treatments include oral and topical pain killers and antibiotics (if caused by bacterial infection).

Lower Respiratory Tract Infections

Lower Respiratory-tract Infections include pneumonia, pulmonary tuberculosis, lung abscess and bronchitis.

1. Pneumonia

Pneumonia is a form of acute respiratory infection. It can cause mild to life-threatening illness. In pneumonia, the alveoli of one or both lungs are inflamed and are filled with pus and fluid. It makes breathing painful and limits oxygen intake. Pneumonia is most commonly caused by viruses or bacteria. It is the single largest infectious cause of death in children worldwide.

Pneumonia killed more than 808 000 children under the age of 5 in 2017, accounting for 15% of all deaths of children under 5 years.

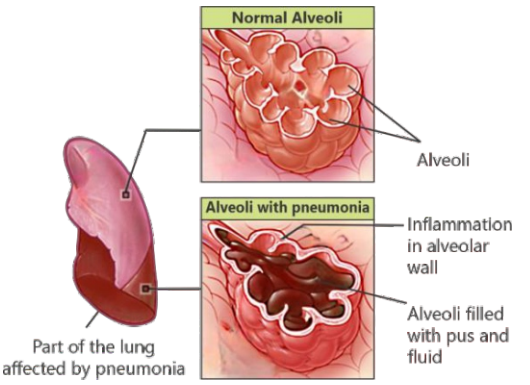


Figure 10.12: Pneumonia

A variety of organisms, primarily bacteria (particularly *Streptococcus pneumoniae*) or viruses (e.g., human rhinovirus) and less commonly fungi, can cause pneumonia.

Symptoms: Its symptoms include cough with phlegm, shortness of breath, chest pain, fever, blueness of skin, loss of appetite, high heat rate, and fatigue.

Treatment: Specific antibiotics are used to treat bacterial pneumonia. Analgesics, also used to reduce fever and pain. Vaccination prevents against certain bacterial and viral pneumonias both in children and adults.

2. Pulmonary Tuberculosis

Tuberculosis (TB) is a chronic infection caused by bacteria *Mycobacterium tuberculosis* It can affect many parts of the body but it generally affects the lungs. The tuberculosis of the lungs is called pulmonary tuberculosis. It is highly contagious and spreads through cough or sneezes. The bacteria enter the lungs, multiply and cause inflammation and damage to the lung tissue, including the alveoli. The damage to the alveoli can lead to the formation of small cavities or holes in the lung tissue, which can make it difficult for the lungs to function properly. In advanced stages, the alveoli are so damaged that the lungs may become unable to supply the body with enough oxygen. This can lead to a condition called respiratory failure, which is a medical emergency.

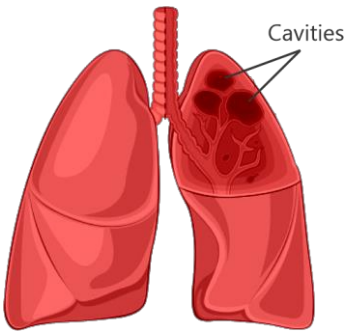


Figure 10.13: A lung affected with TB

Symptoms: Major symptoms of pulmonary tuberculosis are cough-with blood, intermittent intermittent fever usually in the evening, night sweats, weight loss, anorexia, depression, weakness and dry cough, chest pain due to Inflammation of the pleura of the lungs.

Treatment: includes the use of multiple antibioticsover a long period of time (for 9 months) regularly.

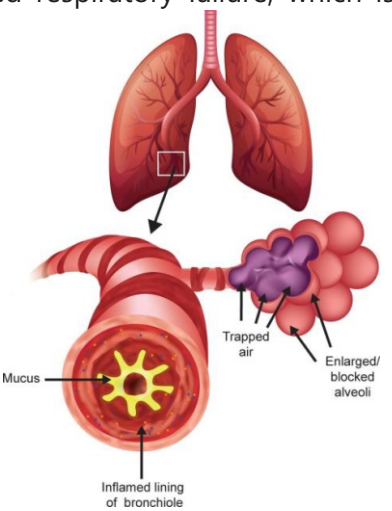


Figure 10.14: A lung affected by COPD

Disorders of the Lungs

Chronic obstructive pulmonary disease (COPD) is an important disorder of the lungs.

1. Chronic Obstructive Pulmonary Disease (COPD)

Chronic obstructive pulmonary disease (COPD) is a chronic inflammatory disease of lungs. The common causes of COPD are tobacco smoking, long terms exposure to harmful pollutants and chemical fumes etc., A small percentage genetic predisposition (protein alpha-1 antitrypsin deficiency) can also develop COPD, even without smoking or significant exposure to pollutants.

Symptoms: The symptoms of COPD are persistent cough with mucus (sputum), shortness of breath, wheezing, chest, fatigue and frequent respiratory tract infections.

Treatment: COPD is incurable but by minimizing exposure to smoke, pollutants, and chemicals, this disease can slow its progression. Others therapies include bronchodilators, inhaled corticosteroids, pulmonary rehabilitation, and oxygen therapy. In some severe cases, surgery such as lung transplantation may be considered.

Chronic bronchitis is a type of COPD. It involves inflammation and narrowing of the bronchial tubes in the lungs. It leads to increased mucus production, which can further block the airways and make breathing difficult. This disease lasts for three months to two years. It is caused by long-term exposure to irritants such as cigarette smoke, air pollution, or industrial dusts **Symptoms** of chronic bronchitis are almost same as of COPD such as wheezing, shortness of breath, chest tightness, and frequent respiratory infections.. Chronic bronchitis can be managed by quitting smoking. Other **treatments** are bronchodilators, pulmonary rehabilitation, and in some cases oxygen therapy.

Emphysema

Emphysema is a type of COPD. In emphysema, the inner walls of alveoli are damaged, causing them to eventually rupture. This creates one larger air space instead of many small ones and reduces the surface area available for gas exchange. The primary cause of emphysema is smoking. It can also be caused by long-term exposure to air pollution, dust, or chemical fumes. Emphysema disease can also be caused by a genetic deficiency of a protein called alpha-1 antitrypsin.

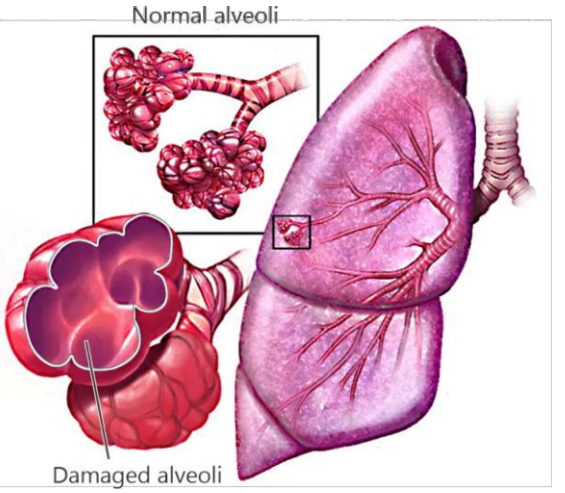


Figure 10.15: Emphysema

Symptoms: The symptoms of emphysema include shortness of breath, coughing, wheezing, fatigue, and chest tightness.

Treatment: Quitting smoking is the most important step in managing emphysema, as continued smoking can speed up the progression of disease. Other treatments include bronchodilators, inhaled steroids, oxygen therapy, and pulmonary rehabilitation.

EXERCISE

MULTIPLE CHOICE QUESTIONS

1. During inhalation, diaphragm;
   (a) Contracts and moves upward (b) Contracts and moves downward
   (c) Relaxes and moves upward (d) Relaxes and moves downward
2. Which part of the respiratory system acts as the respiratory surface?
   (a) Larynx (b) Trachea (c) Bronchi (d) Alveoli
3. How many oxygen molecules can attach with a haemoglobin molecule?
   (a) 1 (b) 2 (c) 3 (d) 4
4. What is TRUE about respiratory pigments?
   (a) Transport oxygen from lungs to tissues
   (b) Transport oxygen and carbon dioxide in equal amounts
   (c) Transport less oxygen and more carbon dioxide
   (d) Regulate the pH of blood
5. Which respiratory pigment is found in muscle tissue?
   (a) Haemoglobin (b) Melanin (c) Myoglobin (d) Chlorophyll
6. What is the maximum amount of air that can be inhaled or exhaled during a respiratory cycle?
   (a) Tidal volume (b) Vital capacity
   (c) Inspiratory reserve volume (d) Expiratory reserve volume
7. In what form is carbon dioxide primarily transported in the bloodstream?
   (a) Dissolved in plasma (b) Bound to haemoglobin
   (c) Converted to bicarbonate ions (d) None of the above
8. Which of the following treatments is commonly used to manage pulmonary TB?
   (a) Antibiotics (b) Cough syrup (c) Surgery (d) Chemotherapy
9. Which of the following is a common cause of pneumonia?
   (a) Bacterial infection (b) Viral infection
   (c) Fungal infection (d) All of these

10. Emphysema is characterized by:
    (a) Inflammation of airways (b) Narrowing of airways
    (c) Destruction of the alveoli in lungs (d) Fluid build-up in lungs

SECTION 2: SHORT QUESTIONS

1. Define respiratory surface and list its properties.
2. How nasal cavity functions in filtering the inhaled air?
3. Trace the path of air through different parts of the respiratory system.
4. Describe the structure and function of alveoli.
5. What is the role of diaphragm during inhalation and exhalation?
6. What the three ways of the transport of carbon dioxide in blood?
7. What are the advantages of having millions of alveoli rather than a pair of simple balloon-like lungs?
8. Differentiate between:
    - Internal and external respiration
    - Upper and lower respiratory tract
    - Bronchi and bronchioles
    - Haemoglobin and myoglobin

LONG QUESTIONS

1. Describe the mechanism of inhalation and exhalation.
2. Describe the transport of oxygen through blood.
3. Describe the transport of carbon dioxide through blood.
4. Describe the structure and function of haemoglobin.
5. Describe the causes, symptoms and treatment of sinusitis.
6. Describe the causes, symptoms and treatment of pneumonia and pulmonary tuberculosis.
7. Describe causes, symptoms and treatment of emphysema.

INQUISITIVE QUESTIONS

1. How does the structure of the alveoli optimize the exchange of gases like oxygen and carbon dioxide?
2. How do diseases like chronic obstructive pulmonary disease (COPD) affect gaseous exchange efficiency?
3. Can you explain the process of external respiration versus internal respiration in the context of gaseous exchange?
4. How does the transport of like oxygen in the bloodstream support cellular respiration?
5. What are the environmental factors that can influence gaseous exchange in humans?

Chapter 11

HUMAN CIRCULATORY SYSTEM

STUDENTS'LEARNING OUTCOMES

After studying this chapter, the students will be able to:

- State the location of heart in the body and define the role of pericardium.
- Describe the structure of the walls of heart and rationalize the thickness of the walls of each chamber.
- Trace the flow of blood through the heart as regulated by the valves.
- State the phases of heartbeat.
- Explain the role of SA node, AV node and Purkinje fibers in controlling the heartbeat.
- List the principles and uses of Electrocardiogram.
- Describe the detailed structure of arteries, veins and capillaries.
- Describe the role of arterioles in vasoconstriction and vasodilation.
- Describe the role of precapillary sphincters in regulating the flow of blood through capillaries.
- Trace the path of the blood through the pulmonary and systemic circulation (coronary, hepatic-portal and renal circulation).
- Compare the rate of blood flow through arteries, arterioles, capillaries, venules and veins.
- Define blood pressure.
- State the role of baroreceptors and volume receptors in regulating the blood pressure.
- Define the term thrombus and differentiate between thrombus and embolus.
- Identify the factors causing atherosclerosis and arteriosclerosis.
- Categorize Angina pectoris, heart attack, and heart failure as the stages of cardiovascular disease development.
- State the congenital heart problem related to the malfunctioning of cardiac valves.
- Describe the principles of angiography.
- Outline the main principles of coronary bypass, angioplasty and open-heart surgery.
- Define hypertension and describe the factors that regulate blood pressure and can lead to hypertension and hypotension.
- List the changes in lifestyles that can protect man from factors that regulate blood pressure and can
- lead to hypertension and hypotension.
- List the changes in lifestyles that can protect man from hypertension and cardiac problems.
- Describe the formation, composition and function of intercellular fluid.
- Compare the composition of intercellular fluid with that of lymph.
- State the structure and role of lymph capillaries, lymph vessels and lymph trunks.
- Describe the functions of lymph nodes and state the role of spleen as containing lymphoid tissue.

Humans have two systems for the transport of different materials in different parts of body i.e., blood circulatory system and lymphatic system. The closed blood circulatory system of humans

Recalling:
Blood is the medium in which dissolved nutrients, gases, hormones, and wastes are transported throughout the body. It is composed of two main components (i) plasma and (ii) cells or cell-like bodies (white blood cells, red blood cells, platelets). In a healthy person, plasma constitutes about 55% by volume of the blood, and cells or cell-like bodies about 45% by volume of the blood.

consists of blood, heart, and blood vessels (arteries, capillaries and veins).

11.1- Structure And Functioning Of Heart

Human heart is a hard-working pump that moves blood through body. It is situated in the middle of chest cavity (between the lungs). Its back surface is near vertebral column while its front surface is behind sternum and rib cartilages.

The heart is usually felt to be on the left side because the left side of heart is stronger and larger, since it pumps to all body parts.
Because the heart is between the lungs, the left lung is smaller than the right lung and has a cardiac notch in its border to accommodate the heart.

Pericardium

Heart is enclosed in a sac called **pericardium** (Figure 11.1). Pericardium separates heart from surrounding organs. It is composed of the following two layers;

1. Outer layer of pericardium is called **fibrous pericardium**. It is made of strong connective tissue. It protects heart against external pressure and shocks. It also prevents excessive dilation of heart.
2. Inner layer of pericardium is called **serous pericardium** It is a sac, made of two layers i.e.,
   a) Outer **parietal** pericardium - present beneath fibrous pericardium.
   b) Inner **visceral** pericardium (also called epicardium) - closely attached to the underlying heart.

The space between parietal and visceral pericardium is called **pericardial cavity**. It contains up to 50 mL pericardial fluid. It lubricates heart and protects it from infections.

Wall of the Heart

The wall of heart is composed of three layers. The inner layer of pericardium i.e., epicardium makes the outer lining of heart wall. Beneath epicardium, there is the thickest layer of heart wall i.e., **myocardium**. Myocardium is made of cardiac muscles. **Endocardium** is present beneath myocardium. It is a single layer of epithelial cells and make 1 .

the inner linings of heart chambers (Figure 1 .1)

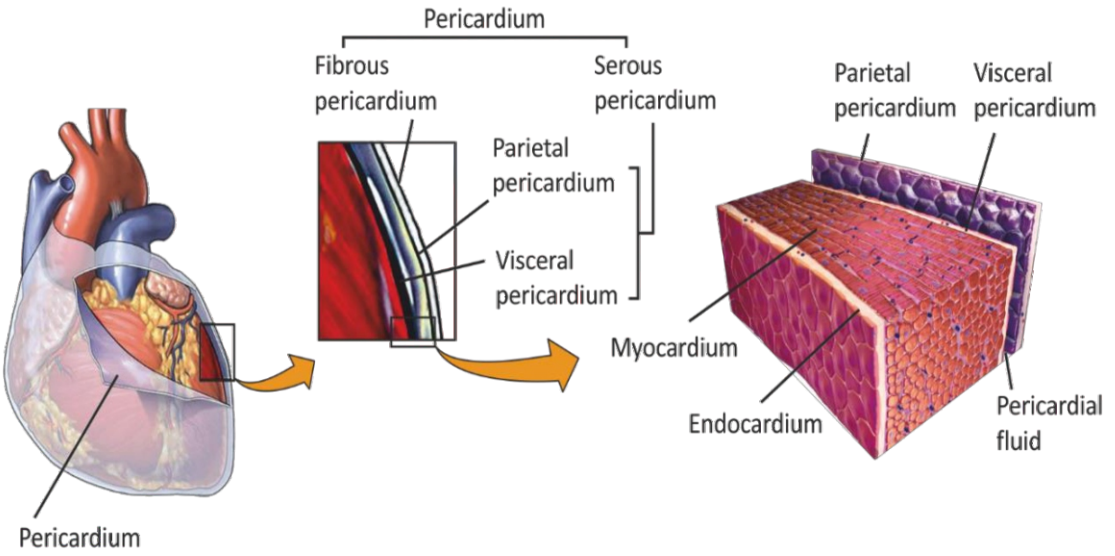


Figure 11.1: Pericardium and heart wall

Chambers and Valves of Heart

There are four chambers of heart i.e., two upper thin-walled **atria** and two lower thick-walled **ventricles**. Atria receive blood from body and pass it to ventricles, which distribute blood to body. Atria and ventricles are separated by **atrioventricular septum**. The left and right atria are separated from each other by an **interatrial septum**. Similarly, the left and right ventricles are separated from each other by an **interventricular septum**. It is much thicker than the interatrial septum.

At the entrance points of ventricles (in atrioventricular septum), there are two atrioventricular valves i.e., a tricuspid valve and a bicuspid valve. **Tricuspid valve** (made of three cusps) is present between right atrium and right ventricle. **Bicuspid (mitral) valve** (made of two cusps) is present between left atrium and left ventricle. When ventricles contract, tricuspid and bicuspid valves close and prevent the back flow of blood into atria.

At the exit points of ventricles, there are two **semilunar valves** (with shapes like a half-moon). These are called pulmonary valve and aortic valve. **Pulmonary valve** is located at the base of pulmonary artery while **aortic valve** is present at the base of aorta. When ventricles relax, pulmonary and aortic valves close. So, they prevent back flow of blood from pulmonary artery and aorta into ventricles.

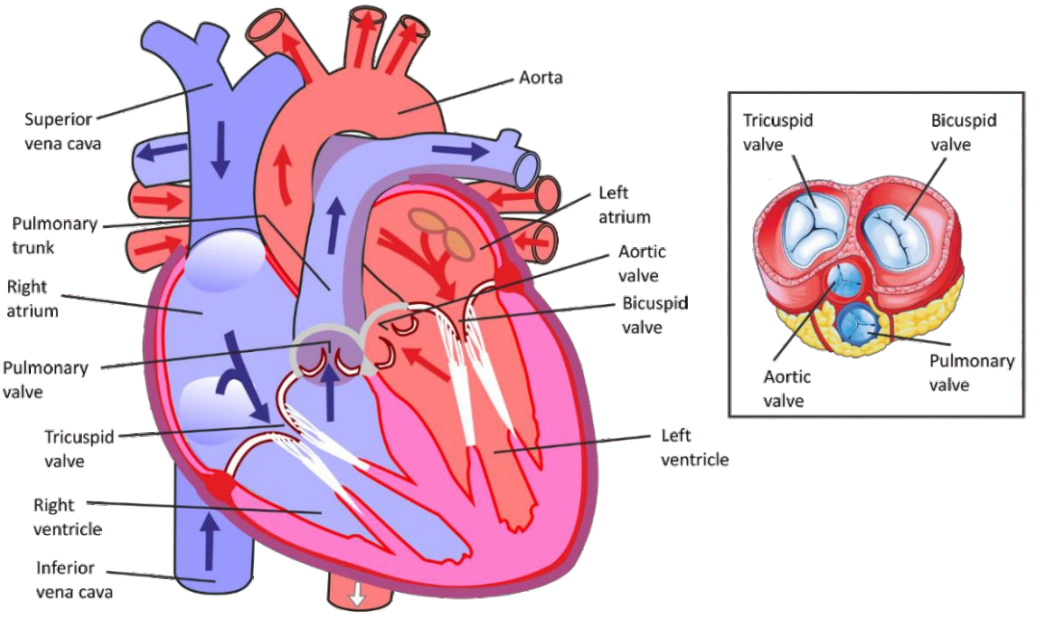


Figure 11.2: Human Heart and valves

Circulation of Blood through HEART

Human heart functions as a **double pump**. It carries out pulmonary circulation (supply of blood to lungs) and systemic circulation (supply of blood to all organs of body – except lungs). Complete separation of deoxygenated (right side) and oxygenated (left side) blood is maintained in heart.

The right atrium receives deoxygenated blood from body via two veins i.e., superior vena cava and inferior vena cava. Right atrium passes this blood to right ventricle via tricuspid valve. When right ventricle contracts, deoxygenated blood is passed to pulmonary trunk via semilunar pulmonary valve. The pulmonary trunk divides into left and right pulmonary arteries which carry this blood to lungs.

The oxygenated blood from lungs is brought to left atrium by pulmonary veins. Left atrium passes this blood to left ventricle via bicuspid (or mitral) valve. When left ventricle contracts, oxygenated blood is passed to aorta via semilunar aortic valve. Aorta carries this blood to all parts of body (except lungs).

The wall of left ventricle is thicker (about 3 times) than that of the right ventricle because it has to push the blood to all over body.

Cardiac Cycle Heartbeat

Heart works in continuous cycles. Its chambers relax and are passively filled with blood from large veins. Then, its chambers contract and propel the blood throughout body. Its alternating relaxations and contractions are collectively called a cardiac cycle or one **heartbeat**.

While atria are relaxed and being filled with blood, the ventricles are also relaxed. This relaxed period of heart chambers is called **diastole**. During diastole, both atria are filled with blood. As blood accumulates in atria, their blood pressure rises, due to which both of them contract. This is called **atrial systole** It passes the blood through tricuspid and bicuspid valves into the two relaxed ventricles. When ventricles are filled with blood, both of them contract. This is called **ventricular systole** and it pumps the blood to pulmonary arteries and aorta. During ventricular systole, tricuspid and bicuspid valves close while pulmonary and aortic valves open.

In one complete heartbeat, diastole lasts about 0.4 sec, atrial systole takes about 0.1 sec, and the ventricular systole lasts about 0.3 sec. In one's life, heart beats about 2.5 billion times, without stopping.

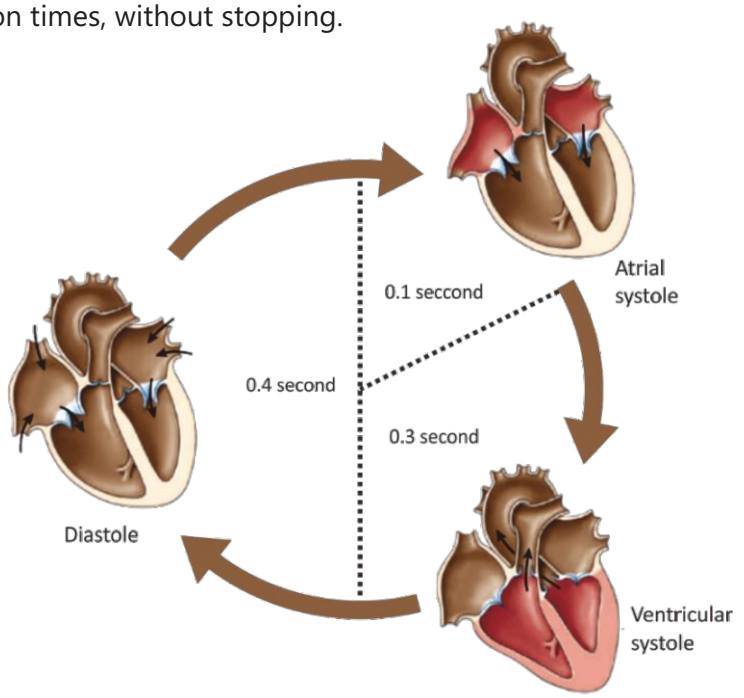


Figure 11.3: Cardiac cycle (one heartbeat)

Sounds of a Heartbeat

When both ventricles contract simultaneously to pump the blood to pulmonary arteries and aorta, the tricuspid and bicuspid valves close and **"lubb"** sound is made. Similarly, when ventricular systole ends and both ventricles relax simultaneously, the pulmonary and aortic semilunar valves close and **"dubb"** sound is made. —Lubb-dubb|| can be heard with the help of a stethoscope.

Most cases of heart murmurs are not serious, and those that prove serious can be corrected by replacing the damaged valves with artificial ones or with valves taken from an organ donor.

If the valves are not closing fully, or if they open narrowly, turbulence is created within the heart. This turbulence can be heard as a heart murmur. A murmur sounds like a hiss.

Control of Heartbeat (Heart Excitation and Contraction)

The pumping of heart is initiated by the **Sinoatrial Node** (SA node) or **pacemaker**. The sinoatrial node consists of a small cluster of cardiac muscle cells. It is embedded in the upper wall of right atrium. Heartbeat starts when SA node sends electrical impulses to the walls of atria. It causes both atria to contract simultaneously. The impulses then travel to an **atrioventricular node** (AV node). It is also made of small cluster of cardiac muscle cells. It lies at the lower portion of interatrial septum.

From AV node, the impulses reach an **atrioventricular bundle** or **bundle of His**. It is a network of fibres present in interventricular septum. AV bundle divides into left and right branches, which end at the **Purkinje fibres** in the walls of the ventricles. Stimulation of these fibres causes the ventricles to contract almost simultaneously (Figure 11.4). There is a delay of about 0.15 second in conductance of impulses from the SA node to AV node, permitting atrial systole to be completed before ventricular systole begins.

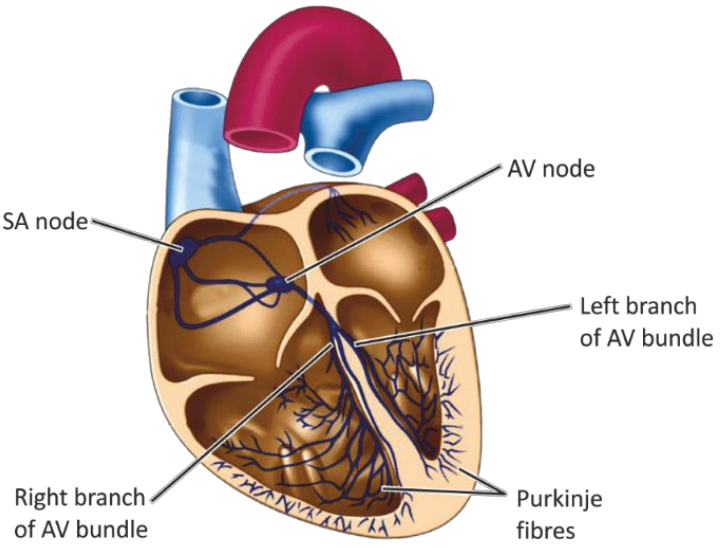


Figure 11.4: Pacemaker and its connections

If there is some block in the flow of the electrical impulses, or if the impulses initiated by SA node are weak; it may delay the rhythmicity of heartbeat or stop it. In such patients of weak SA node, **artificial pacemaker** is used. It is a battery- operated device that is surgically transplanted near the AV node. It emits electrical signals that trigger normal heartbeats.

Rate of Heartbeat

In an adult, about 8,000 litres of blood move through 96,000 km of blood vessels every day.

The heart of an average adult beats about 70 times per minute. It pumps the entire blood volume (about 5 litres) every minute. The normal speed of heartbeat is made and maintained by pacemaker and AV node. Brain also exerts some influence on heart rate. For example, during fever and exercise, the control centre in brain sends nerve signals to both the pacemaker and the AV node, making them to increase the heart rate. It is to cope with the situation. In contrast, when we are asleep or at rest, the brain's control centre slows down the activity of pacemaker and AV node.

Electrocardiogram

The recording of electrical potentials, generated by the currents of cardiac impulses, is known as electrocardiogram (ECG). When cardiac impulse passes over the surface of heart, a minute electrical current is generated. This current spreads into the tissues surrounding heart. This minute electrical current also travels to the surface of body. In ECG, the electrical potentials generated by this current are measured and recorded. For this purpose, electrodes are placed on skin on the opposite sides of heart. The electrodes are attached to a machine called **electrocardiograph** that records electrical potentials generated by this current. ECG helps to diagnose the abnormalities in conduction system of heart. ECG shows the following waves of electrical impulses produced at specific events of cardiac cycle. (Figure 11.5).

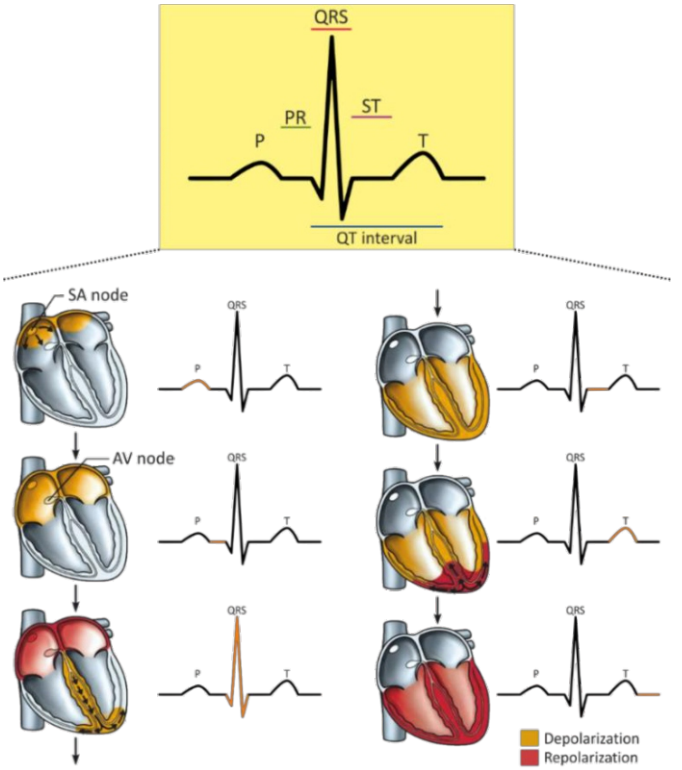


Figure 11.5: ECG reading of a single heartbeat

P wave: It shows beginning of atrial depolarization, initiated by SA node. It causes atrial contraction. Irregular or absent P waves may indicate arrhythmia (lack of rhythmicity).

PR segment: It shows the completion of atrial depolarization. It is usually 0.12 to 0.20 seconds. A prolonged PR indicates a first-degree heart block.

QRS: It shows the beginning of depolarization of ventricles. Atrial re-polarization also occurs during this phase. Abnormalities in the QRS complex may indicate bundle branch block, ventricular tachycardia (faster rate of contraction), or other ventricular abnormalities.

Some abnormal babies may have blueness (cyanosis) of skin. They are called blue babies. It is due to the mixing of oxygenated and deoxygenated blood between two atria. Mixed blood is supplied to the body of new born babies resulting in blueness of skin. Cyanosis results due to the failure of **interatrial foramen** to close, during development. Interatrial foramen is a temporary opening in the embryonic heart between right and left atria. Normally, it is closed during development. Cyanosis may also happen due to failure of **ductus arteriosus** to fully constrict, during development. Ductus arteriosus is a temporary channel between the embryonic pulmonary artery and aorta. Normally, it constricts during development.

ST segment: It shows the completion of depolarization of ventricles. It can be depressed in ischemia (decreased flow of blood and oxygen to heart muscles) and elevated in myocardial infarction. This segment ordinarily lasts about 0.08 second.

T wave: It represents the beginning of repolarization of ventricles. T wave abnormalities may indicate electrolyte disturbance. The hyper-acute T wave shows the earliest findings of acute myocardial infarction.

QT interval: The QT interval is from the beginning of the QRS complex to the end of the T wave. A normal QT interval is usually about 0.40 seconds.

11.2- Blood Vessels

Arteries, veins, and capillaries are the main blood vessels in human circulatory system.

1. Arteries

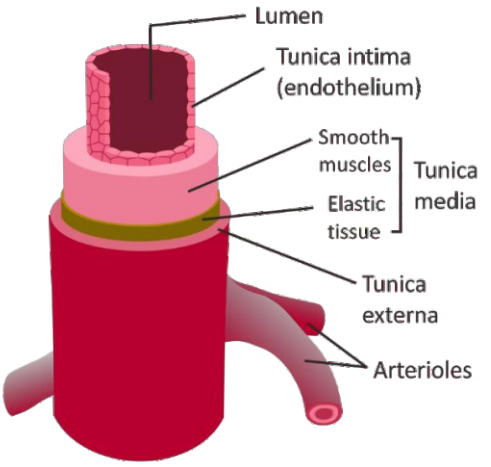


Figure 11.6: Structure of artery

Arteries are the blood vessels which carry blood away from heart to different parts of body. All arteries carry oxygenated blood, except pulmonary arteries. The central core of artery is **lumen**. The walls of arteries are made up of three layers. Outer layer i.e., **tunica externa** or adventitia is made of connective and elastic tissue. Middle layer i.e., **tunica media** is made of thick muscular tissue and elastic fibres. Inner layer i.e., **tunica intima** is made of thin layer of endothelial cells. Middle layer is important and it can withstand higher blood pressure during ventricular systole. Arteries divide into smaller vessels called **arterioles**. Arterioles divide repeatedly until they form a dense network of very fine branches i.e., capillaries.

2. Capillaries

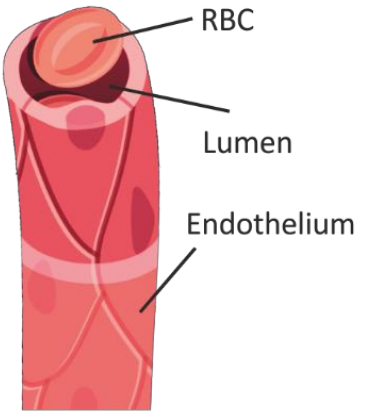


Figure 11.7: Structure of capillary

These vessels are formed by the division of arterioles. Capillaries join to form venules. Capillaries penetrate all tissues and have approach to the cellular level. The walls of capillaries are made of a single layer of **endothelial** cells. The internal diameter of a capillary is about 8 micrometres. Capillaries are the sites where materials are exchanged between blood and body tissues by diffusion or active transport. Water and diffusible substances can pass through capillary walls. Materials pass through the endothelial cells or through the intercellular spaces of capillary wall. Some materials are also taken up by capillary wall cells by endocytosis. The capillary wall cells then pass these materials to the other side by exocytosis.

No cell of the body is more than 100 micrometres away from a capillary. Capillaries are so narrow that RBCs must pass through them in single line. It is estimated that the total length of capillaries in an adult human is over 80, 600 kilometres, enough to encircle the globe twice!

The pressure within capillaries causes a continuous leakage of fluid from the blood plasma into tissues. This fluid, known as **interstitial fluid** consists of water with dissolved nutrients, hormones, gases, wastes and small proteins. Large proteins, RBCs and platelets remain within capillaries. But some WBCs can squeeze out through the intercellular spaces of capillary wall.

3. Veins

These blood vessels carry blood from different parts of the body towards heart. All veins carry deoxygenated blood, except pulmonary veins. The wall of veins has same three layers as are present in arteries. The outer layer i.e., **tunica externa (adventitia)** is made of connective and elastic tissue. The middle layer i.e., **tunica media** is relatively thin and only slightly muscular, with few elastic fibres. The inner layer i.e., **tunica intima** is made of thin layer of endothelial cells.

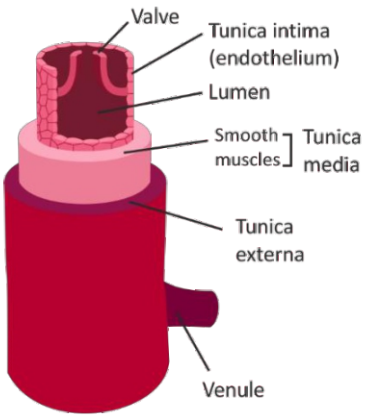


Figure 11.8: Structure of vein

The middle layer of veins is relatively thinner than that of arteries because veins do not have to withstand high blood pressure. An empty artery is still a hollow tube but an empty vein collapses like an empty balloon. **Semilunar valves** are present in veins to prevent the back flow of blood, as it is moving towards heart. The pressure generated by the contraction of surrounding muscles presses veins and assists in the return of blood towards heart.

Smaller veins join to form larger veins and ultimately from vena cavae (inferior vena cava and superior vena cava), which pour blood into the right atrium of heart. Pulmonary veins from lungs empty in left atrium.

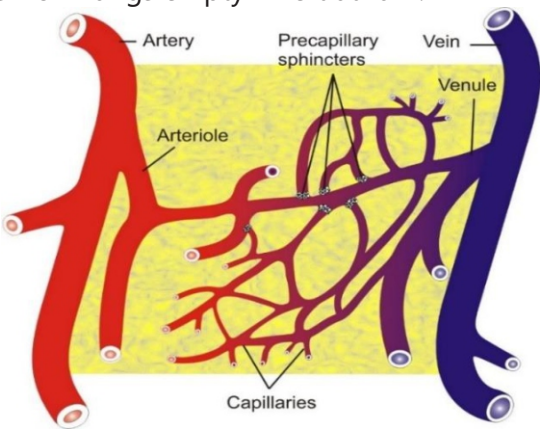


Figure 11.9: Relationship of arterioles, capillaries & venules

Regulation of Blood Flow in Capillaries

The amount of blood flowing in capillaries is controlled by constricting or dilating the capillaries. Nervous stimulation can constrict capillaries and certain chemicals such as histamine can dilate them. Some capillaries are connected with arterioles and venules through loops of other capillaries. The entry of each loop is guarded by a ring of muscles called a **pre-capillary sphincter**. These sphincters regulate the amount of blood flowing through capillaries.

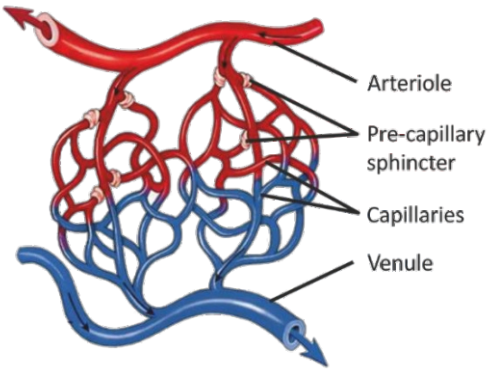


Figure 11.10: Pre-capillary sphincters

Vasoconstriction and Vasodilation inArterioles

In the walls of arterioles, there are more circular muscles than elastic tissue. The contraction of the circular muscles of arterioles is under the control of nervous and endocrine systems. When these muscles contract, arterioles are constricted. It is called **vasoconstriction** and it reduces the flow of blood in arterioles. When these muscles are relaxed, arterioles are dilated. It is called **vasodilation** and it increases blood flow in them.

Vasoconstriction and vasodilation happen in response to changes in metabolic activity of tissues. For example, when metabolic activity in a tissue rises, oxygen decreases and carbon dioxide increases in its interstitial fluid. In its response, the circular muscles of the arterioles in that tissue relax (vasodilation). It increases blood flow in these arterioles and also in capillaries. The increased blood flow supplies more oxygen and removes more carbon dioxide. Similarly, decreased metabolic activity causes vasoconstriction od arterioles.

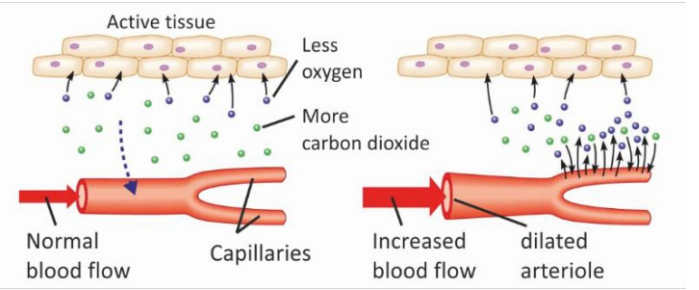


Figure 11.11: Vasodilation

Rate of Blood Flow

The velocity of blood flow is different in different vessels. It is highest in aorta (450-500 mm/sec) and tends to fall along the network of arteries, arterioles and becomes lowest in capillaries (01 mm/sec). It rises again in venules, veins and vena

cavae (250-300 mm/sec). These changes in the velocity of blood result from changes in the total cross section of the vessel system.

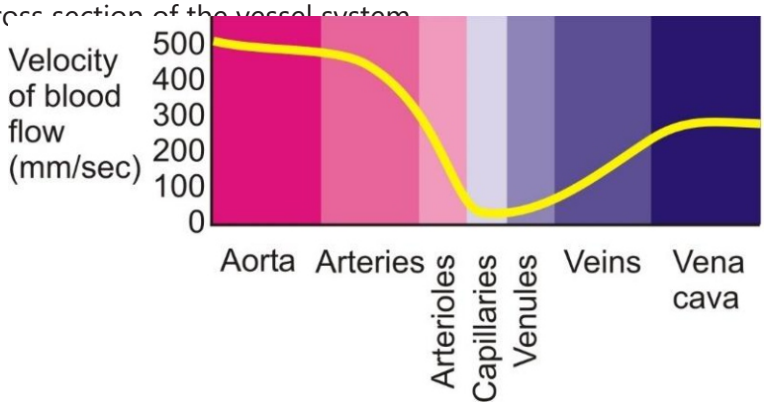


Figure 11.12: Velocity of blood, moving in different vessels

Circulatory Pathways

In humans (and in all mammals and birds), blood circulates throughout body in two main pathways. These are called pulmonary circulation (to and from lungs) and systemic circulation (to and from the other body parts).

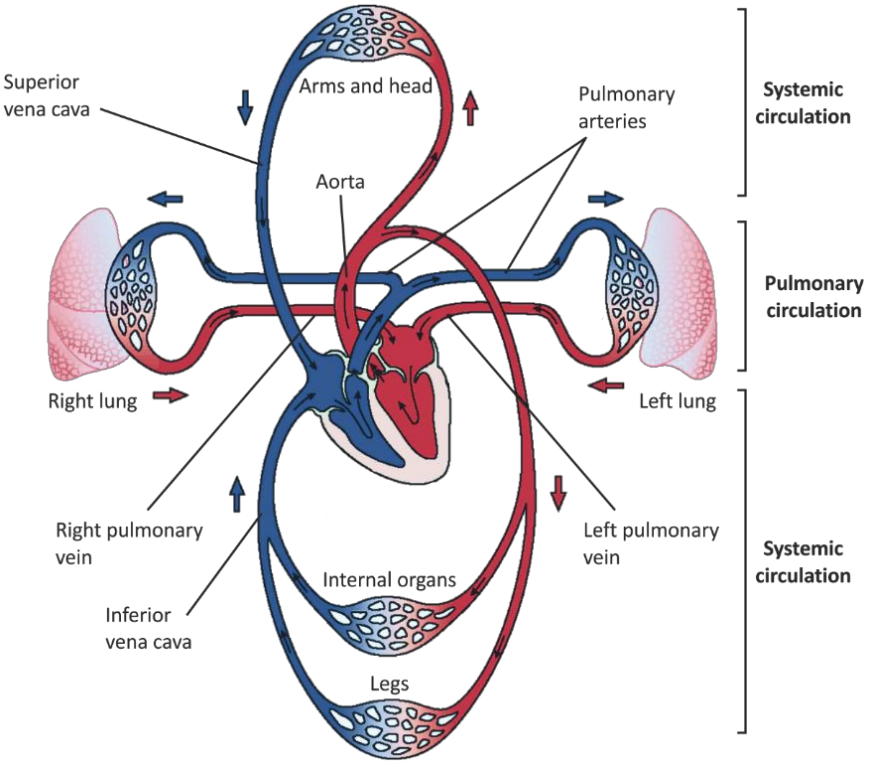


Figure 11.13: Pulmonary and systemic circulations

Pulmonary Circulation

Pulmonary circulation supplies deoxygenated blood to lungs and returns oxygenated blood to heart. A big artery i.e., pulmonary trunk carries deoxygenated blood from the right ventricle of heart. Pulmonary trunk divides into right and left pulmonary arteries, which carry deoxygenated blood to the right and left lungs. Inside each lung, the pulmonary artery divides and makes pulmonary arterioles and lung capillaries. In lung capillaries, blood is oxygenated. Lung capillaries join to form pulmonary venules, which join to form pulmonary vein. Left and right pulmonary veins from lungs open in left atrium.

SystemicCirculation

The systemic circulation supplies oxygenated blood to all the cells, tissues, and organs of the body (except lungs) and returns deoxygenated blood to heart. It consists of the following components:

1. Coronary Circulation

The heart walls are supplied with blood through a small portion of the systemic circulation. Two **coronary arteries** i.e., right and left coronary arteries arise from aorta, near its origin. These arteries divide into many smaller arteries, arterioles and then into capillaries. After supplying oxygenated blood to heart muscles, the capillaries unite to form venules which make many **coronary veins** The coronary veins join to form a **coronary sinus** which opens in right atrium. Small coronary veins drain directly into right atrium

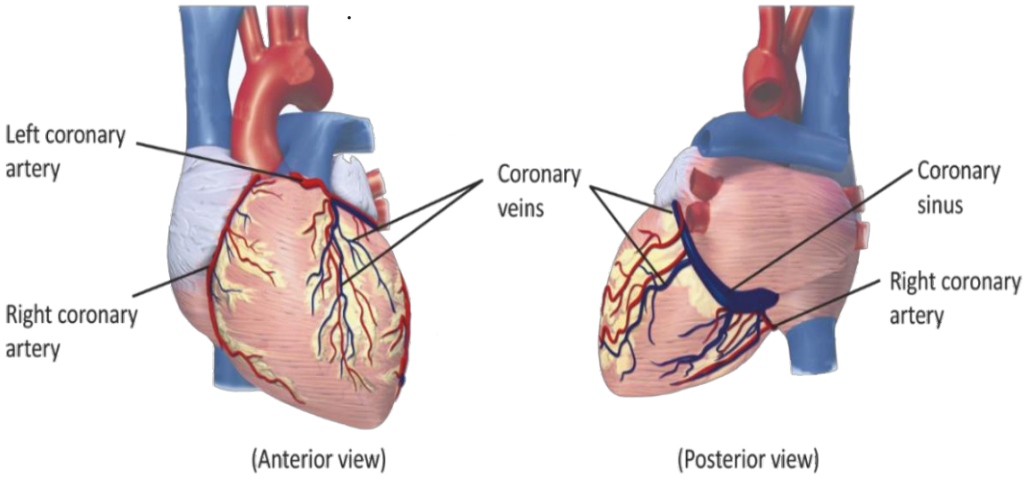


Figure 11.14: Coronary circulation

2. Hepatic Portal Circulation

A portal system is a circulation in which veins end in capillaries. In hepatic portal system, a large **hepatic portal vein** collects blood from spleen and alimentary canal and take it to liver. The blood from liver is taken to heart through **hepatic veins**.

The blood that comes from alimentary canal to liver contains substances that are absorbed from small intestine. These substances pass through liver before going to heart. Liver removes harmful substances from blood and absorbs nutrients for storage before sending this blood to heart. Hepatic portal system extends from the lower portion of oesophagus to the upper part of anal canal.

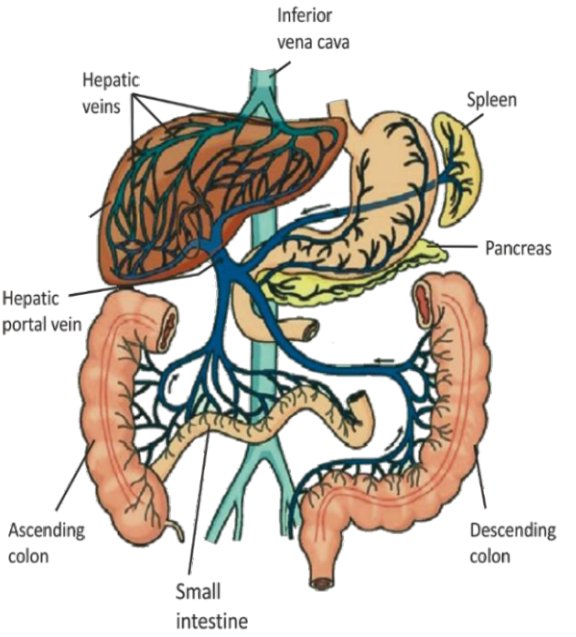


Figure 11.15: Hepatic portal system

3. Renal Circulation

It is another important component of the systemic circulation. Right and left renal arteries carry oxygenated blood to the right and left kidneys. Inside the kidney, each renal artery divides repeatedly to make smaller arteries. The smaller arteries branch into several **afferent arterioles**, which supply blood to nephrons (units of kidney). Each afferent arteriole divides to make the capillaries of **glomeruli**.

The capillaries of glomeruli unite to make **efferent arteriole**, which divides to make two sets of capillaries i.e., (i) **peri-tubular capillaries** (around nephron tubule in cortical portion of kidney), and (ii) **vasa recta** (around nephron tubule in the medulla of kidney). These capillaries unite to form venules that converge and make smaller veins. The smaller veins unit to form a renal vein.

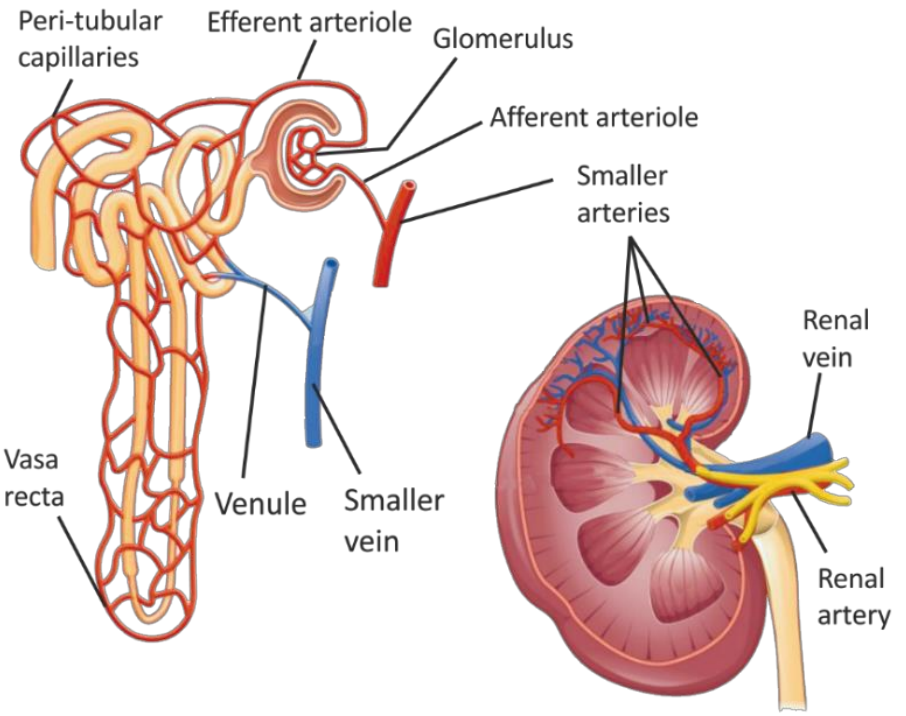


Figure 11.16: Renal portal system

11.3- Blood Pressure

Blood pressure is the measure of force exerted by blood against the inner walls of blood vessels. This force keeps blood flowing from heart to the entire capillary network in body. Although such a pressure occurs throughout the vascular system, the term blood pressure most commonly refers to **systemic arterial blood pressure** Blood pressure is highest in aorta and then gradually reduces in systemic arteries. The walls of arteries are elastic. The flow of blood creates rhythmical throbbing of arteries, which is called as **pulse.**

Arterial blood pressure rises and falls corresponding to the phases of cardiac cycle. When ventricles contract (ventricular systole), heart forces blood into pulmonary arteries and aorta. As a result, the pressure in these arteries rises sharply. The maximum pressure during ventricular systole is called **systolic pressure** Systolic pressure in a normal young adult is **120 mm Hg**. When ventricles relax (diastole), the arterial pressure drops. The lowest pressure that remains in arteries before the next ventricular contraction is called **diastolic pressure** Diastolic pressure in a normal young adult is **75-85 mm Hg**.

Conventionally, the readings of blood pressure are expressed as 120/80. The instrument sphygmomanometer is used for the manual measurement of systolic and diastolic blood pressures. In this instrument, rise and fall in mercury column shows the readings of blood pressure.

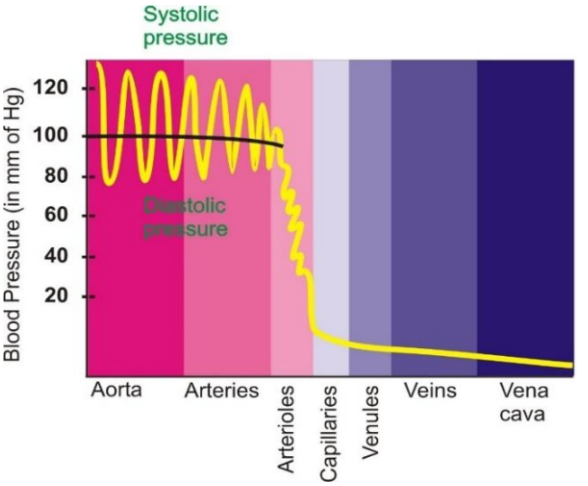


Figure 11.17: Systolic & diastolic blood pressures

Regulation of Blood Pressure

Pressure receptors, known as baroreceptors, are present in carotid arteries (arteries that supply blood to the head region and brain) and aortic arch (portion of artery that bends between the ascending and descending aorta). When blood pressure falls, baroreceptors activate sensory neurons that send information to brain. The control centre in brain reacts by increasing the rate and force of contraction of heart, and by causing vasoconstriction in arterioles. Both these changes restore blood pressure to normal.

The long-term regulation of blood pressure is done through hormones. Certain hormones regulate the volume of blood by effecting the reabsorption of water and salt in kidneys. When there is a decrease in blood volume and blood pressure, special receptors present in brain create thirst. They also stimulate posterior pituitary gland to secrete **antidiuretic hormone (ADH)**. ADH stimulates kidneys to retain more water in blood, excreting less in urine. It restores the blood volume and ultimately blood pressure. ADH also constricts arterioles, which raises arterial blood pressure.

The walls of right atrium contain endocrine cells that secrete **atrial natriuretic hormone (ANH)**. When there is stretching of the atrium by an increased blood volume, the right atrium secretes ANH. It speeds up the excretion of salts and water through urine, which lowers the blood volume and pressure.

11.4- Cardiovascular Disorders

Cardiovascular disorders are the leading cause of death in developed and developing countries. These involve the disorders of blood vessels and heart. Atherosclerosis and arteriosclerosis are the major contributors to cardiovascular disorders.

Atherosclerosis means ~~–~~deposition within arteries||. Various materials may accumulate in arteries e.g., fatty materials, abnormal amounts of smooth muscle cells, cholesterol, fibrin, and cellular debris of various kinds. All these build-ups impair the

proper functioning of arteries. The accumulation of cholesterol is thought to be the prime contributor to atherosclerosis. Atherosclerosis can lead to heart attacks, because it causes the narrowing of arteries and increases the risk of the formation of thrombus.

Arteriosclerosis means ―hardening of arterial walls‖. It occurs when calcium is deposited in arterial walls. The blood flow through these arteries is restricted and arteries cannot expand normally. This forces the heart to work harder. Severe atherosclerosis usually leads to arteriosclerosis.

Various diagnostic tests are performed on cardiovascular patients to locate the exact problem and to measure the severity of disease. The important tests are ECG and angiography. You have learnt about the readings of ECG, and here you would go through the basic learning of angiography.

Angiography

Coronary angiography is an X-ray examination of blood vessels or chambers of heart. In order to create the X-ray pictures, a physician guides a small tube-like device called **catheter** through the large arteries of body. When the tip of catheter reaches the opening of coronary arteries, a special fluid (called a **contrast medium** or dye) is injected in catheter. This fluid is visible in X-ray machine. Pictures (**angiograms**) of fluid in coronary artery are obtained. If clots are present in the lumen of a coronary artery, the artery appears narrow.

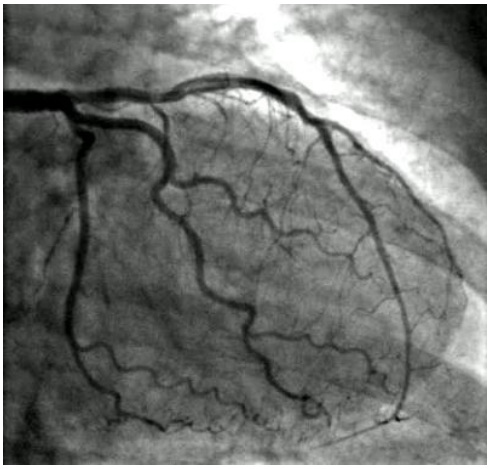


Figure 11.18: An angiogram, showing blood flow in coronary arteries

By changing the **diagnostic catheter** to a **guiding catheter**, physicians can also pass an instrument into coronary artery through the catheter. The most commonly used instruments are guide wires and balloon dilation catheters (see angioplasty).

Thrombosis

Thrombosis is the formation of thrombus. Thrombus is a solid mass or plug of blood constituents (clot) in a blood vessel. This mass may block (wholly or only in part) the vessel. Thrombus formation may be due to; (i) irritation or infection of lining of blood vessels, (ii) reduced rate of blood flow, due to long periods of inactivity, or (iii) pneumonia, tuberculosis, emphysema etc.

Formation of thrombus in a blood vessel and then its carriage to any other location is called **thromboembolism**.

Thrombosis blocks the blood flow to organs. A thrombosis in coronary arteries causes heart attack. Similarly, a thrombus in the vessels of brain causes stroke. A thrombus may be dislodged and carried to some other locations in the circulatory system. Such a thrombus is called **embolus**.

Heart Problems and Treatments

We know that coronary arteries supply oxygen and nutrients to cardiac muscles. If blood flow is blocked in coronary arteries, it results in insufficient supply of blood to one or more parts of cardiac muscle. If heart muscles die due to no supply of oxygen and nutrients, the condition is known as **myocardial infarction** (heart attack).

Heart disease and coronary artery disease are the leading causes of death in developed countries.

Blockage of coronary arteries is usually due to gradual build-up of lipids (especially **cholesterol**) in the inner wall of coronary artery. If such conditions persist, chest pain, called **angina pectoris**, can result during periods of stress or physical exertion. Angina indicates that oxygen demands are greater than its delivery and a heart attack may occur in future.

Recovery from a heart attack is possible if the damaged portion of heart is small enough that the other blood vessels in heart can enlarge their capacity and resupply the damaged tissues.

If lifestyle changes and medication haven't relieved the symptoms or if the narrowed coronary arteries are at imminent risk of a heart attack, coronary bypass surgery or angioplasty is performed.

Coronary Bypass Surgery

The open or beating-heart surgery is done when heart is still beating.

It is one of the most common and effective procedures to compensate the blockage of blood to cardiac muscles. In this surgery, surgeon takes a healthy blood vessel from leg, arm, chest or abdomen of the patient. He attaches the ends of blood vessel above and below the blocked coronary artery. So, blood is bypassed around the damaged or blocked area.

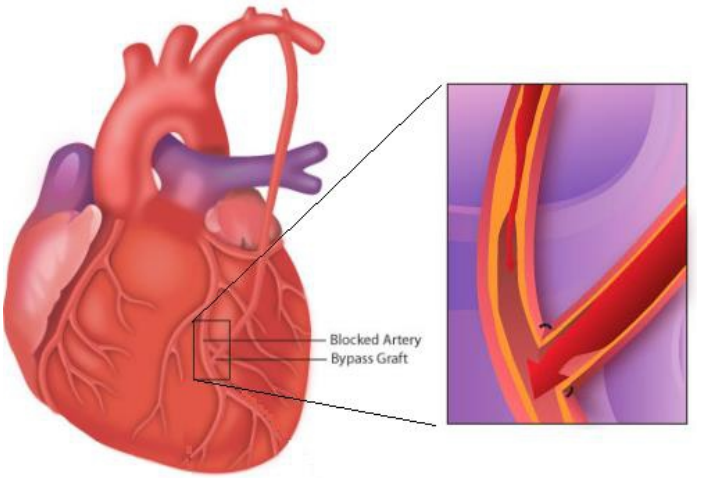


Figure 11.19: Coronary bypass

Coronary bypass surgery doesn't cure the underlying disease process i.e., atherosclerosis or coronary artery disease. Lifestyle changes — especially smoking cessation

— are crucial to reduce the chance of future blockages and heart attacks, even after successful bypass surgery. In addition, patients need to make other lifestyle changes, such as reducing certain types of fat in diet, increasing physical activity, and controlling high blood pressure, diabetes and other risk factors for heart disease.

Angioplasty and Stenting

Angioplasty is a procedure that opens a blocked or narrowed artery. During an angioplasty, a small wire called a catheter, under x-ray guidance, is passed through the narrowed coronary artery. A small sausage-shaped balloon is then advanced over the wire into the narrowed section of artery. The balloon is then inflated to dilate the narrowed section of the artery. Once the artery is dilated, a small amount of dye is injected to confirm the successful dilatation.

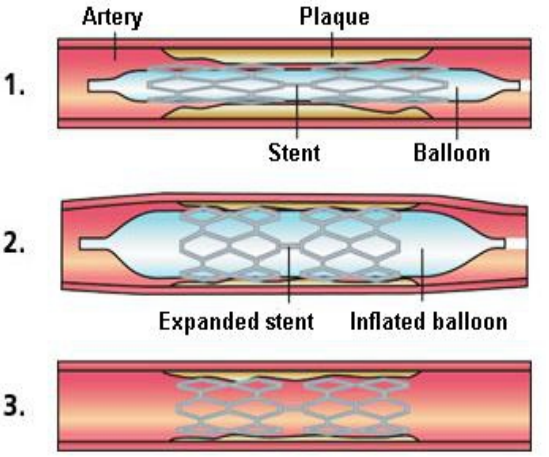


Figure 11.20: Angioplasty and stenting

Stenting may also be done during angioplasty. A **stent** is an expandable stainless steel mesh tube, mounted on a balloon catheter. When the stent/balloon is positioned within the narrowed artery, the balloon is inflated. The inflated balloon expands the stent and the artery. The balloon is removed and the stent remains in place. The stent supports the artery walls and keep the artery open and dilated.

Hypertension

A chronic (long lasting) elevation in blood pressure is called hypertension. It occurs when blood pressure consistently remains above 140/90. Any abnormality in nervous or hormonal mechanisms of blood pressure regulation may cause hypertension. Other causes of hypertension include stress, obesity, high salt intake, and smoking. There may also be hereditary reasons of hypertension.

Whenever blood pressure is chronically elevated, there is an increased chance of the rupture of blood vessels. When this occurs in brain, it is called **brain haemorrhage**. It damages the delicate structure of brain. Hypertension also weakens cardiac muscles. If hypertension is prolonged, heart is unable to pump effectively and blood flow cannot be maintained to meet needs of tissues. In such conditions, blood may be retained in heart and lungs. It is called **congestive heart failure**. Hypertension can also damage the nephrons of kidneys. It leads to further retention of salts and water in blood and therefore further hypertension.

Chest pain, including angina, does not occur during congestive heart failure.

11.5- LYMPHATIC SYSTEM OF HUMAN

In human, in addition to the blood circulatory system, there is another system responsible for the transport of materials. It also returns the materials from tissues to blood. This system is called lymphatic system. It consists of lymph vessels, lymphoid masses, lymph nodes and lymph-the fluid which flows in the system.

Lymph Vesselsand Lymph

Recalling:
The branches of lymph capillaries in villi, are called lacteals. Fatty acids and glycerol are absorbed into the epithelial cells of villi where they form triglycerides. The triglycerides are coated with proteins to form chylomicrons, which enter the lacteals of villi.

Lymphatic system begins with small vessels called **lymph capillaries**, which have blind endings in extracellular fluid (interstitial fluid). Pressure of the interstitial fluid forces it to enter into lymph capillaries. Lymph capillaries are more permeable than blood capillaries. So, larger molecules can also enter lymph capillaries. When interstitial fluid enters lymph capillaries, it is called **lymph**. Lymph capillaries join to form larger **lymphatic vessels** (or lymphatics or lymph vessels). Lymph vessels join to form larger lymph ducts. There are two main lymph ducts i.e., **right lymphatic duct** and **thoracic duct** These vessels open into right and left subclavian veins (veins that drain blood from the arms and shoulders to the heart), respectively. The flow of lymph is always from body tissues towards thoracic duct. It is maintained by the activity of skeletal muscles, movement of viscera and breathing movements. The valves present in lymph vessels prevent the back flow of lymph.

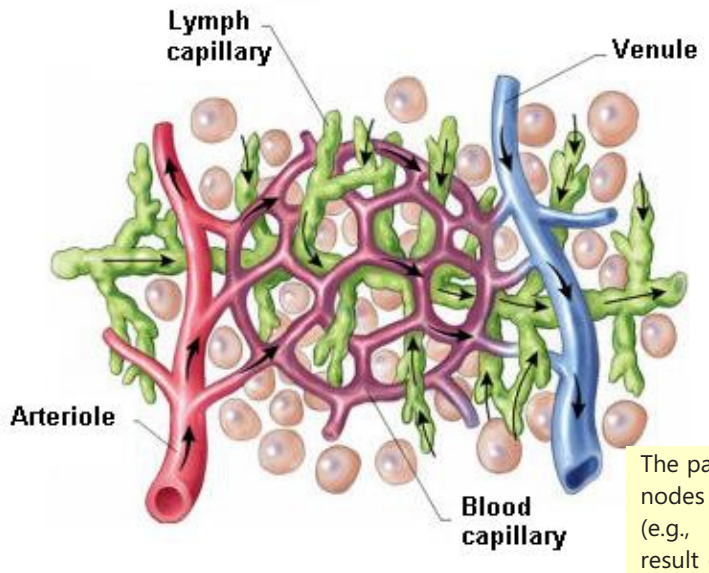


Figure 11.21: Formation of lymph

The painful swelling of lymph nodes in certain diseases (e.g., mumps) is largely a result of the accumulation of dead lymphocytes and macrophages.

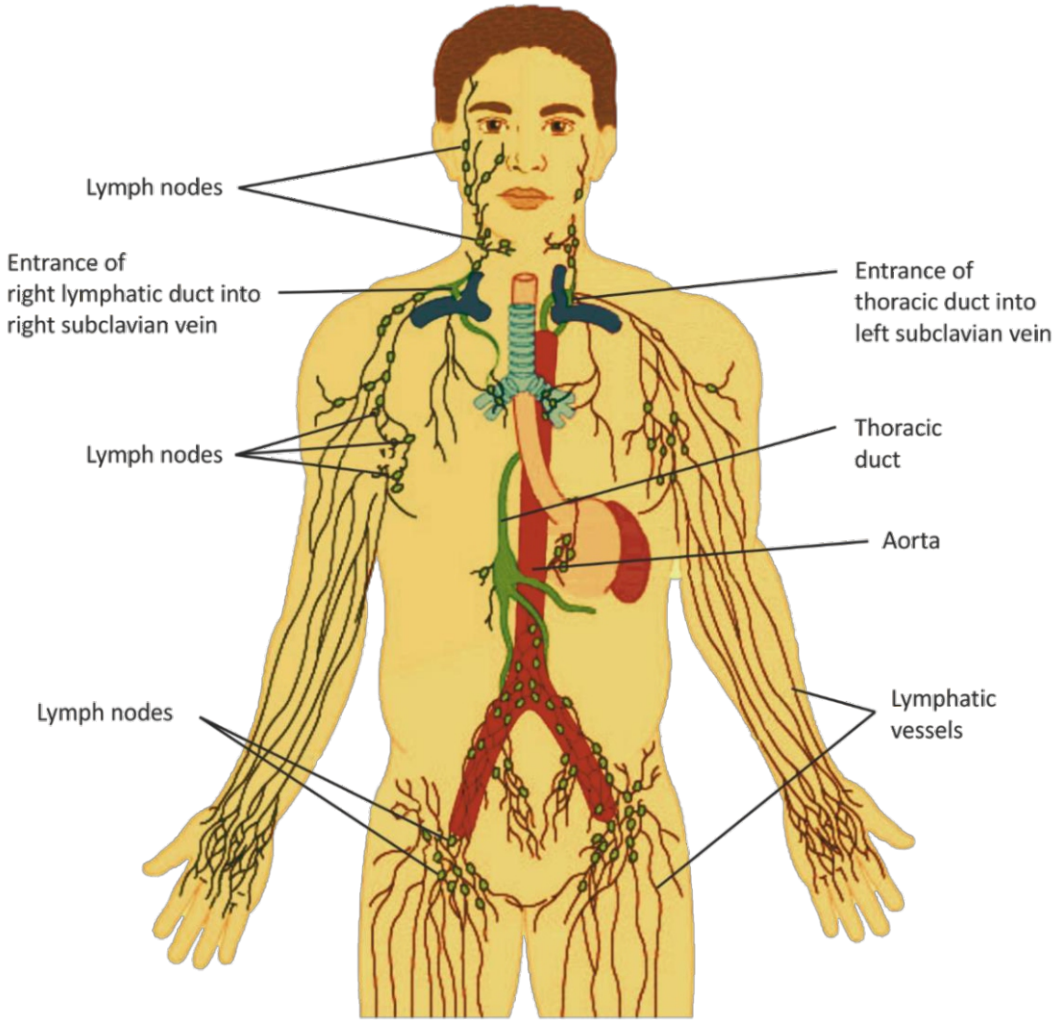


Figure 11.22: Human lymphatic system

Functions of the Lymphatic System

Lymphatic system returns the excess fluid and dissolved proteins and other substances to blood. In an average person, about three litres more fluid leaves blood capillaries daily. But it is absorbed by lymphatic capillaries and returned to bloodstream, before the blood enters heart. Lymphatic system also helps to defend body against foreign invaders. Lymph nodes filter lymph. They have lymphocytes and macrophages that destroy bacteria and viruses present in lymph. Spleen filters blood through its macrophages and lymphocytes that destroy foreign particles and aged RBCs. Spleen also functions to store RBCs.

Lymph Nodes and Lymphoid Masses

At certain spots, the lymph vessels have masses of connective tissue where lymphocytes are present. These are **lymph nodes**. Several afferent lymph vessels enter a lymph node and the lymph is drained by a single efferent lymph vessel. Lymph nodes are present in the neck region, axilla and groin areas of man. In addition to lymph nodes, several **lymphoid masses** are present in different areas e.g., in the mucosa and submucosa of alimentary canal. The larger lymphoid masses are spleen, thymus, tonsils and adenoids. These produce lymphocytes.

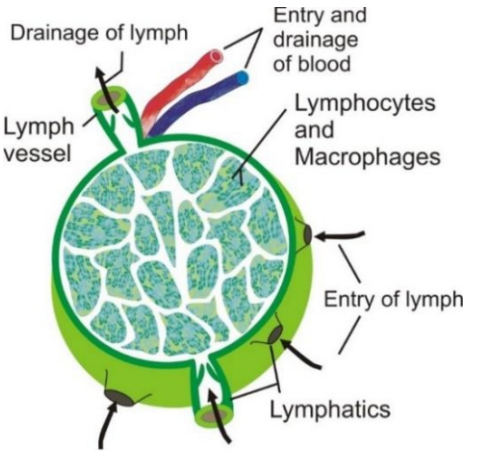


Figure 11.23: A lymph node

EXERCISE

MULTIPLE CHOICE QUESTIONS

1. Compared to vein, an artery;
   (a) Has thinner walls (b) Is located more superficially
   (c) Carries blood away from an organ (d) Has no internal valves
2. Bicuspid valve guards the opening between;
   (a) Stomach and intestine (b) Pulmonary vein and left atrium
   (c) Right atrium and right ventricle (d) Left atrium and left ventricle
3. What is the state of bicuspid and tricuspid valves at the end of the first heart sound?
   (a) Bicuspid is closed, tricuspid is open (b) Bicuspid is open, tricuspid is closed
   (c) Both are open (d) Both are closed
4. By beating at normal speed, our heart pumps how much blood per minute?
   (a) 2 litres (b) 3 litres (c) 5 litres (d) 8 litres
5. Closure of tricuspid and bicuspid valves produces sound;
   (a) —Lubb‖ (b) —Dubb‖
   (c) First Lubb‖ then —Dubb‖ (d) None of these but —murmurs‖

6. SA-node initiates heartbeat in;
   (a) Right atrium only (b) Right atrium and partially left also
   (c) Right and left both (d) Left atrium and partially right also
7. Systolic pressure in young man is;
   (a) 60 mm of Hg (b) 80 mm of Hg (c) 100 mm of Hg (d) 120 mm of Hg
8. Blood pressure is highest in _____ and blood moves most slowly in;
   (a) Veins, capillaries (b) Arteries, capillaries
   (c) Capillaries, arteries (d) Veins, arteries
9. Instead of normal —lub-dubb|| sound, a —lub-hiss, lub-hiss|| sound indicates;
   (a) Blocked coronary artery (b) Damaged pacemaker
   (c) Defective semilunar valve (d) High blood pressure
10. In humans which one is the other system for the transport of materials, than blood circulatory system?
   (a) Lymphatic system (b) Digestive system
   (c) Nervous system (d) Respiratory system

SHORT QUESTIONS

1. What is the main difference between the walls of an artery and a vein?
2. Enlist the four valves present in heart and also state their locations.
3. State the phases of heartbeat.
4. List the principles and uses of Electrocardiogram.
5. Define angiography and angioplasty.
6. What is meant by Purkinje fibres?
7. What do you mean by vasoconstriction and vasodilation?
8. What is the rate of blood flow in different types of blood vessels?
9. State the role of baroreceptors and volume receptors in regulating the blood pressure.
10. Differentiate between thrombus and embolus.

LONG QUESTIONS

1. Describe the structure of the walls of heart and rationalize the thickness of the walls of each chamber.
2. Describe the flow of blood through heart as regulated by the valves.
3. Explain how a heartbeat is initiated and controlled.
4. Describe the detailed structure of arteries, veins and capillaries.
5. Describe the role of precapillary sphincters in regulating the flow of blood through capillaries.
6. Write the components of pulmonary circulation.
7. What are the main components of coronary, hepatic-portal and renal circulation?
8. Define blood pressure and explain systolic and diastolic pressure.

9. Define the term thrombus and differentiate between thrombus and embolus.
10. Identify the factors causing atherosclerosis and arteriosclerosis.
11. Write notes on Angina pectoris, heart attack, and heart failure.
12. Outline the main principles of coronary bypass and angioplasty.
13. Define hypertension and describe the factors that regulate blood pressure and can lead to hypertension and hypotension.
14. List the changes in life styles that can protect man from hypertension and cardiac problems.
15. Describe the structure and role of lymph capillaries, lymph vessels and lymph ducts.

INQUISITIVE QUESTIONS

1. Why is the pressure in the pulmonary circulation lower than in the systemic circulation?
2. Why is it so important for the human heart to develop early and begin functioning within the developing embryo?
3. Justify how vasoconstriction or vasodilation is reflective of emotions.
4. Justify in what way the blood circulatory system is dependent on the lymphatic system.
5. Interpret why the swelling of the lymph nodes is a cause of concern.
6. Trace the path of lymph from a lymph capillary until it is returned to the blood.

Chapter 12

HUMAN SKELETAL & MUSCULAR SYSTEMS

STUDENTS'LEARNING OUTCOMES

After studying this chapter, the students will be able to:

- Describe the structure of bone and compare it with that of cartilage.
- Explain the functions of osteoblasts, osteoclasts and osteocytes.
- Describe three types of joints i.e. fibrous joints, cartilaginous joints and synovial joints and give example of each.
- Describe the disorders of human skeleton (disc-slip, spondylosis, sciatica, arthritis, osteoporosis)
- and their causes.
- Describe the injuries in joints (dislocation and sprain) and their first aid treatment.
- Compare smooth muscles, cardiac muscles and skeletal muscles.
- Describe the ultrastructure of the skeletal muscle.
- Explain the sliding filaments model of muscle contraction.
- Describe the action of antagonistic muscles in the movement of knee joint.
- Explain muscle fatigue, cramps and tetany.
- Differentiate between tetanus and muscle tetany.

Support and movement are fundamental aspects of human biology, enabling us to perform a wide range of activities from basic locomotion to complex taks. This chapter delves into the structure of bones and cartilage, which provide the necessary support framework for the body. We will explore the various tyspes of joints, and examine the unique features of the three types of muscles—skeletal, smooth, and cardiac—that drive motions. The sliding filament model will be discussed to understand muscle contraction at a molecular level. Additionally, we will look at common disorders affecting the skeletal and muscular systems, highlighting their impact on human health and mobility.

12.1- BONES AND CARTILAGE

Bones, cartilage, and other connective tissues make an internal framework called skeleton that provides structural support, protects vital organs, and produces movement and locomotion.

Structure of Bone

Bones are made of connective tissue reinforced with calcium and specialized bone cells. The bone's surface is covered by a tough membrane called **periosteum**. The thick layer under periosteum is made of hard material and is called **compact bone**. It makes up

The broad ends of a bone are called **epiphysis** while the middle part along the length of bone is called **diaphysis** or shaft.

the majority of the bone tissue (Fig. 12.1). The basic structural units of compact bone are called **Haversian systems** A Haversian system is made of;

i. **Lamellae:** These are concentric layers of mineralized extracellular matrix that contains **collagen fibres** and small, needle-shaped crystals of calcium phosphate. The crystals are brittle but rigid, giving bone great strength. Collagen, on the other hand, is flexible but weak. As a result, bone is both strong and flexible.

ii. **Lacunae and Osteocytes:** The lamellae are separated by small spaces called lacunae. **Osteocytes**, which are mature bone cells, are located in the lacunae. Osteocytes are connected to each other and to the Haversian canal by small channels called **canaliculi**

iii. **Haversian canal:** The concentric layers of lamellae surround a central canal called the Haversian canal. It contains blood vessels, nerves, and lymphatic vessels.

In addition to these structures, there are small channels that run perpendicular to the Haversian canals and connect them with each other and with the periosteum. They also contain blood vessels, nerves, and lymphatic vessels. Collagen fibres anchor the periosteum to the underlying bone tissue, providing additional strength and stability to the bone.

Beneath the compact bone there is **spongy bone** (Fig. 12.1). It has a latticework structure consisting of bony spikes that make it light and strong.

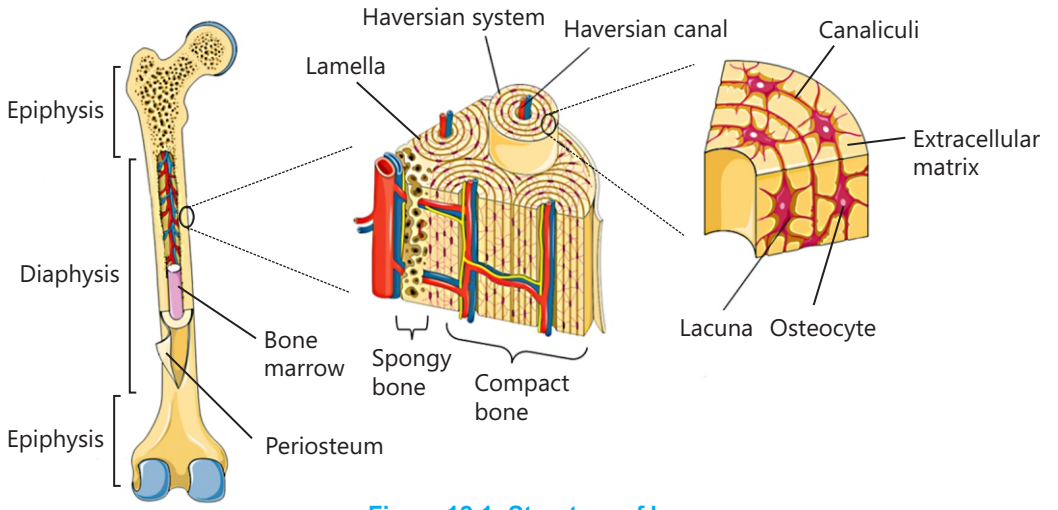


Figure 12.1: Structure of bone

Bone Marrow

Many bones also contain a soft tissue called bone marrow, which can be either red or yellow. Red bone marrow is found in spongy bone, the ends of long bones, ribs, vertebrae, the sternum, and the pelvis. It produces red blood cells, platelets, and

white blood cells. Yellow bone marrow fills the shafts of long bones. It consists mostly of fat cells and serves as an energy reserve. It can also be converted to red bone marrow and produce blood cells when severe blood loss occurs.

Despite their number and size, bones make up less than 20% of the body's mass.

Bones are not dry, rigid structures, as they appear. They are moist, living tissues.

Types of Bone Cells

There are three types of cells i.e., osteoblasts, osteocytes, and osteoclasts involved in the development, growth and remodelling of bones.

Osteoblasts are bone forming cells that synthesize and secrete unmineralized ground substance. Once the osteoblasts are surrounded by matrix, they become the osteocytes.

Osteocytes are mature bone cells which maintain healthy bone tissue by secreting enzymes and bone mineral content. They also regulate the calcium release from bone tissue to blood. **Osteoclasts** develop from macrophages and are involved in bone resorption, i.e., they break down bone and release calcium and phosphate in blood. The work of osteoclasts is important to the growth and repair of bone.

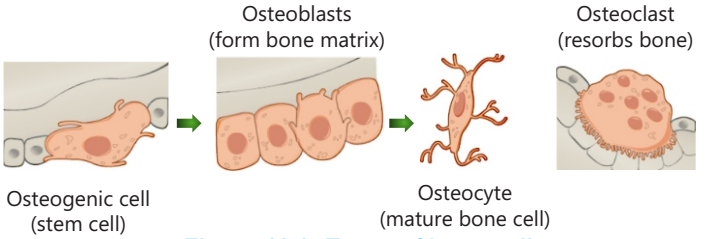


Figure 12.2: Types of bone cells

Bone Development

The process of bone formation is also called **osteogenesis** It begins during embryonic development and continues throughout life, playing a vital role in growth, maintenance, and repair of bones. There are two primary pathways of osteogenesis.

Even after bones have fully formed, osteogenesis continues in the form of bone remodelling. This ongoing process involves the breakdown of old bone by osteoclasts and the formation of new bone by osteoblasts.

1. The formation of long bones e.g., femur and humerus, involves the transition of cartilage into bone. In this process, the center of cartilage begins to harden (calcify), and the chondrocytes (cartilage cells) in this area die, leaving behind cavities. Blood vessels penetrate these cavities and introduce osteoblasts and osteoclasts. Osteoblasts (bone-forming cells) start building bone tissue, replacing the cartilage with new bone. The step by which cartilage is replaced by bone by the deposition of minerals is called **ossification** (Fig. 12.3). Osteoclasts (bone-resorbing cells) break down

the calcified cartilage, making room for more bone tissue to form. As the bone matures, some osteoblasts become trapped within the bone tissue and transform into osteocytes (mature bone cells), which help maintain the bone structure. This process continues until all cartilage is changed to a bone except some cartilage that remains only at the articular (joint) surfaces of the bones.

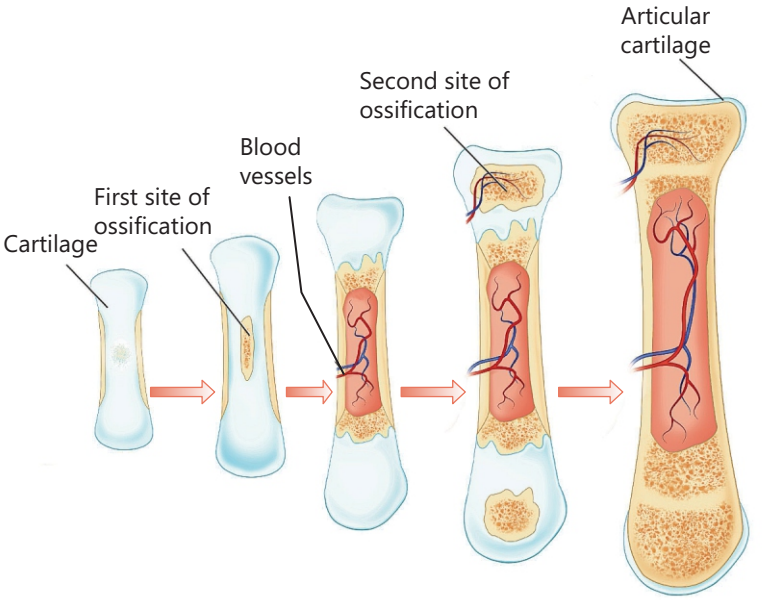


Figure 12.3: Development of bone from cartilage

2. A few bones, e.g., some bones of the skull, develop directly into hard bone without forming cartilage first. In these cases, the osteocytes are initially scattered randomly throughout the embryonic connective tissue but soon fuse into layers and become flat plates of bone.

Structure of Cartilage

As described in the previous paragraph, most of the cartilage of foetus is replaced by bone. However, some cartilage remains throughout life and provides flexibility. For example, at the areas between bones, at the end of nose, in the outer ear, and along the inside of the trachea.

A layer of connective tissue called **perichondrium** surrounds the cartilage. It contains blood vessels, lymphatic vessels, and nerves that supply the cartilage tissue. Inside perichondrium is the **cartilage matrix** which is composed of collagen, elastin, proteoglycans, and other fibres. It gives the tissue its strength, flexibility, and resistance to compression. Unlike other connective tissues, there are no blood vessels inside cartilage matrix. The cells of cartilage are supplied by diffusion. Because of this, it heals very slowly.

The cartilage cells, called **chondrocytes**, are present within small spaces called **lacunae**, which are embedded in cartilage matrix. Chondrocytes are responsible for synthesizing and maintaining the matrix of cartilage (Fig. 12.4).

Cartilage Types

Cartilage can be classified into three types. **Hyaline** cartilage is the most common type and is found in the nose, trachea, and the articulating surfaces of bones in joints. **Fibrocartilage** is found in areas of the body that experience high stress and tension, such as the intervertebral discs and the pubic symphysis. **Elastic cartilage** is found in the external ear and epiglottis.

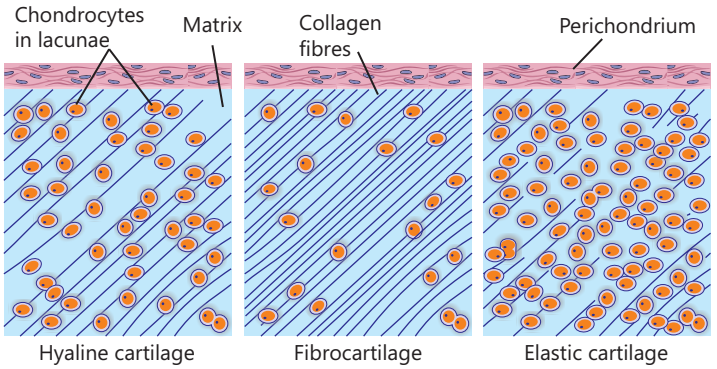


Figure 12.4: Cartilage types

Comparison between Bone and Cartilage

Feature	Bone	Cartilage
External covering	Periosteum	Perichondrium
Cell types	Osteoblast, osteocytes and osteoclasts	Chondrocytes
Extracellular matrix	Contains calcium crystals and collagen fibres	Contains collagen and other fibres
Blood vessels	Present	Absent
Growth & repair	Have the ability to grow and repair themselves throughout life	Has limited ability to repair itself, as it has no direct blood supply

Arrangement of Bones in Skeleton

Human skeletal system consists of 206 bones. Skeleton has two main divisions i.e., axial skeleton and appendicular skeleton (Fig. 12.5).

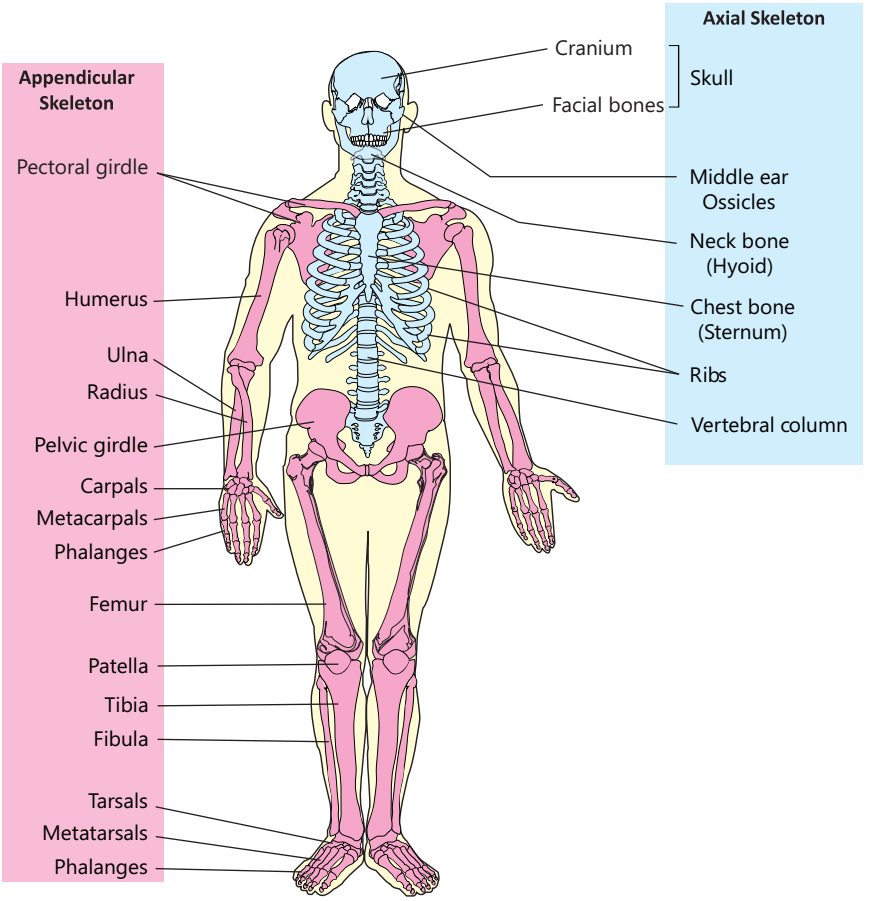


Figure 12.5: Human skeleton

Axial Skeleton

The axial skeleton forms the axis of the body. Its bones support and protect the organs of the head, neck, and chest. It consists of skull, ribs, spine, and sternum.

a- Skull: It consists of the following 22 bones.

- Eight **cranial bones** form cranium (brain box). The 2 paired bones are parietal bones and temporal bone. The 4 unpaired bones are frontal bone, occipital bone, ethmoid bone, and sphenoid bone.
- Fourteen **facial bones** are attached to the cranium. The 6 paired bones are lacrimal, zygomatic, nasal bones, inferior nasal concha, maxilla and palatine. The 2 unpaired bones are mandible (jaw bone) and vomer.

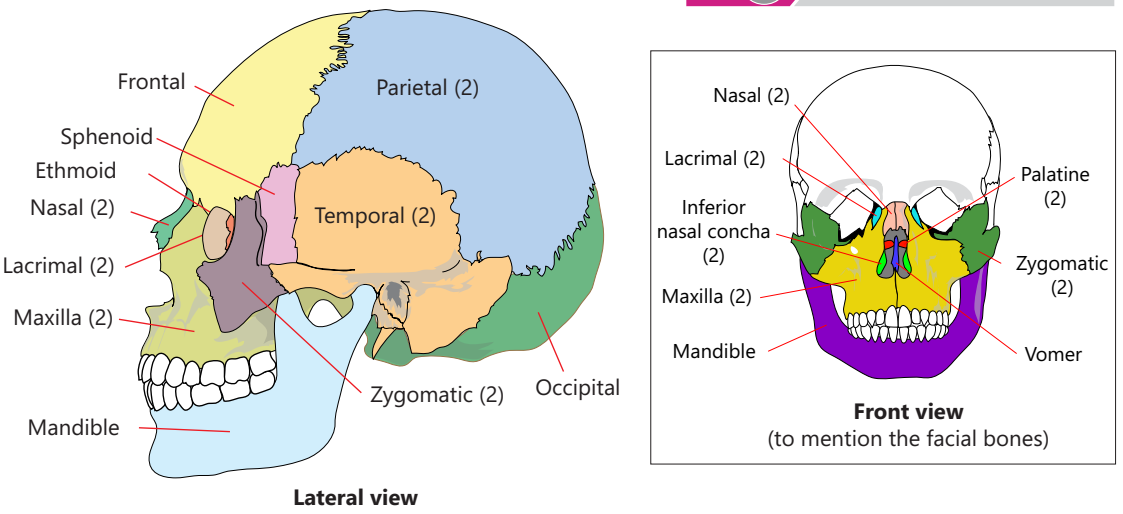


Figure 12.6: Human skull

b- Middle ear: There are 6 bones (3 pairs) in middle ears. These are called ossicles and include malleus, incus and stapes.

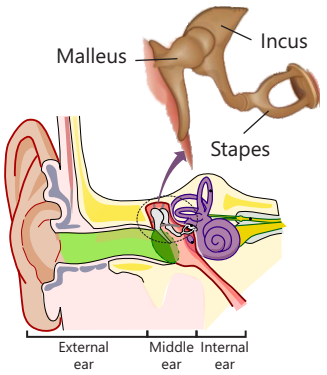


Figure 12.7: Middle ear ossicles

c- Neck bone: Hyoid bone is a small single bone which lies at the base of skull below the tongue. It does not articulate with any other bone of head.

d- Vertebral column: It consists of 33 bones called vertebrae. The vertebrae make five groups:

(i) Seven cervical vertebrae: These are the vertebrae of the neck. The first one is called atlas and the second one is called axis.

(ii) Twelve thoracic vertebrae: These are rib-carrying vertebrae and are found in chest region.

(iii) Five lumbar vertebrae; These are present in abdominal region.

(iv) Five sacral vertebrae; These are five fused vertebrae forming the sacrum. The sacrum articulates with the iliac bones of the hip to form the back of the pelvis.

(v) Four coccygeal vertebrae or coccyx; these vertebrae are fused in the adults. Sacral and coccygeal vertebrae are together called pelvic vertebrae.

e- Rib Cage & Chest bone: The rib cage consists of 24 bones (12 pairs) called ribs and a sternum. The sternum (chest bone) is a long flat bone located in the central part of the chest. The ribs articulate posteriorly with the thoracic vertebrae. On anterior side, 7 pairs of ribs attach directly with the sternum by means of separate costal cartilages. These are called true ribs. The 8^{th}, 9^{th} and 10^{th} pairs attach to the sternum by means of a common costal cartilage and are called false ribs. The last 2 pairs of ribs (11^{th} and 12^{th}) are known as floating ribs, because they do not attach to the sternum.

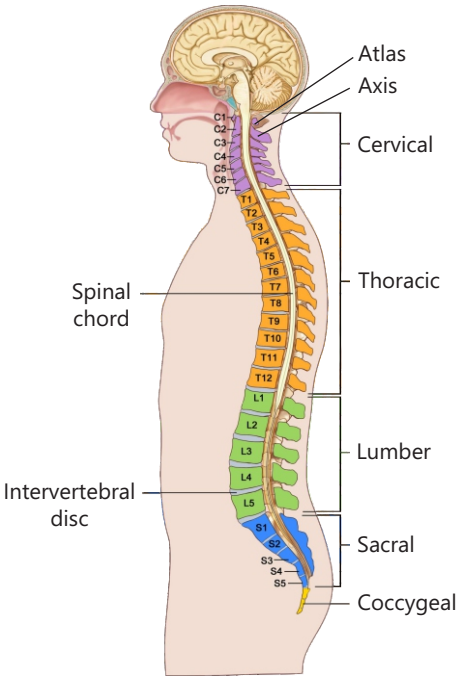


Figure 12.8: Vertebral column

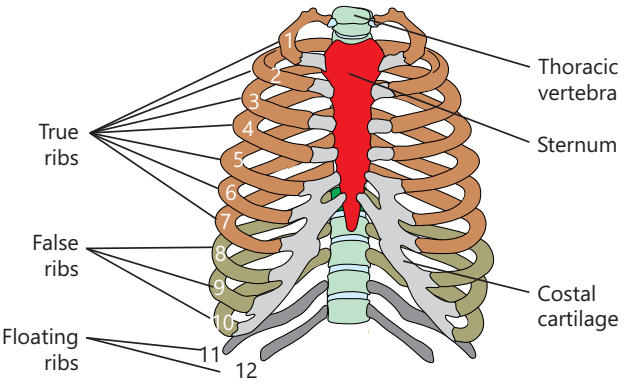


Figure 12.9: Rib cage

Appendicular skeleton

Appendicular skeleton includes the bones present in appendages (arms and legs). These are pectoral girdle, pelvic girdle, forelimbs and hindlimbs.

a- Pectoral girdle: It consists of 2 pairs i.e., a pair of clavicles (collar bones) and a pair of scapulae (shoulder bones). One end of each clavicle articulates with the sternum. The other end articulates with the scapula.

b- Forelimbs: Each forelimb (arm, wrist, hand, fingers) consists of the following 30 bones.

i. One humerus: It is a long bone, the end of which has a spherical head, which fits into the glenoid cavity.

ii. One ulna and one radius: These are long bones. Ulna is on the inner side of arm while radius is on outer side (thumb side). Ulna is slightly bigger than radius.
iii. Eight carpels: There short bones present in two rows and form the wrist. The upper row articulates with the radius and forms the wrist joint.
iv. Five metacarpals: These bones make up the palm of the hand.
v. Fourteen phalanges: Each finger has 3 phalanges while the thumb has 2 phalanges.

c- Pelvic girdle: It is made up of two hip bones. Each hip bone contains 3 bones i.e., ileum, ischium and pubis. In each hip bone, there is a bony socket, called acetabulum that is composed of the fusion of three bones. The two hip bones are joined at the front by the pubic symphysis (a cartilaginous joint that connects the pubic bones at the midline of the body).

d- Hindlimbs: Each hindlimb (leg, ankle, foot, toes) consists of 30 bones.

i. One femur: It is a long thigh bone. Its head fits into the acetabulum of pelvic girdle.
ii. One patella or kneecap: It is embedded in a long tendon which runs over the knee joint.
iii. One tibia and one fibula: Tibia or shin bone is the large bone in the leg. Fibula or outer bone is a thin bone that joins the tibia just below the knee joint and just above the ankle.
iv. Seven tarsals: These are short bones which are tightly attached to form the ankle.
v. Five metatarsals: These bones articulate with the tarsal and phalanges to form the sole of the foot.
vi. Fourteen phalanges: Each toe has 3 phalanges while the big toe comprises 2 phalanges.

Joints

A joint is a place where two bones or bone and cartilage come together. Three major kinds of joints are found in human body i.e., fibrous (immoveable) joints, cartilaginous (slightly moveable) joints and synovial (freely moveable) joints (Figure 12.10-a).

1- Fibrous Joints

In fibrous joints, the bones are directly connected to each other by fibrous connective tissue consisting mainly of collagen. These joints permit no movement of bones. Examples of fibrous joints include:

Sutures that occur only between the immovable bones of the skull.
Joints between the tibia and fibula bones in the lower leg.
Joints between teeth and their sockets in the jawbone.

2- Cartilaginous Joints

In these joints, the bones are connected by a layer of cartilage. Cartilaginous joints allow little movement of the bones. There are two main types of cartilaginous joints:

In some cartilaginous joints, the bones are connected by hyaline cartilage. For example, the joint between the first rib and sternum.

In some cartilaginous joints, the bones are connected by fibrocartilage. For example, pubic symphysis in the pelvic girdle and intervertebral discs.

3- Synovial joints

Synovial joints are the most common type of joint in the human body, and they allow a wide range of movement. A smooth, tough, and elastic hyaline cartilage, called **articular cartilage**, covers the ends of the bones in the joint. It provides a smooth and frictionless surface for movement. A **fibrous capsule** surrounds the synovial joint and helps to hold the bones together. The fibrous capsule is composed of an outer layer of ligaments and an inner lining of synovial membrane, which secretes **synovial fluid**, which lubricates the joint. Strong bands of connective tissue that connect the bones in the joint are call **ligaments**.

There are six main types of synovial joints based on the range of motion.

1- Ball-and-socket joints allow motion in all directions e.g., shoulder and hip joints.

2- Hinge joints allow movement in only one plane, like a door hinge e.g., elbow and knee joints.

3- Pivot joints allow rotational movement around a single axis e.g., joint between the first and second vertebrae of the neck.

4- Ellipsoidal joints allow movement in two planes, but not rotation e.g., joint of wrist with radius.

5- Saddle joints allow movement in two planes because one bone has a concave surface and the other has a convex surface e.g., thumb joint.

6- Gliding joints allow gliding movements between bones e.g., joints between the vertebrae and the joints between the bones in wrist and ankle.

Joint Transplantation

It is a surgical procedure in which a damaged joint is replaced with a healthy natural joint (from donor) or an artificial joint. The most common types of joint transplantation are:

Total joint replacement: In this procedure, the entire damaged joint is replaced with an artificial joint made of metal, plastic, or ceramic.

Partial joint replacement: In this procedure, only the damaged part of the joint is replaced with an artificial component. This is often used in the knee joint.

Allograft transplantation: In this procedure, a healthy joint from a donor is transplanted to replace the damaged joint. This technique is often used in the ankle and knee joints.

Chondrocyte implantation: In this procedure, chondrocytes from patient's own joint are implanted into the damaged joint. This technique is often used in the knee joint.

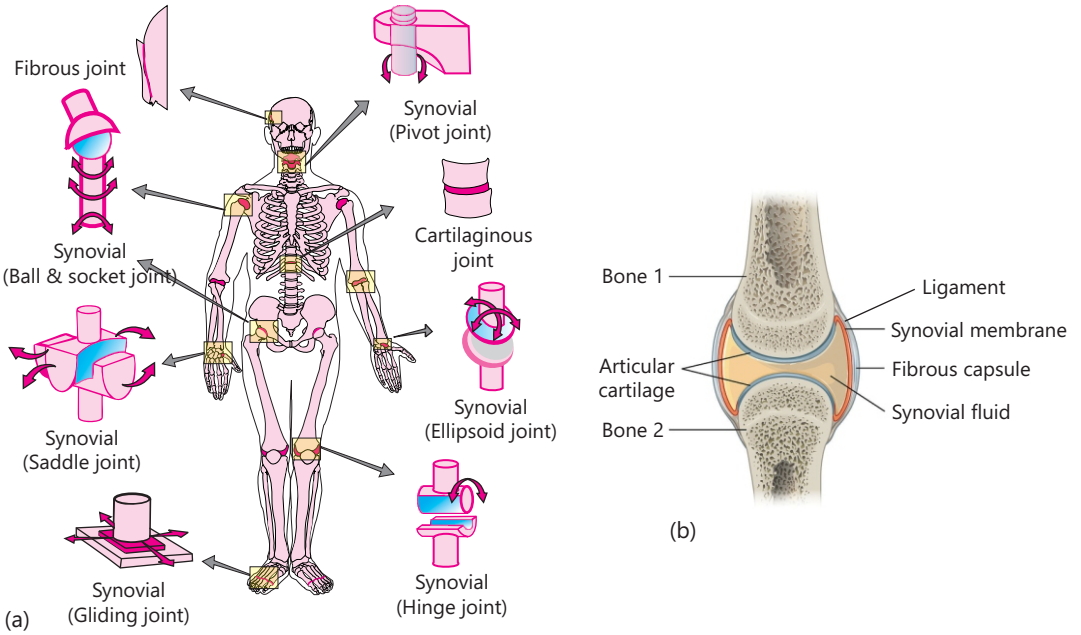


Figure 12.10: (a)- Types of joints; (b)- Structure of a synovial joint

Human Skeleton & Musculature helps in Bipedal Posture

The bipedal posture of humans is linked to skeleton and musculature in several ways.

1. The human vertebral column has a distinctive S-shaped curve, which helps to distribute weight evenly and maintain balance while standing and walking.
2. Human pelvis is shorter and broader, which helps to stabilize the torso and support the body's weight on two legs.
3. The human femur is also angled inward towards the knee joint, which helps to keep the body's centre of mass over the feet. It allows stability while standing and walking.
4. The muscles are located in the buttocks, are much larger in humans. They play a crucial role in stabilizing the torso and propelling the body forward while walking.
5. The calf muscles are also well-developed in humans, providing power for walking and running.
6. Human foot has a longitudinal arch that helps to absorb shock and distribute weight evenly across the foot.
7. The toes are shorter and less prehensile, allowing the foot to function more effectively as a lever during walking and running.

Problems due to Improper Posture

Improper posture can negatively affect bones and joints, causing:

Vertebral Misalignment: This can lead to back and neck pain, and herniated discs by putting pressure on vertebrae and nerves.

Joint Strain: Poor posture can strain neck, shoulders, hips, and knees, leading to pain, inflammation, and potentially arthritis.

Muscle Imbalances: Overused and underused muscles from poor posture can pull bones and joints out of alignment.

12.2- Disorders of Skeletal System

Skeletal system is susceptible to a wide range of disorders that can impact its structure and function. These disorders can affect any part of the skeletal system, including bones, joints, and connective tissues.

Disorders of the Skeleton

1- Disc Slip

The intervertebral discs between vertebrae act as shock absorbers and help in movement. A herniated or slipped disc occurs when the outer layer of the intervertebral disc tears or ruptures, causing the inner gel-like substance to leak out and press against nearby nerves or spinal cord. It may be due to a trauma, degenerative changes due to aging, or repetitive strain on vertebral column. Symptoms of slipped disc include pain, numbness, and tingling in the affected area, weakness or loss of muscle function, and in severe cases, bowel or bladder dysfunction.

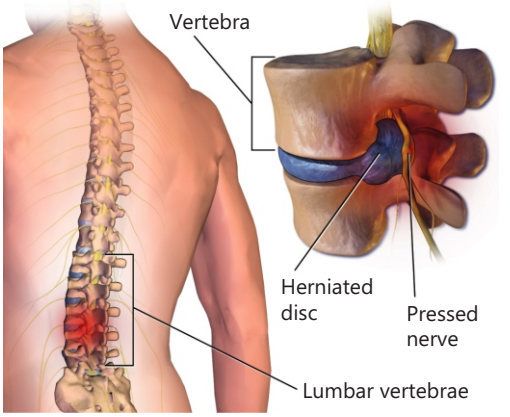


Figure 12.11: Disc slip (herniation)

2- Spondylosis

Spondylosis means degeneration of vertebrae, intervertebral discs, ligaments or cartilage of vertebral column. It may result in narrowing and fusion of intervertebral disc and development of bone outgrowths. It puts pressure on the nerves or spinal cord. Spondylosis is most common in the lower back (lumbar vertebrae) and neck (cervical vertebrae). The most common cause is the natural degeneration of intervertebral discs. It occurs with aging, genetic factors, trauma, and prolonged periods of poor posture and obesity. Symptoms include back or neck pain, stiffness, and reduced range of motion.

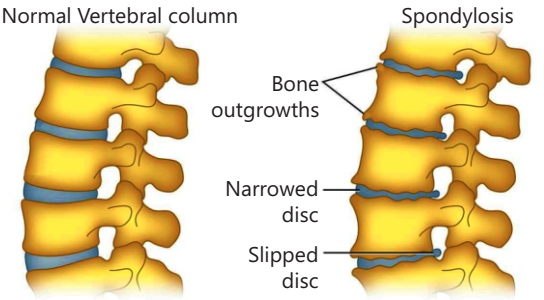


Figure 12.12: Spondylosis

3- Sciatica

Sciatica means compression or irritation of the sciatic nerve. The sciatic nerve starts from lower back and goes down through the buttocks into each leg. Sciatica is often caused by a herniated disc or bulging disc, which can put pressure on the sciatic nerve. Other causes of sciatica include trauma, infection, inflammation, and spondylosis.

Symptoms include pain or discomfort in the lower back, buttocks, legs, or feet, tingling or numbness in the legs or feet, weakness or difficulty moving the legs or feet.

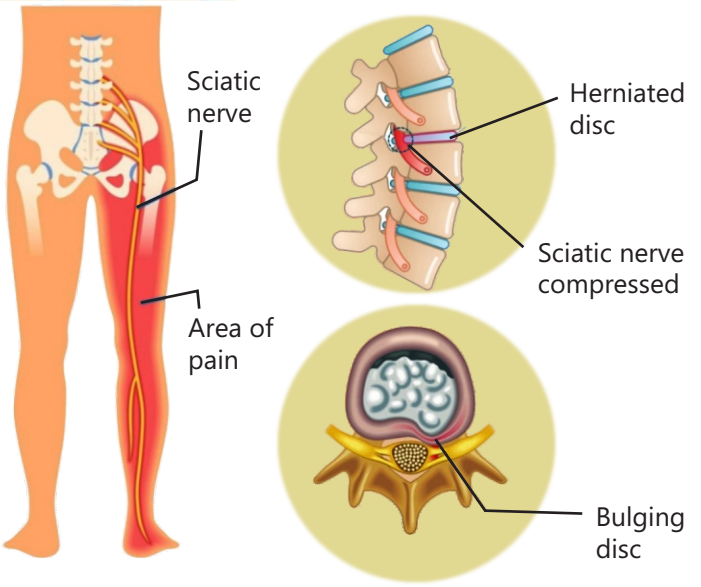


Figure 12.13: Sciatica and its causes

4- Arthritis

Arthritis include different inflammator conditions that affect th joints. Symptoms of all type include joint pain an stiffness. Other symptom may include redness, warmth, swelling in affected joints. The following are important types of arthritis.

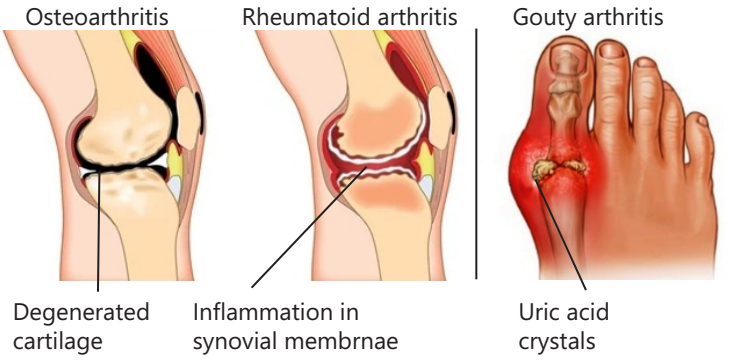


Figure 12.14: Types of arthritis

Osteoarthritis is the most common type. It occurs when the articular cartilage at the ends of bones in joints gradually softens and disintegrates. It affects knee, hip and intervertebral joints.

Rheumatoid arthritis is the result of an autoimmune disorder in which synovial membrane becomes inflamed. Most commonly, the wrist and hands are involved.

Gouty arthritis (or gout) occurs when there is a build-up of uric acid in the blood, which can form crystals in the joints and cause inflammation. The most

common joint affected is the joint of the big toe. Other joints (knees, wrists and fingers) may also be affected.

5- Osteoporosis

Osteoporosis is a condition characterized by weakened bones that are more prone to fractures and breaks. It occurs when bone density decreases, making the bones fragile and porous. Its causes include:

As people age, bone mass naturally decreases. But it can be more pronounced in some individuals.

In women, a drop in oestrogen levels after menopause accelerates bone loss.

Lack of calcium and vitamin D in the diet can impair bone health. Calcium is crucial for bone strength, while vitamin D helps the body absorb calcium.

Lack of weight-bearing exercise can lead to weakened bones.

Certain treatments such as long-term use of corticosteroids, can contribute to bone loss.

Smoking and alcohol consumption can also increase the risk of osteoporosis.

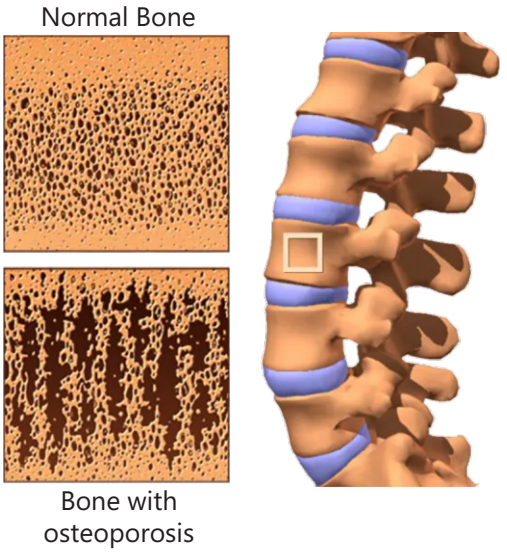


Figure 12.15: Normal bone and osteoporosis

Injuries to Joints

Joints can be subject to a variety of injuries, which can result in pain, swelling, and reduced motion. Here are some common injuries to joints:

1- Dislocations

A dislocation is when the bones in a joint are forced out of their normal positions. This can happen as a result of a sudden impact or trauma. A severe dislocation can cause tearing of the muscles, ligaments and tendons. Symptoms include swelling, intense pain, and immobility of the affected joint. Rheumatoid arthritis can also cause joint dislocation. A dislocated joint can only be successfully corrected by a physiotherapist. Surgery may be needed to repair or tighten the stretched ligaments.

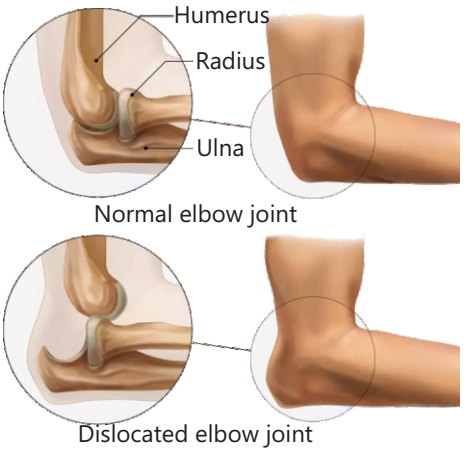


Figure 12.16: Dislocation in elbow joint

2- Sprain

A sprain is an injury to the ligaments that connect bones in a joint. Commonly injured ligaments are in the ankle, knee and wrist. This can happen when the joint is forced beyond its normal range of motion, causing the ligaments to stretch or tear. Sprains are usually treated with physical therapy. Dressings is done to immobilize the sprain and provide support.

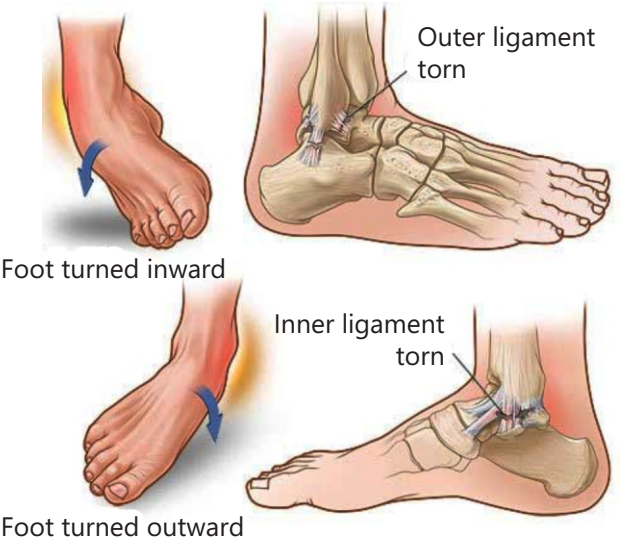


Figure 12.17: Ankle sprain

First aid Treatment for Dislocation and Sprain

First aid treatment for dislocation and sprain includes the following steps (Fig. 12.18):

1. **Immobilize the affected area:** Keep the affected area immobile and do not attempt to re-align the dislocated joint. Use a sling or splint to support the limb.

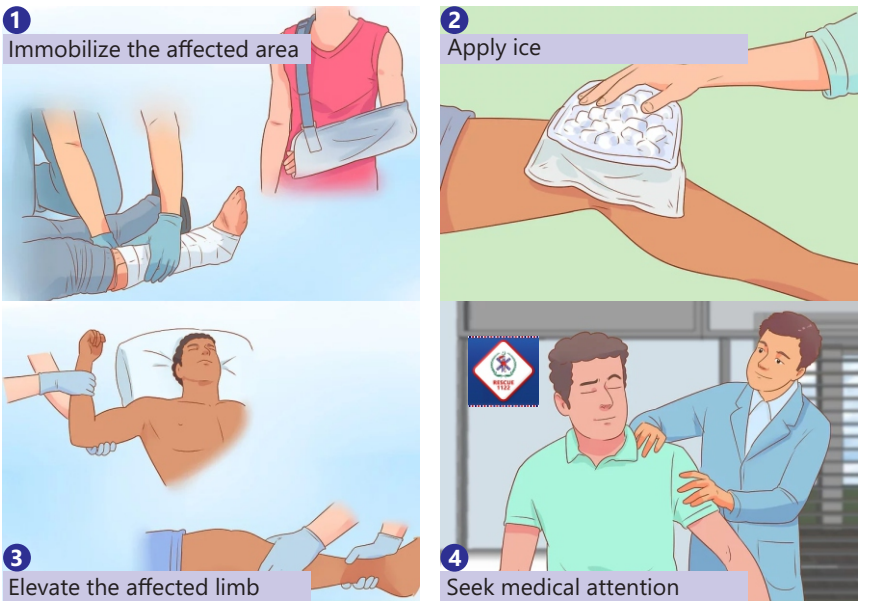


Figure 12.18: First aid treatment for dislocation or sprain

2. **Apply ice:** Apply an ice pack or cold compress to the affected area to reduce swelling and pain.

3. **Elevate the affected limb:** In the case of dislocation, if possible, elevate the affected limb above to help reduce swelling.
4. **Seek medical attention:** Dislocations and sprain require medical attention, so call for emergency medical services 1122 or take the person to the hospital for further evaluation and treatment.

12.3- MUSCLES

Muscle is defined as the tissue that can contract in a coordinated way to produce movements of body parts or whole body. The individual cells of muscle are called **muscle fibres** or **myofibres**.

Muscles' ability to contract and relax not only enables the body to move, but also provides the force that pushes substances, such as blood and food, through the body.

Types of Muscles

Human body has three types of muscle tissues: skeletal, smooth, and cardiac (Fig. 12.19).

Although our focus in this chapter is on humans, it is important to realize that essentially all animals employ muscles. For example, when a mosquito flies, its wings are moved rapidly through the air by quickly contracting flight muscles. When an earthworm burrows through the soil, its movement is driven by strong muscles pushing its body past the surrounding soil.

1- Skeletal Muscles

Skeletal muscles are responsible for moving parts of the body, such as the limbs, trunk, and face. The muscle fibres of skeletal muscles are elongated cells with striations. Because their contractions are usually consciously controlled, skeletal muscles are called as voluntary muscles.

2- Smooth Muscles

Smooth muscles are present in the walls of the stomach, intestines, blood vessels, and other internal organs. Smooth muscle fibres are spindle-shaped, have a single nucleus and lack striations. Smooth muscle fibres are surrounded by connective tissue. Because most of their movements cannot be consciously controlled, smooth muscle is referred to as involuntary muscle.

3- Cardiac Muscles

These are found only in the walls of the heart. Their fibres branch extensively. The muscle fibres of cardia muscles are striated like skeletal muscle, but each cell usually contains one nucleus located near the centre.

Comparison of three types of muscle tissues

Property	Skeletal Muscle	Smooth Muscles	Cardiac Muscles
Appearance	Regular striped	Un-striped	Irregular striped
Cell shape	Spindle or cylindrical	Spindle	Branched
Number of nuclei	Many per cell	One per cell	One per cell
Voluntary control	Have voluntary control	Usually, no voluntary control	No voluntary control

Function	To move skeleton	To move substances through hollow organs	To pump blood

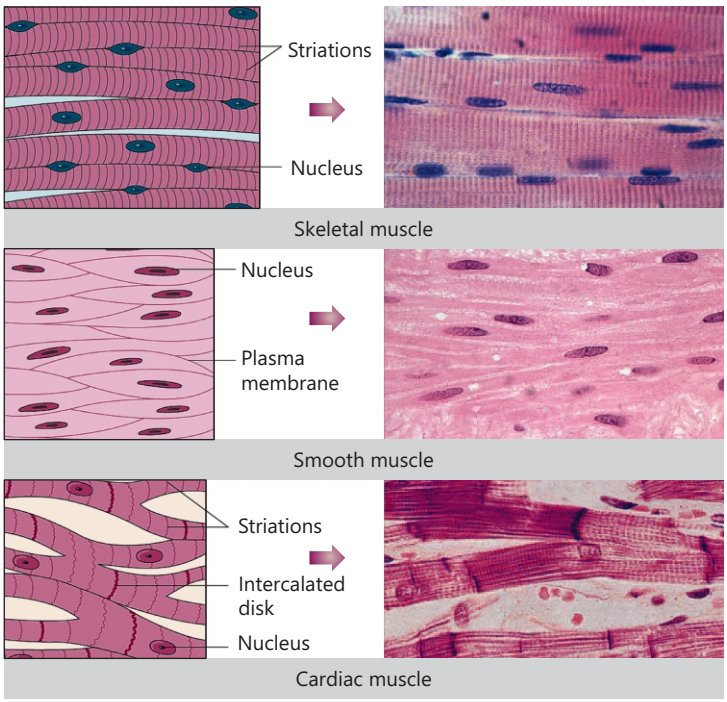


Figure 12.19: Types of muscles

Structure of Skeletal Muscles

The cells of skeletal muscles i.e., muscle fibres (myofibres) are in the form of bundles which are enclosed by collagen fibres and connective tissue. At the ends of a skeletal muscle, the collagen and connective tissue forms **tendons** which attach the muscle to bones.

Ultrastructure of Skeletal Muscles

Each skeletal muscle cell i.e., muscle fibre is a cylindrical multinucleated cell, enclosed by a plasma membrane called **sarcolemma** (Fig. 12.20). Its cytoplasm is called **sarcoplasm** and it contains **sarcoplasmic reticulum (SR)**. The sarcolemma penetrates deep into the cell to form hollow elongated tubes, the **transverse tubules (T-tubules)**. The T-tubules reach the ends of SR.

Each muscle fibre contains a bundle of 4 to 20 elongated threadlike structures called **myofibrils**. Myofibrils are made up of two types of filaments: thick filaments composed of **myosin** and thin filaments composed of **actin**. The thick filaments create dark bands called **A-bands**, while the thin filaments create light bands called **I-bands**. These alternating dark and light bands give skeletal muscle its striped (striated) appearance.

We can summarize the structural organization of a skeletal muscle as;

A skeletal muscle is made of groups of cells called muscle fibres.

Each muscle fibre contains bundles of myofibrils in its cytoplasm.

Each myofibril is made of 2 types of myofilaments (myosin and actin).

The thin actin filaments are attached to protein discs called **Z-lines**. The section between two Z-lines is a **sarcomere**, the smallest unit of muscle contraction. Within a sarcomere, the thin filaments extend from the Z-line toward the center, where they overlap with thick filaments. This overlap creates the **A-band**, with a lighter central region called the **H-band**, where no overlap occurs (Fig. 12.20).

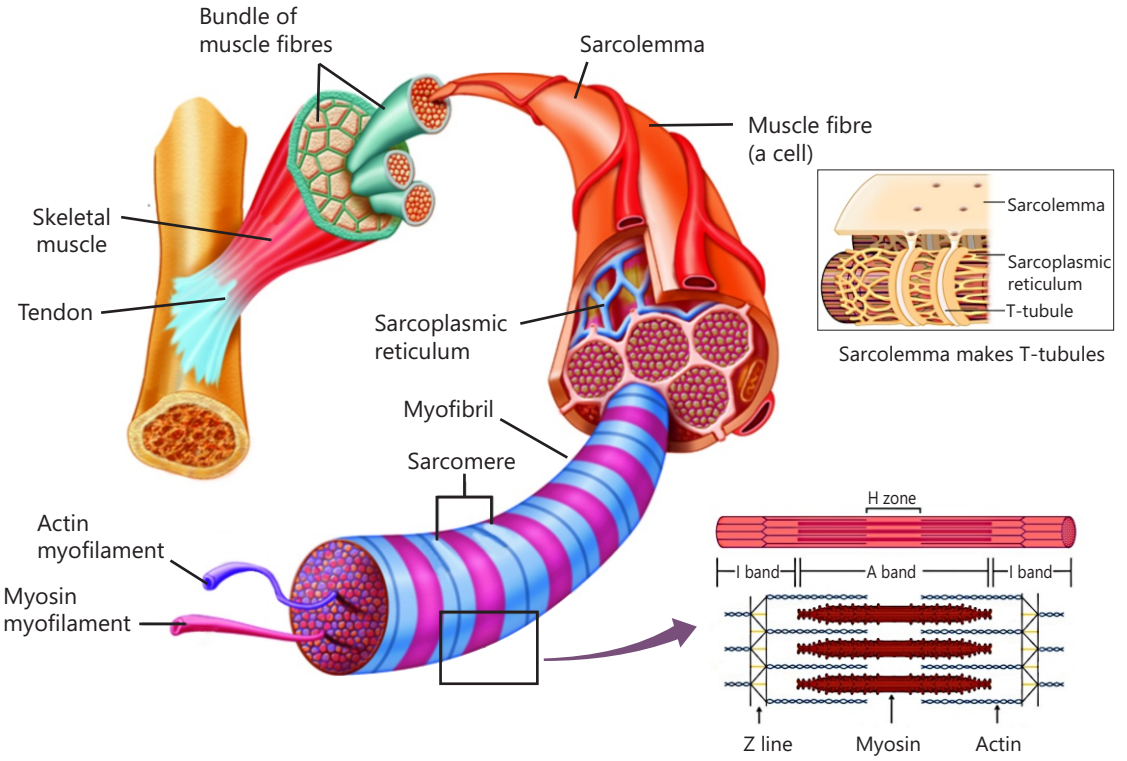


Figure 12.20: Ultrastructure of skeletal muscle

During muscle contraction, the thin filaments slide deeper into the A-band, causing the H-band and I-band to narrow. The A-bands are pulled closer together, shortening the muscle. The center of the H-band may have a dark line called the **M line** which helps stabilize the thick filaments.

Biochemistry of Myofilaments

Thick myofilaments, about 16 nm in diameter, are made up of many myosin proteins. Each myosin protein consists of two intertwined polypeptide chains, ending in a globular "head." These myosin heads extend from the thick filaments and connect to actin during muscle contraction (Fig. 12.21).

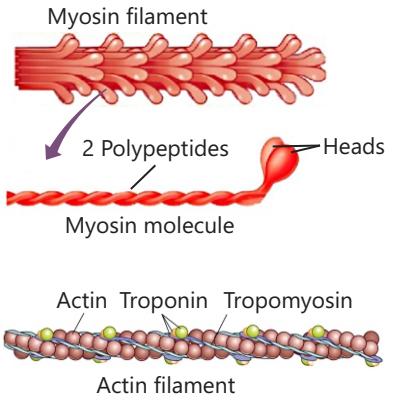


Figure 12.21: Structure of myofilaments

Thin myofilaments, 7-8 nm in diameter, are made of three proteins: (i) Core is made of two twisted strands of actin. (ii) Two strands of **tropomyosin** wrap about actin core and stiffen it. In a relaxed muscle fibre, they block myosin binding sites on actin. (iii) **Troponin** protein is present at regular intervals on thin myofilaments. It is made of three polypeptides. One polypeptide is inhibitory and binds to actin; second polypeptide binds to tropomyosin to keep it in place. The third polypeptide binds to calcium ions.

Mechanism of Muscle Contraction - Sliding Filament Model

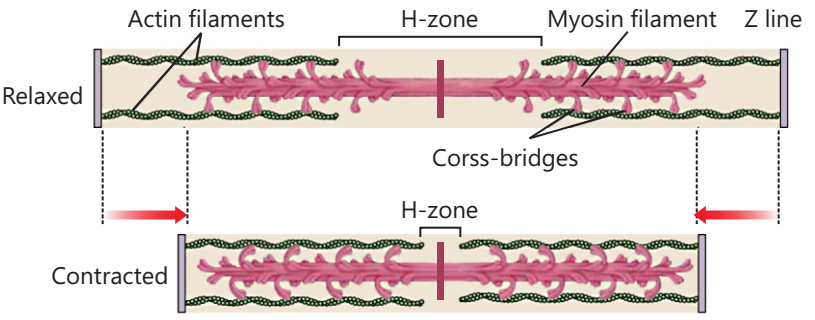


Figure 12.22: Sliding filament model of muscle contraction

The sliding filament model explains how a muscle contracts. According to this model, a muscle contracts when its thin myofilaments slide past the thick ones so that they overlap to a greater degree. It occurs in the following steps (Fig. 12.23);

1- Sarcomeres at relaxed state

In a relaxed muscle, sarcomeres are at their normal length. The myosin heads are not bound to actin because the binding sites on actin are blocked by tropomyosin of thin filaments. Troponin, another protein, is attached to tropomyosin. Myosin heads have hydrolysed ATP into ADP and Pi.

When a nerve impulse reaches sarcolemma, a neurotransmitter (acetylcholine) is released by motor neuron at the synapse. It

2- Arrival of Nerve Impulse

When a nerve impulse reaches the muscle fibre, it travels along the sarcolemma to the T-tubules and then to the sarcoplasmic reticulum (SR). The SR releases calcium ions into the cytosol. These calcium ions bind to troponin, causing it to shift tropomyosin away from the myosin-binding sites on actin.

stimulates the sarcolemma to produce its own electrochemical impulses which are carried into the muscle fibre to the T tubules.

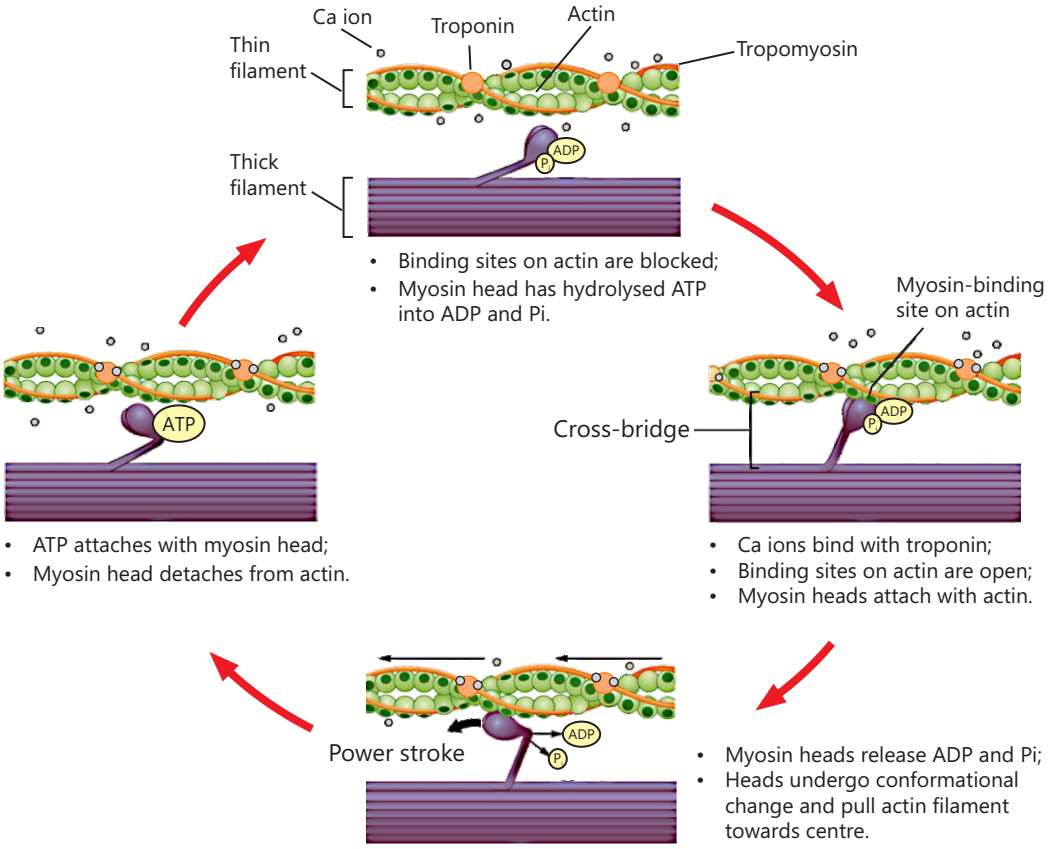


Fig. 12.23: Steps of a power-stroke (cross bridge cycle)

3- Cross-bridges and Power-stroke

When binding sites on actin are exposed, the myosin heads bind to them and form **cross-bridges**. Once the cross-bridges are formed, the myosin heads release the ADP and Pi, and undergo conformational change. They bend towards the centre of sarcomere, pulling actin filaments with them. This pulling action is called a **power stroke**. It shortens the sarcomere, bringing Z-lines closer together and H-zone disappears. It occurs simultaneously in all sarcomeres, causing the muscle to contract. The adjacent A-bands of sarcomeres come closer to each other but do not shorten.

4- Separation of Myosin Heads from Actin

After pulling, the myosin head receives a new molecule of ATP. This allows the head to detach from actin. Splitting of this ATP into ADP and Pi puts the head into its original conformation, allowing the cross-bridge cycle to begin again.

After death, the cells can no longer produce ATP and therefore the cross-bridges cannot be broken. It causes the muscle stiffness of death, or **rigor mortis**. A living cell, however, always has enough ATP to allow the myosin heads to detach from actin.

Arrangement of Skeletal Muscles at Moveable Joints

Skeletal muscles are attached to bones by tough connective tissues called **tendons**. Typically, a muscle has two attachment points on different bones. The end attached to the stationary bone during contraction is called the **origin**, while the end attached to the bone that moves is the **insertion**. The middle part of the muscle is known as the **belly** (Fig. 12.24).

For the movement of bones at a joint in two directions muscles work in pairs. They produce opposing actions when they contract. Such arrangement of muscles is called antagonistic arrangement. In such arrangement, when one muscle, called **flexor**, contracts it bends the bone at joint. When the opposing muscle, called **extensor**, contracts it straightens the bone at joints.

During such antagonistic action, when a muscle e.g., flexors contracts, the other muscle i.e., extensor is relaxed and vice versa.

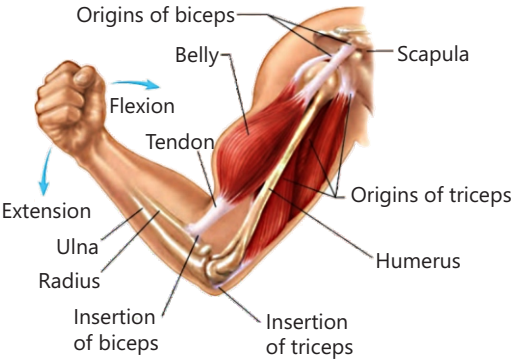


Figure 12.24: Arrangement of skeletal muscles at elbow joint

Movement at Knee Joint

The knee joint is located between the femur (thigh bone) and the tibia and fibula (lower leg bones). Flexion, or bending, of the lower leg is done by the **hamstrings**. It is a group of three muscles at the back of the thigh. The hamstrings originate at the pelvic girdle and the top of the femur, with insertions at the upper parts of the fibula and tibia.

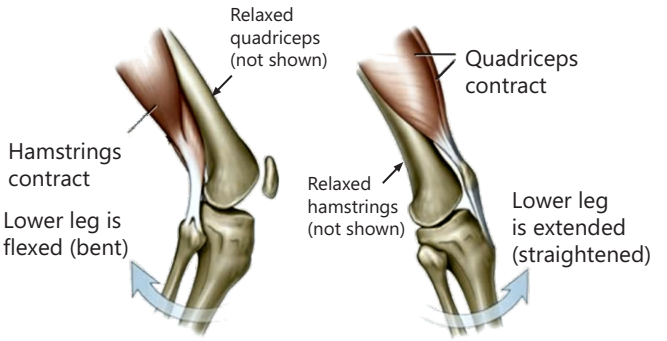


Figure 12.25: Movement at knee joint

Extension, or straightening, of the lower leg is done by the **quadriceps**. It is a group of four muscles at the front of the thigh. The quadriceps originate at the ilium

(part of the pelvic girdle) and femur, with insertions at the patella (kneecap) and tibia. When the hamstrings contract, the lower leg bends and the quadriceps relax. When the quadriceps contract, the lower leg straightens and the hamstrings relax.

Muscle Disorders

The following are some common muscle disorders.

1- Muscle Fatigue

Muscle fatigue means a decline in muscle performance that occurs after prolonged or intense physical activity or due to some disease. Its symptoms include pain, decreased muscle strength, and reduced endurance. The following factors contribute to muscle fatigue:

During exercise, the muscles use ATPs to contract. When the supply of ATPs is depleted, the muscle is no longer able to contract.

As muscles work, they produce metabolic wastes e.g., lactate, hydrogen ions, and reactive oxygen. These wastes contribute to muscle fatigue.

When muscle fibres are repeatedly activated, they are not able to effectively handle calcium ions, which can impair muscle function.

Prolonged or intense exercise can cause small amounts of damage to muscle fibres, leading to inflammation and reduced muscle function.

Muscle fatigue typically improves with rest. If it is severe, it requires medical attention.

2- Muscle Cramps

Muscle cramps are sudden, involuntary, and often painful contractions of a muscle or group of muscles. They usually last from a few seconds to several minutes and most commonly occur in the legs and feet. Common causes include dehydration, an imbalance of salts, overuse or injury of the muscle, certain medications (like diuretics), and medical conditions such as diabetes, liver disease, and nerve damage.

To relieve muscle cramps, gently stretch and massage the affected muscle. Applying heat or cold to the area and using pain-relieving medications can also help.

3- Tetany

Tetany is a condition characterized by involuntary muscle contractions or spasms due to increased muscle tone and hyperexcitability of the nerves. These contractions can occur in various parts of the body such as hands, feet, face, or larynx. The most common cause of tetany is hypocalcaemia (low level of calcium in blood) which may be due to vitamin D deficiency, renal failure, or thyroid disorders. Tetany may also be due to other salts imbalances, such as low level of magnesium in blood. Treatment for tetany depends on the underlying cause. If tetany is caused by salts imbalances, treatment may involve calcium or magnesium supplements or intravenous fluids to restore electrolyte balance.

Difference between Tetany and Tetanus

Tetany and tetanus are different conditions often confused due to their similar names:

1. Tetany involves increased muscle tone and overactive nerves, causing involuntary muscle contractions or spasms. Tetanus is a severe bacterial infection caused by *Clostridium tetani*, which produces a toxin affecting the nervous system, leading to muscle stiffness and spasms.
2. Tetany can affect various body parts like the hands, feet, face, or larynx. Tetanus mainly affects the jaw and neck muscles.
3. Tetany can result from issues like electrolyte imbalances or nerve problems. Tetanus is caused by a specific bacterial infection.
4. Tetanus is more serious and potentially life-threatening compared to tetany.

Muscles pull but do not push.

Muscles can only pull, not push. This is because muscle fibres are designed to contract and shorten, pulling on tendons and thus moving bones. When a muscle contracts, it pulls on the bone via the tendon, and when it relaxes, the bone moves back to its original position.

Muscles cannot push because they only generate force by pulling. If a muscle were to push, it would need to be attached to bones at both ends and make both ends move closer together, which is not possible in the body. Muscles are usually attached to bone at only one end.

Skeleton is a system of rods and levers

The skeleton works like a system of rods and levers. Bones act as the rods, giving structure and support to the body and protecting internal organs.

In this system, joints serve as fulcrums (pivot points) for the levers, allowing movement. Muscles generate the effort or force, while the weight or resistance being moved is the load.

For example, when lifting a weight, the bicep muscle in the upper arm acts as a lever. The elbow joint is the fulcrum, the bicep provides the effort, and the weight is the load.

EXERCISE

MULTIPLE CHOICE QUESTIONS

1. Which structures are part of the appendicular skeleton?
   (a) Ethmoid bone (b) Floating ribs (c) Lumber vertebrae (d) Humerus bone
2. The term muscle fibre or myofibre refers to;
   (a) A cellular organelle (b) A cell
   (c) A tissue (d) An organ
3. Which of these extends the entire length of a muscle fibre?
   (a) Sarcomere (b) Myofibril (c) Myosin filament (d) Actin filament
4. Actin filaments are made of proteins;
   (a) Myosin and troponin (b) Actin and troponin
   (c) Actin and myosin (d) Actin, tropomyosin and troponin
5. In a muscle, the Z-line are the proteins for the attachment of the ends of;
   (a) Actin filaments (b) Myosin filaments

(c) Both actin and myosin filaments (d) Sarcomeres

6. Sarcomere is a part between;
   (a) Two H-lines (b) Two A-bands (c) Two Z-lines (d) Two I-bands
7. Which part of muscle fibre releases calcium ions which trigger contraction?
   (a) Sarcolemma (b) Sarcoplasm
   (c) T-tubules (d) Sarcoplasmic reticulum
8. Which statement is correct to describe sliding filament model of muscle contraction?
   (a) Myosin filaments pull on the sarcomere so that actin filaments are shortened.
   (b) Myosin filaments pull on actin filaments so that sarcomere is shortened.
   (c) Actin filaments pull on myosin filaments so that sarcomere is shortened.
   (d) Actin filaments pull on sarcomere so that myosin filaments are shortened.
9. When a muscle fibre shortens, which of the following also shortens?
   (a) Actin filament (b) Myosin filament (c) Sarcomere (d) Z-line
10. Which statement correctly describes an event of muscle contraction?
    (a) Myosin heads bind to troponin.
    (b) ATP binds to the actin binding site.
    (c) ATP is used to detach the myosin head from actin.
    (d) Troponin blocks the binding sites.
11. Tendons connect bone and;
    (a) Bone (b) Ligaments (c) Muscle (d) Cartilage
12. What is true about antagonistic pair of muscles?
    (a) It provides a backup if one of the muscles is injured
    (b) One muscle pushes while other pulls
    (c) It allows muscles to produce opposing movements
    (d) It doubles the strength of contraction

SHORT QUESTIONS

1. Name three types of cells associated with bone and write their functions.
2. Name the bones of cranium.
3. Enlist the bones in the five groups of vertebrae.
4. What bones make the rib cage.
5. Name the bones of pectoral girdle and pelvic girdle.
6. Name the bones of forelimbs and hindlimbs.
7. What is fibrous joint? Give examples.
8. Name the steps involved in bone repair.
9. What skeletal structures are affected from the osteoarthritis?
10. List the major parts of skeletal muscle fibre.
11. What do you mean by I-band, A-band and H-zone?
12. Describe the antagonistic arrangement of skeletal muscles.

13. Ligaments are elastic while tendons are hard. Justify.
14. Draw a diagram of sarcomere and label its parts.
15. Differentiate between:
    - Compact and spongy bone
    - Axial skeleton and appendicular skeleton
    - True ribs, false ribs and floating ribs
    - Rheumatoid arthritis and osteoarthritis
    - Fibrous and cartilaginous joints
    - Cartilaginous and synovial joint
    - Osteoblasts and osteocytes
    - Tropomyosin and troponin
    - Ligament and tendon
    - Tetany and tetanus

LONG QUESTIONS

1. Explain the structure of bone.
2. Describe the structure of three types of cartilage.
3. Write the cause and symptoms of joint dislocation, spondylosis, and sciatica.
4. Describe the types of arthritis, with their causes, symptoms and treatments.
5. Describe the three types of muscles.
6. Explain the ultrastructure of skeletal muscle.
7. Write a detailed note on the sliding filament model of muscle contraction.
8. Explain the action of antagonistic muscles in the movement of knee joint.
9. Draw a diagram of sarcomere and label its parts.
10. Describe causes and symptoms of muscle fatigue, cramps and tetany.
11. Justify how the main functions of the skeleton are to act as a system of rods and levers.
12. Justify why do the muscles pull but do not push.

INQUISITIVE QUESTIONS

1. Why is calcium essential for both the structural integrity of bones and the process of muscle contraction?
2. Why is the human skeleton designed with both rigid bones and flexible joints instead of being made of a single solid structure?
3. Why do muscles always work in pairs (antagonistic muscles) rather than alone?
4. Why does prolonged inactivity or space travel lead to muscle atrophy and bone weakening??

Glossary

A

Active Site - The region on an enzyme where the substrate binds and the reaction occurs.

Acylglycerol - A type of lipid composed of glycerol and fatty acids.

Aerobic Respiration - Energy-releasing process that uses oxygen to break down glucose.

Algae - Simple autotrophic organisms, often aquatic, ranging from unicellular to multicellular forms.

Alveoli - Tiny air sacs in the lungs where gas exchange between air and blood occurs.

Amino Acids - Building blocks of proteins, each containing an amino group and a carboxyl group.

Amylase - An enzyme that breaks down starch into maltose and glucose.

Anaerobic Respiration - Energy-releasing process in the absence of oxygen.

Angina pectoris - Chest pain caused by reduced blood flow to the heart muscles.

Angiography - A medical imaging technique used to view blood vessels.

Angioplasty - A procedure to restore blood flow through a blocked artery.

Annual ring (in plants) - A ring in a tree trunk representing one year of growth.

Antagonistic muscles - Pairs of muscles that work in opposition to move a body part.

Antibody - A protein produced by B-lymphocytes that binds to specific antigens to neutralize them.

Antigen - A foreign substance that triggers an immune response.

Arthritis - Inflammation of the joints causing pain and stiffness.

Atherosclerosis - Build-up of fatty deposits in the walls of arteries, narrowing them.

Atria (of heart) - The upper chambers of the heart that receive blood returning to the heart.

AV node - Atrioventricular node; relays electrical signals from atria to ventricles.

B

Bacteria - Prokaryotic, unicellular microorganisms that may be beneficial or pathogenic.

Binary Fission - A method of asexual reproduction in prokaryotes where one cell divides into two.

Biodiversity - The variety of living organisms in a particular habitat or ecosystem.

Bioenergetics - The study of energy flow and transformation in living organisms.

Bioinformatics - The application of computational tools to analyze biological data.

Biological Classification - The systematic grouping of organisms into categories based on evolutionary relationships.

Biomolecule - Organic molecules such as carbohydrates, proteins, lipids, and nucleic acids found in living organisms.

Bronchi - Two large tubes that branch from the trachea and carry air into the lungs.

Bronchi - The two main branches of the trachea that lead into the lungs.

C

Calvin Cycle - A series of biochemical reactions in the chloroplast stroma that convert carbon dioxide into glucose.

Capillaries - Smallest blood vessels where exchange of gases and nutrients occurs.

Cartilaginous Joint - A joint where bones are connected by cartilage, allowing limited movement.

Cell - The basic structural and functional unit of life.

Cell Membrane - Semi-permeable membrane enclosing the cytoplasm, controlling movement of substances.

Cell Theory - The theory stating that all living things are composed of cells, and all cells come from pre-existing cells.

Cell Wall - A rigid outer structure in plant, fungal, and some prokaryotic cells.

Cellular Respiration - The process by which cells break down glucose to release energy.

Chemiosmosis - The movement of ions across a membrane to generate ATP, driven by the electron transport chain.

Chlorophyll - Green pigment found in chloroplasts responsible for capturing light energy in photosynthesis.

Chloroplast - A plant cell organelle where photosynthesis takes place.

Chromosome - A thread-like structure composed of DNA and proteins, found in the nucleus.

Glossary

Chronic Obstructive Pulmonary Disease - A group of lung diseases that cause airflow blockage and breathing problems.

Collenchyma - A type of plant tissue with thickened cell walls that provide support and flexibility.

Companion Cell - A type of cell in the phloem that supports the function of sieve tube elements.

Cytoplasm - Jelly-like substance within cells, excluding the nucleus, that contains organelles.

D

Dark Reactions (of Photosynthesis) - The light-independent reactions that use ATP and NADPH to convert carbon dioxide into glucose.

Decomposer - Organism that breaks down dead organic matter and recycles nutrients.

Denaturation - Loss of an enzyme's shape and function due to external stress such as heat or pH.

Diaphragm - Dome-shaped muscle involved in the process of breathing.

Diastase - A group of enzymes that break down starch into sugars.

Diffusion - Passive movement of molecules from an area of high concentration to low concentration.

Digestion - The breakdown of large food molecules into smaller, absorbable components.

Disaccharide - A carbohydrate formed by the combination of two monosaccharides.

Disc-slip - A condition where a spinal disc herniates and presses on nearby nerves.

DNA (Deoxyribonucleic Acid) - A type of nucleic acids; carries genetic information.

Domain - The highest taxonomic rank, above kingdom; includes Bacteria, Archaea, and Eukarya.

Double Circulation - A system of blood flow where blood passes through the heart twice in one complete cycle.

Duodenum - The first part of the small intestine where most chemical digestion occurs.

E

ECG - Electrocardiogram; a recording of the electrical activity of the heart.

Electron Microscope - A microscope that uses electrons to view very small objects in high detail.

Electron Transport Chain - A series of protein complexes in mitochondria that transfer electrons and produce ATP.

Embolus - A traveling blood clot or other substance that can block blood vessels.

Emphysema - A chronic lung disease involving damage to the alveoli.

Endocrine Gland - A gland that secretes hormones directly into the bloodstream.

Endocytosis - The process by which a cell engulfs substances from its surroundings.

Endoplasmic Reticulum - A cell organelle involved in protein and lipid synthesis.

Enzyme - A biological catalyst that speeds up chemical reactions in cells.

Enzyme inhibitor - A substance that reduces or blocks enzyme activity.

Epicardium - The outermost layer of the heart wall.

Exocrine Gland - A gland that releases its secretions through ducts to specific locations.

Exocytosis - The release of substances from a cell by the fusion of a vesicle with the membrane.

F

Fermentation - Anaerobic process that converts glucose to energy and by-products like alcohol or lactic acid.

Fibrous Joint - A joint where bones are joined by fibrous tissue and allow little to no movement.

Flagella - Long, whip-like structures used for locomotion in some cells.

Fungi - A kingdom of non-photosynthetic organisms with cell walls made of chitin.

G

Gastric gland - Glands in the lining of the stomach that secrete gastric juice.

Gastric juice - A mixture of hydrochloric acid, pepsinogen, and mucus secreted by gastric glands.

Gastrin - A hormone that stimulates secretion of gastric juice.

Gene - A segment of DNA that codes for a specific protein or trait.

Genetic Code - The sequence of bases in DNA or RNA that determines the sequence of amino acids.

Genome - The complete set of genes or genetic material in a cell or organism.

Glossary

Glycolysis - The first step of cellular respiration that breaks down glucose into pyruvate.

Golgi Apparatus - Organelle that modifies, packages, and transports proteins and lipids.

H

Haemoglobin - Oxygen-carrying protein found in red blood cells.

Halophytes - Plants adapted to grow in salty environments.

Heartbeat - One complete cycle of contraction and relaxation of the heart muscles.

Homeostasis - Maintenance of stable internal conditions in an organism.

Hormone - A chemical messenger produced by glands that regulate body functions.

Hydrolases - Enzymes that catalyze the hydrolysis of chemical bonds.

Hydrophytes - Plants adapted to live in water or very wet conditions.

Hypertension - Abnormally high blood pressure.

Hypertonic solution - A solution with higher solute concentration, causing water to leave a cell.

Hypotonic solution - A solution with lower solute concentration, causing water to enter a cell.

I

Ileum - The final part of the small intestine involved in the absorption of nutrients.

Immune System - The body's defence system against infectious organisms.

Immunity - The ability of an organism to resist disease.

Ingestion - The process of taking food into the body through the mouth.

Insulin - A hormone that regulates blood sugar levels.

Isomerases - Enzymes that catalyze the rearrangement of atoms within a molecule.

Isotonic solution - A solution with equal solute concentration as another solution, resulting in no net water movement.

J

Jejunum - The middle part of the small intestine where absorption of nutrients occurs.

Joint - The location where two or more bones meet. It allows movement and flexibility.

K

Kingdom - A high-level taxonomic category grouping related organisms; e.g., Animalia, Plantae.

Krebs Cycle - A series of chemical reactions in mitochondria that generate energy through the oxidation of acetyl-CoA.

L

Larynx - Voice box located in the throat involved in breathing and sound production.

Ligases - Enzymes that catalyze the joining of two molecules using energy from ATP.

Light Reactions (of Photosynthesis) - The light-dependent reactions in the thylakoid membranes that produce ATP and NADPH.

Lipase - An enzyme that breaks down fats into fatty acids and glycerol.

Lipid - A type of biomolecule including fats and oils used for long-term energy storage.

Lyases - Enzymes that catalyze the breaking of bonds without hydrolysis or oxidation.

Lymph - A clear fluid that circulates in the lymphatic system and helps in immunity.

M

Mesophytes - Plants that grow best in moderate conditions with adequate water.

Mitochondria - Powerhouse of the cell that generates energy (ATP) via aerobic respiration.

Monosaccharide - The simplest form of carbohydrate, consisting of a single sugar molecule.

Mucus - A thick, slippery substance secreted by membranes, protecting linings of the digestive and respiratory tracts.

Mutation - A change in the DNA sequence of a gene.

Myosin - A protein involved in muscle contraction.

N

Nucleic Acid - Biomolecule made of nucleotides, including DNA and RNA.

Nucleoside - A molecule consisting of a nitrogenous base attached to a sugar, without a phosphate group.

Nucleotide - The basic building block of nucleic acids (DNA and RNA), consisting of a sugar, phosphate group, and nitrogenous base.

Glossary

Nucleus - Control center of the cell containing DNA.

O

Osmosis - The diffusion of water across a selectively permeable membrane.

Osteoblasts- Cells that build new bone tissue.

Osteoclasts- Cells that break down bone tissue.

Osteocytes - Mature bone cells that maintain bone structure.

Osteoporosis- A condition where bones become weak and brittle.

Otitis media - Infection or inflammation of the middle ear.

Oxidoreductases - Enzymes that catalyze oxidation-reduction reactions.

P

Pathogen - A microorganism that causes disease.

Pentose - A five-carbon sugar found in nucleotides, such as ribose and deoxyribose.

Pepsin - An active enzyme in the stomach that digests proteins.

Pepsinogen - An inactive enzyme precursor secreted by stomach cells, converted to pepsin in acidic conditions.

Pericardium - A double-walled sac that encloses and protects the heart.

Peristalsis - Wave-like muscle contractions that move food through the digestive tract.

Phloem - Plant tissue that transports food from leaves to other parts.

Phospholipid - A lipid containing a phosphate group, important in cell membranes.

Photoperiodism - The response of organisms to the length of day or night.

Photosynthesis- Process by which green plants make food using sunlight, water, and carbon dioxide.

Plasmid - A small, circular DNA molecule found in bacteria, independent of chromosomal DNA.

Pleura - A double-layered membrane surrounding the lungs.

Polysaccharide - A complex carbohydrate formed by the linkage of many monosaccharides.

Prostaglandins - Lipid compounds that have hormone-like effects, such as regulating inflammation.

Protease - An enzyme that breaks down proteins into amino acids.

Protein - Biomolecule made of amino acids essential for growth and repair.

Pulse - The rhythmic throbbing of arteries as blood is pumped by the heart.

Purkinje fibers - Specialized fibers that carry electrical impulses in the heart's ventricles.

R

Red Blood Cells (RBCs)-Cells that carry oxygen from the lungs to the body tissues.

Rennin - An enzyme in the stomach of infants that helps digest milk proteins.

Respiration - The process of breaking down food to release energy.

Ribosome - Organelle where protein synthesis takes place.

RNA (Ribonucleic Acid)- A nucleic acid involved in protein synthesis and gene regulation.

S

SA node - Sinoatrial node; the heart's natural pacemaker.

Sciatica - Pain caused by irritation or compression of the sciatic nerve.

Sclerenchyma - A plant tissue composed of thick-walled cells that provide structural support.

Secretin - A hormone that stimulates the pancreas to release bicarbonate into the small intestine.

Segmentation (in small intestine) - Rhythmic contractions that mix food and increase contact with digestive enzymes.

Sequence homology - Similarity in nucleotide or amino acid sequences between organisms.

Sieve Tube Element - A phloem cell responsible for transporting sugars in plants.

Sinusitis- Inflammation of the sinus cavities.

Skeleton - The framework of bones that supports and protects the body.

Sliding filaments model - A theory explaining muscle contraction through the sliding of actin and myosin filaments.

Species - A group of organisms capable of interbreeding and producing fertile offspring.

Spondylosis - Degeneration of the spine, often associated with aging.

Sprain - Stretching or tearing of ligaments in a joint.

Glossary

Steroids - Lipid molecules with four fused rings, including hormones like testosterone and cholesterol.

Stomata - Pores on the leaf surface for gas exchange.

Structural homology - Similarity in body structures due to shared ancestry.

Synovial Joint - A freely movable joint enclosed by a fluid-filled capsule.

Systematics - The study of evolutionary relationships among organisms.

T

Tendon - A fibrous connective tissue that attaches muscle to bone.

Terpene - A class of hydrocarbons found in plant essential oils.

Thrombus - A blood clot formed in a blood vessel.

Thylakoid - Membrane-bound compartments inside chloroplasts where light-dependent reactions occur.

Trachea - Windpipe that connects the larynx to the bronchi.

Tracheid - A type of elongated xylem cell that conducts water and provides structural support.

Translocation of Food - The movement of food (mainly sugars) through the phloem from source to sink.

Transpiration - Loss of water vapor from plant leaves through stomata.

Tropic movement - Movement of a plant in response to a directional stimulus (e.g., light, gravity).

V

Vaccine - A substance used to stimulate the production of antibodies and provide immunity.

Vasoconstriction - Narrowing of blood vessels.

Vasodilation - Widening of blood vessels.

Vein - Blood vessel that carries blood toward the heart.

Ventricles (of heart) - The lower chambers of the heart that pump blood out to the body and lungs.

Vernalization - The induction of flowering in plants by exposure to low temperatures.

Villi - Finger-like projections in the small intestine that increase surface area for absorption.

Viruses - A non-cellular infectious agent that replicates only inside host cells.

W

Waxes - Lipids composed of long-chain fatty acids and alcohols, used for protection in plants and animals.

White Blood Cells (WBCs) - Cells involved in defending the body against infection.

X

Xerophytes - Plants adapted to survive in dry environments.

X-ray Crystallography - A technique used to determine the three-dimensional structure of molecules by analyzing the pattern of X-ray diffraction.

Xylem - Vascular tissue in plants that conducts water and minerals from roots to shoots.

Z

Zygote - The single cell formed by the fusion of male and female gametes.