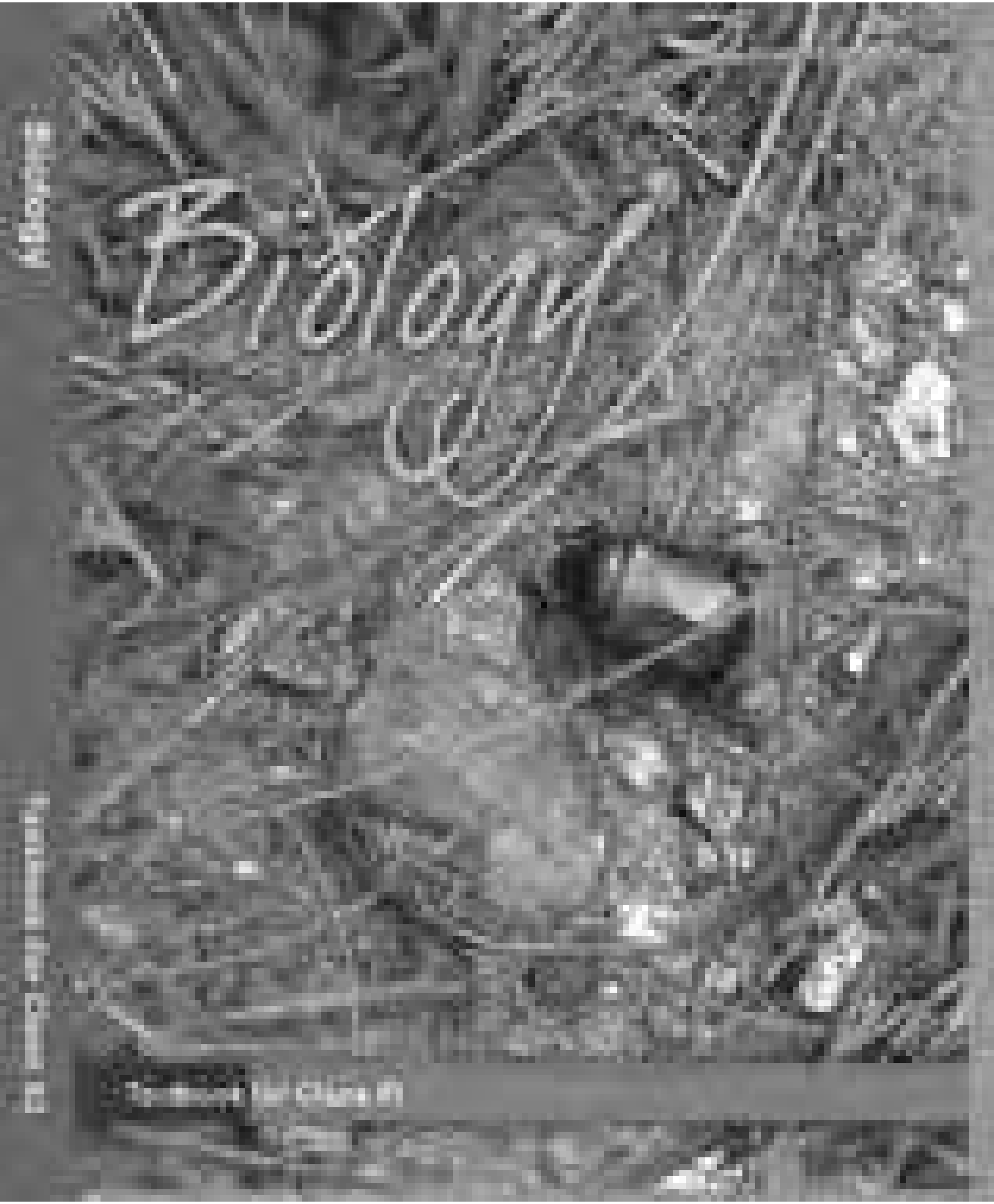
Biology

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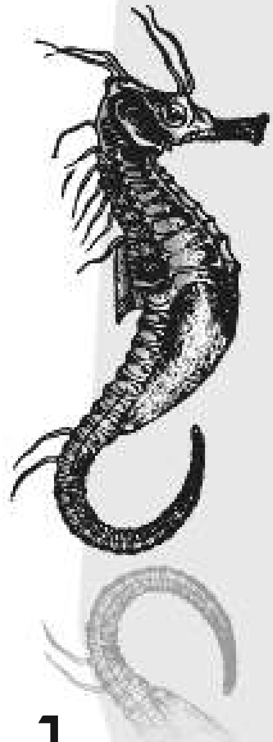


UNIT 1

DIVERSITY IN THE LIVING WORLD

Biology is the science of life forms and living processes. The living world comprises an amazing diversity of living organisms. Early man could easily perceive the difference between inanimate matter and living organisms. Early man deified some of the inanimate matter (wind, sea, fire etc.) and some among the animals and plants. A common feature of all such forms of inanimate and animate objects was the sense of awe or fear that they evoked. The description of living organisms including human beings began much later in human history. Societies which indulged in anthropocentric view of biology could register limited progress in biological knowledge. Systematic and monumental description of life forms brought in, out of necessity, detailed systems of identification, nomenclature and classification. The biggest spin off of such studies was the recognition of the sharing of similarities among living organisms both horizontally and vertically. That all present day living organisms are related to each other and also to all organisms that ever lived on this earth, was a revelation which humbled man and led to cultural movements for conservation of biodiversity. In the following chapters of this unit, you will get a description, including classification, of animals and plants from a taxonomist's perspective.

Ernst Mayr
(1904 – 2004)

Born on 5 July 1904, in Kempten, Germany, ERNST MAYR, the Harvard University evolutionary biologist who has been called 'The Darwin of the 20th century', was one of the 100 greatest scientists of all time. Mayr joined Harvard's Faculty of Arts and Sciences in 1953 and retired in 1975, assuming the title *Alexander Agassiz Professor of Zoology Emeritus.* Throughout his nearly 80-year career, his research spanned ornithology, taxonomy, zoogeography, evolution, systematics, and the history and philosophy of biology. He almost single-handedly made the origin of species diversity the central question of evolutionary biology that it is today. He also pioneered the currently accepted definition of a biological species. Mayr was awarded the three prizes widely regarded as the *triple crown* of biology: the *Balzan Prize* in 1983, the *International Prize for Biology* in 1994, and the *Crafoord Prize* in 1999. Mayr died at the age of 100 in the year 2004.

How wonderful is the living world ! The wide range of living types is amazing. The extraordinary habitats in which we find living organisms, be it cold mountains, deciduous forests, oceans, fresh water lakes, deserts or hot springs, leave us speechless. The beauty of a galloping horse, of the migrating birds, the valley of flowers or the attacking shark evokes awe and a deep sense of wonder. The ecological conflict and cooperation among members of a population and among populations of a community or even the molecular traffic inside a cell make us deeply reflect on – what indeed is life? This question has two implicit questions within it. The first is a technical one and seeks answer to what living is as opposed to the non-living, and the second is a philosophical one, and seeks answer to what the purpose of life is. As scientists, we shall not attempt answering the second question. We will try to reflect on – what is living?

1.1 What is 'Living'?

When we try to define 'living', we conventionally look for distinctive characteristics exhibited by living organisms. Growth, reproduction, ability to sense environment and mount a suitable response come to our mind immediately as unique features of living organisms. One can add a few more features like metabolism, ability to self-replicate, self-organise, interact and emergence to this list. Let us try to understand each of these.

All living organisms grow. Increase in mass and increase in number of individuals are twin characteristics of growth. A multicellular organism grows by cell division. In plants, this growth by cell division occurs continuously throughout their life span. In animals, this growth is seen only up to a certain age. However, cell division occurs in certain tissues to replace lost cells. Unicellular organisms also grow by cell division. One can easily observe this in *in vitro* cultures by simply counting the number of cells under the microscope. In majority of higher animals and plants, growth and reproduction are mutually exclusive events. One must remember that increase in body mass is considered as growth. Non-living objects also grow if we take increase in body mass as a criterion for growth. Mountains, boulders and sand mounds do grow. However, this kind of growth exhibited by non-living objects is by accumulation of material on the surface. In living organisms, growth is from inside. Growth, therefore, cannot be taken as a defining property of living organisms. Conditions under which it can be observed in all living organisms have to be explained and then we understand that it is a characteristic of living systems. A dead organism does not grow.

Reproduction, likewise, is a characteristic of living organisms. In multicellular organisms, reproduction refers to the production of progeny possessing features more or less similar to those of parents. Invariably and implicitly we refer to sexual reproduction. Organisms reproduce by asexual means also. Fungi multiply and spread easily due to the millions of asexual spores they produce. In lower organisms like yeast and hydra, we observe budding. In *Planaria* (flat worms), we observe true regeneration, i.e., a fragmented organism regenerates the lost part of its body and becomes, a new organism. The fungi, the filamentous algae, the protonema of mosses, all easily multiply by fragmentation. When it comes to unicellular organisms like bacteria, unicellular algae or *Amoeba*, reproduction is synonymous with growth, i.e., increase in number of cells. We have already defined growth as equivalent to increase in cell number or mass. Hence, we notice that in single-celled organisms, we are not very clear about the usage of these two terms – growth and reproduction. Further, there are many organisms which do not reproduce (mules, sterile worker bees, infertile human couples, etc). Hence, reproduction also cannot be an all-inclusive defining characteristic of living organisms. Of course, no non-living object is capable of reproducing or replicating by itself.

Another characteristic of life is metabolism. All living organisms are made of chemicals. These chemicals, small and big, belonging to various classes, sizes, functions, etc., are constantly being made and changed into some other biomolecules. These conversions are chemical reactions or metabolic reactions. There are thousands of metabolic reactions occurring simultaneously inside all living organisms, be they unicellular or multicellular. All plants, animals, fungi and microbes exhibit metabolism. The sum total of all the chemical reactions occurring in our body is metabolism. No non-living object exhibits metabolism. Metabolic reactions can be demonstrated outside the body in cell-free systems. An isolated metabolic reaction(s) outside the body of an organism, performed in a test tube is neither living nor non-living. Hence, while metabolism is a defining feature of all living organisms without exception, isolated metabolic reactions *in vitro* are not living things but surely living reactions. **Hence, cellular organisation of the body is the defining feature of life forms.**

Perhaps, the most obvious and technically complicated feature of all living organisms is this ability to sense their surroundings or environment and respond to these environmental stimuli which could be physical, chemical or biological. We sense our environment through our sense organs. Plants respond to external factors like light, water, temperature, other organisms, pollutants, etc. All organisms, from the prokaryotes to the most complex eukaryotes can sense and respond to environmental cues. Photoperiod affects reproduction in seasonal breeders, both plants and animals. All organisms handle chemicals entering their bodies. All organisms therefore, are 'aware' of their surroundings. Human being is the only organism who is aware of himself, i.e., has self-consciousness. **Consciousness therefore, becomes the defining property of living organisms.**

When it comes to human beings, it is all the more difficult to define the living state. We observe patients lying in coma in hospitals virtually supported by machines which replace heart and lungs. The patient is otherwise brain-dead. The patient has no self-consciousness. Are such patients who never come back to normal life, living or non-living?

In higher classes, you will come to know that all living phenomena are due to underlying interactions. Properties of tissues are not present in the constituent cells but arise as a result of interactions among the constituent cells. Similarly, properties of cellular organelles are not present in the molecular constituents of the organelle but arise as a result of interactions among the molecular components comprising the organelle. These interactions result in emergent properties at a higher level of organisation. This phenomenon is true in the hierarchy of organisational complexity at all levels. Therefore, we can say that living organisms are self-replicating, evolving and self-regulating interactive systems capable of responding to external stimuli. Biology is the story of life on earth. Biology is the story of evolution of living organisms on earth. All living organisms – present, past and future, are linked to one another by the sharing of the common genetic material, but to varying degrees.

1.2 Diversity in the Living World

If you look around you will see a large variety of living organisms, be it potted plants, insects, birds, your pets or other animals and plants. There are also several organisms that you cannot see with your naked eye but they are all around you. If you were to increase the area that you make observations in, the range and variety of organisms that you see would increase. Obviously, if you were to visit a dense forest, you would probably see a much greater number and kinds of living organisms in it. Each different kind of plant, animal or organism that you see, represents a species. The number of species that are known and described range between 1.7-1.8 million. This refers to **biodiversity** or the number and types of organisms present on earth. We should remember here that as we explore new areas, and even old ones, new organisms are continuously being identified.

As stated earlier, there are millions of plants and animals in the world; we know the plants and animals in our own area by their local names. These local names would vary from place to place, even within a country. Probably you would recognise the confusion that would be created if we did not find ways and means to talk to each other, to refer to organisms we are talking about.

Hence, there is a need to standardise the naming of living organisms such that a particular organism is known by the same name all over the world. This process is called **nomenclature**. Obviously, nomenclature or naming is only possible when the organism is described correctly and we know to what organism the name is attached to. This is **identification.**

In order to facilitate the study, number of scientists have established procedures to assign a scientific name to each known organism. This is acceptable to biologists all over the world. For plants, scientific names are based on agreed principles and criteria, which are provided in International Code for Botanical Nomenclature (ICBN). You may ask, how are animals named? Animal taxonomists have evolved International Code of Zoological Nomenclature (ICZN). The scientific names ensure that each organism has only one name. Description of any organism should enable the people (in any part of the world) to arrive at the same name. They also ensure that such a name has not been used for any other known organism.

Biologists follow universally accepted principles to provide scientific names to known organisms. Each name has two components – the **Generic name** and the **specific epithet**. This system of providing a name with two components is called **Binomial nomenclature**. This naming system given by Carolus Linnaeus is being practised by biologists all over the world. This naming system using a two word format was found convenient. Let us take the example of mango to understand the way of providing scientific names better. The scientific name of mango is written as *Mangifera indica*. Let us see how it is a binomial name. In this name *Mangifera* represents the genus while *indica*, is a particular species, or a specific epithet. Other universal rules of nomenclature are as follows:

1. Biological names are generally in Latin and written in italics. They are Latinised or derived from Latin irrespective of their origin.
2. The first word in a biological name represents the genus while the second component denotes the specific epithet.
3. Both the words in a biological name, when handwritten, are separately underlined, or printed in italics to indicate their Latin origin.
4. The first word denoting the genus starts with a capital letter while the specific epithet starts with a small letter. It can be illustrated with the example of *Mangifera indica*.

Name of the author appears after the specific epithet, i.e., at the end of the biological name and is written in an abbreviated form, e.g., *Mangifera indica* Linn. It indicates that this species was first described by Linnaeus.

Since it is nearly impossible to study all the living organisms, it is necessary to devise some means to make this possible. This process is **classification**. Classification is the process by which anything is grouped into convenient categories based on some easily observable characters. For example, we easily recognise groups such as plants or animals or dogs, cats or insects. The moment we use any of these terms, we associate certain characters with the organism in that group. What image do you see when you think of a dog ? Obviously, each one of us will see 'dogs' and not 'cats'. Now, if we were to think of 'Alsatians' we know what we are talking about. Similarly, suppose we were to say 'mammals', you would, of course, think of animals with external ears and body hair. Likewise, in plants, if we try to talk of 'Wheat', the picture in each of our minds will be of wheat plants, not of rice or any other plant. Hence, all these - 'Dogs', 'Cats', 'Mammals', 'Wheat', 'Rice', 'Plants', 'Animals', etc., are convenient categories we use to study organisms. The scientific term for these categories is **taxa**. Here you must recognise that taxa can indicate categories at very different levels. 'Plants' – also form a taxa. 'Wheat' is also a taxa. Similarly, 'animals', 'mammals', 'dogs' are all taxa – but you know that a dog is a mammal and mammals are animals. Therefore, 'animals', 'mammals' and 'dogs' represent taxa at different levels.

Hence, based on characteristics, all living organisms can be classified into different taxa. This process of classification is **taxonomy**. External and internal structure, along with the structure of cell, development process and ecological information of organisms are essential and form the basis of modern taxonomic studies.

Hence, characterisation, identification, classification and nomenclature are the processes that are basic to taxonomy.

Taxonomy is not something new. Human beings have always been interested in knowing more and more about the various kinds of organisms, particularly with reference to their own use. In early days, human beings needed to find sources for their basic needs of food, clothing and shelter. Hence, the earliest classifications were based on the 'uses' of various organisms.

Human beings were, since long, not only interested in knowing more about different kinds of organisms and their diversities, but also the relationships among them. This branch of study was referred to as **systematics**. The word systematics is derived from the Latin word 'systema' which means systematic arrangement of organisms. Linnaeus used *Systema Naturae* as the title of his publication. The scope of systematics was later enlarged to include identification, nomenclature and classification. Systematics takes into account evolutionary relationships between organisms.

1.3 Taxonomic Categories

Classification is not a single step process but involves hierarchy of steps in which each step represents a rank or category. Since the category is a part of overall taxonomic arrangement, it is called the **taxonomic category** and all categories together constitute the **taxonomic hierarchy**. Each category, referred to as a unit of classification, in fact, represents a rank and is commonly termed as **taxon** (pl.: taxa).

Taxonomic categories and hierarchy can be illustrated by an example. Insects represent a group of organisms sharing common features like three pairs of jointed legs. It means insects are recognisable concrete objects which can be classified, and thus were given a rank or category. Can you name other such groups of organisms? Remember, groups represent category. Category further denotes rank. Each rank or *taxon*, in fact, represents a unit of classification. These taxonomic groups/ categories are distinct biological entities and not merely morphological aggregates.

Taxonomical studies of all known organisms have led to the development of common categories such as kingdom, phylum or division (for plants), class, order, family, genus and species. All organisms, including those in the plant and animal kingdoms have species as the lowest category. Now the question you may ask is, how to place an organism in various categories? The basic requirement is the knowledge of characters of an individual or group of organisms. This helps in identifying similarities and dissimilarities among the individuals of the same kind of organisms as well as of other kinds of organisms.

1.3.1 Species

Taxonomic studies consider a group of individual organisms with fundamental similarities as a **species**. One should be able to distinguish one species from the other closely related species based on the distinct morphological differences. Let us consider *Mangifera indica*, *Solanum tuberosum* (potato) and *Panthera leo* (lion). All the three names, *indica, tuberosum* and *leo,* represent the specific epithets, while the first words *Mangifera, Solanum* and *Panthera* are genera and represents another higher level of taxon or category. Each genus may have one or more than one specific epithets representing different organisms, but having morphological similarities. For example, *Panthera* has another specific epithet called *tigris* and *Solanum* includes species like *nigrum* and *melongena*. Human beings belong to the species *sapiens* which is grouped in genus *Homo*. The scientific name thus, for human being, is written as *Homo sapiens*.

1.3.2 Genus

Genus comprises a group of related species which has more characters in common in comparison to species of other genera. We can say that genera are aggregates of closely related species. For example, potato, tomato and brinjal are three different species but all belong to the genus *Solanum.* Lion (*Panthera leo*), leopard (*P. pardus*) and tiger (*P. tigris*) with several common features, are all species of the genus *Panthera.* This genus differs from another genus *Felis* which includes cats.

1.3.3 Family

The next category, **Family**, has a group of related genera with still less number of similarities as compared to genus and species. Families are characterised on the basis of both vegetative and reproductive features of plant species. Among plants for example, three different genera *Solanum*, *Petunia* and *Datura* are placed in the family Solanaceae. Among animals for example, genus *Panthera*, comprising lion, tiger, leopard is put along with genus, *Felis* (cats) in the family Felidae. Similarly, if you observe the features of a cat and a dog, you will find some similarities and some differences as well. They are separated into two different families – Felidae and Cancidae, respectively.

1.3.4 Order

You have seen earlier that categories like species, genus and families are based on a number of similar characters. Generally, order and other higher taxonomic categories are identified based on the aggregates of characters. Order being a higher category, is the assemblage of families which exhibit a few similar characters. The similar characters are less in number as compared to different genera included in a family. Plant families like Convolvulaceae, Solanaceae are included in the order Polymoniales mainly based on the floral characters. The animal order, Carnivora, includes families like Felidae and Cancidae.

1.3.5 Class

This category includes related orders. For example, order Primata comprising monkey, gorilla and gibbon is placed in class Mammalia along with order Carnivora that includes animals like tiger, cat and dog. Class Mammalia has other orders also.

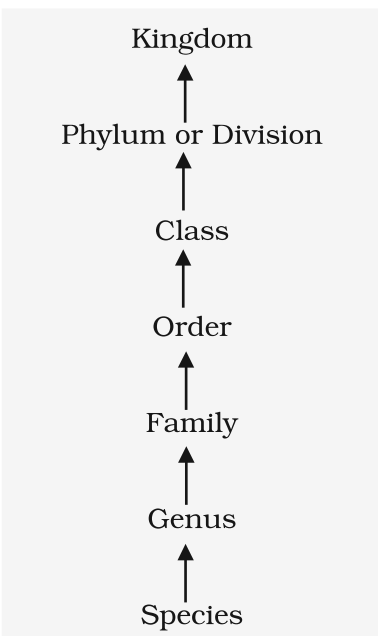


Figure 1.1 Taxonomic categories showing hierarchial arrangement in ascending order

1.3.6 Phylum

Classes comprising animals like fishes, amphibians, reptiles, birds along with mammals constitute the next higher category called Phylum. All these, based on the common features like presence of notochord and dorsal hollow neural system, are included in phylum Chordata. In case of plants, classes with a few similar characters are assigned to a higher category called Division.

1.3.7 Kingdom

All animals belonging to various phyla are assigned to the highest category called Kingdom Animalia in the classification system of animals. The Kingdom Plantae, on the other hand, is distinct, and comprises all plants from various divisions. Henceforth, we will refer to these two groups as animal and plant kingdoms.

The taxonomic categories from species to kingdom have been shown in ascending order starting with species in Figure 1.1. These are broad categories. However, taxonomists have also developed sub-categories in this hierarchy to facilitate more sound and scientific placement of various taxa.

Look at the hierarchy in Figure 1.1. Can you recall the basis of arrangement? Say, for example, as we go higher from species to kingdom, the number of common characteristics goes on decreasing. Lower the taxa, more are the characteristics that the members within the taxon share. Higher the category, greater is the difficulty of determining the relationship to other taxa at the same level. Hence, the problem of classification becomes more complex.

Table 1.1 indicates the taxonomic categories to which some common organisms like housefly, man, mango and wheat belong.

TABLE 1.1 Organisms with their Taxonomic Categories

Common Name	Biological Name	Genus	Family	Order	Class	Phylum/ Division
Man	*Homo sapiens*	*Homo*	Hominidae	Primata	Mammalia	Chordata
Housefly	*Musca domestica*	*Musca*	Muscidae	Diptera	Insecta	Arthropoda
Mango	*Mangifera indica*	*Mangifera*	Anacardiaceae	Sapindales	Dicotyledonae	Angiospermae
Wheat	*Triticum aestivum*	*Triticum*	Poaceae	Poales	Monocotyledonae	Angiospermae

1.4 TAXONOMICAL AIDS

Taxonomic studies of various species of plants, animals and other organisms are useful in agriculture, forestry, industry and in general in knowing our bio-resources and their diversity. These studies would require correct classification and identification of organisms. Identification of organisms requires intensive laboratory and field studies. The collection of actual specimens of plant and animal species is essential and is the prime source of taxonomic studies. These are also fundamental to studies and essential for training in systematics. It is used for classification of an organism, and the information gathered is also stored along with the specimens. In some cases the specimen is preserved for future studies.

Biologists have established certain procedures and techniques to store and preserve the information as well as the specimens. Some of these are explained to help you understand the usage of these aids.

1.4.1 Herbarium

Herbarium is a store house of collected plant specimens that are dried, pressed and preserved on sheets. Further, these sheets are arranged

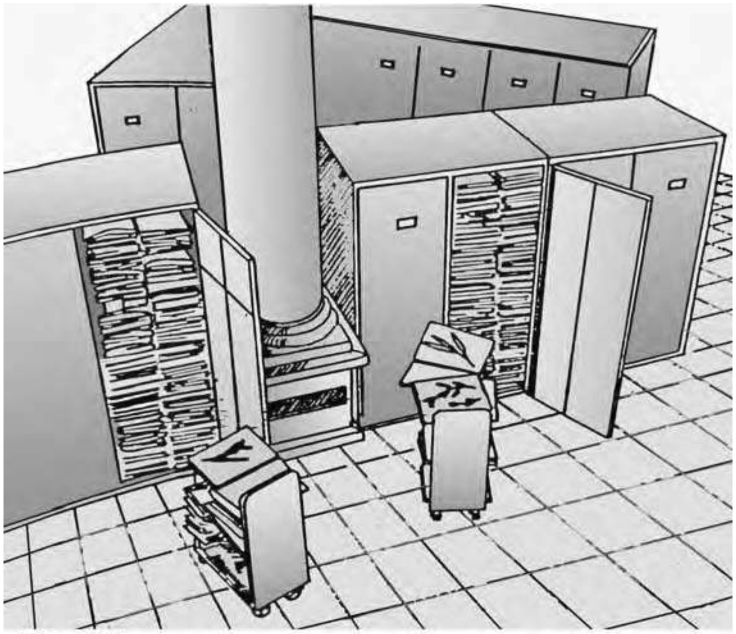


Figure 1.2 Herbarium showing stored specimens

according to a universally accepted system of classification. These specimens, along with their descriptions on herbarium sheets, become a store house or repository for future use (Figure 1.2). The herbarium sheets also carry a label providing information about date and place of collection, English, local and botanical names, family, collector's name, etc. Herbaria also serve as quick referral systems in taxonomical studies.

1.4.2 Botanical Gardens

These specialised gardens have collections of living plants for reference. Plant species in these gardens are grown for identification purposes and each plant is labelled indicating its botanical/scientific name and its family. The famous botanical gardens are at Kew (England), Indian Botanical Garden, Howrah (India) and at National Botanical Research Institute, Lucknow (India).

1.4.3 Museum

Biological museums are generally set up in educational institutes such as schools and colleges. Museums have collections of preserved plant and animal specimens for study and reference. Specimens are preserved in the containers or jars in preservative solutions. Plant and animal specimens may also be preserved as dry specimens. Insects are preserved in insect boxes after collecting, killing and pinning. Larger animals like birds and mammals are usually stuffed and preserved. Museums often have collections of skeletons of animals too.

1.4.4 Zoological Parks

These are the places where wild animals are kept in protected environments under human care and which enable us to learn about their food habits and behaviour. All animals in a zoo are provided, as far as possible, the conditions similar to their natural habitats. Children love visiting these parks, commonly called Zoos (Figure 1.3).

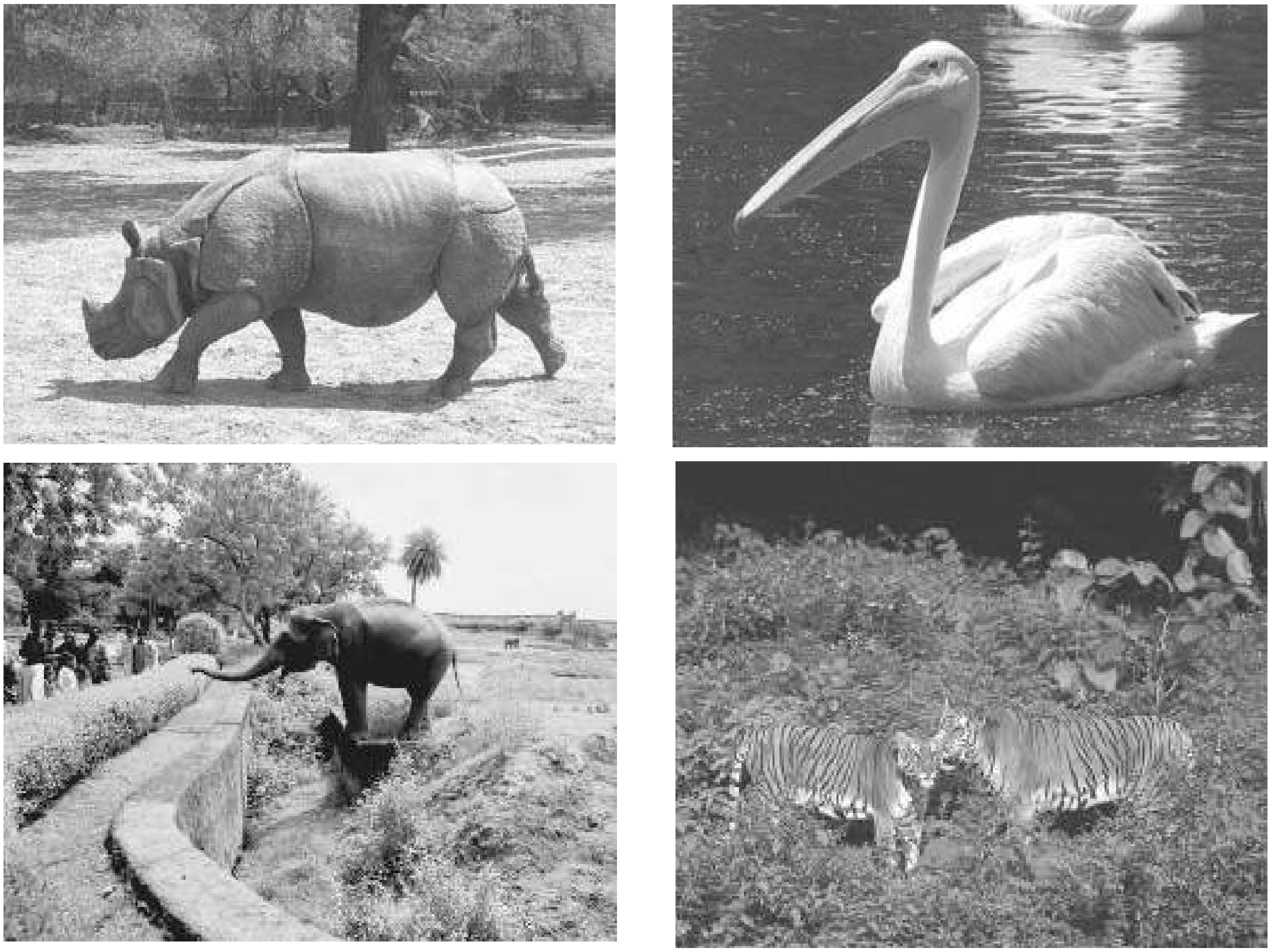


Figure 1.3 Pictures showing animals in different zoological parks of India

1.4.5 Key

Key is another taxonomical aid used for identification of plants and animals based on the similarities and dissimilarities. The keys are based on the contrasting characters generally in a pair called couplet. It represents the choice made between two opposite options. This results in acceptance of only one and rejection of the other. Each statement in the key is called a lead. Separate taxonomic keys are required for each taxonomic category such as family, genus and species for identification purposes. Keys are generally analytical in nature.

Flora, manuals, monographs and catalogues are some other means of recording descriptions. They also help in correct identification. Flora contains the actual account of habitat and distribution of plants of a given area. These provide the index to the plant species found in a particular area. Manuals are useful in providing information for identification of names of species found in an area. Monographs contain information on any one taxon.

Summary

The living world is rich in variety. Millions of plants and animals have been identified and described but a large number still remains unknown. The very range of organisms in terms of size, colour, habitat, physiological and morphological features make us seek the defining characteristics of living organisms. In order to facilitate the study of kinds and diversity of organisms, biologists have evolved certain rules and principles for identification, nomenclature and classification of organisms. The branch of knowledge dealing with these aspects is referred to as taxonomy. The taxonomic studies of various species of plants and animals are useful in agriculture, forestry, industry and in general for knowing our bio-resources and their diversity. The basics of taxonomy like identification, naming and classification of organisms are universally evolved under international codes. Based on the resemblances and distinct differences, each organism is identified and assigned a correct scientific/biological name comprising two words as per the binomial system of nomenclature. An organism represents/occupies a place or position in the system of classification. There are many categories/ranks and are generally referred to as taxonomic categories or taxa. All the categories constitute a taxonomic hierarchy.

Taxonomists have developed a variety of taxonomic aids to facilitate identification, naming and classification of organisms. These studies are carried out from the actual specimens which are collected from the field and preserved as referrals in the form of herbaria, museums and in botanical gardens and zoological parks. It requires special techniques for collection and preservation of specimens in herbaria and museums. Live specimens, on the other hand, of plants and animals, are found in botanical gardens or in zoological parks. Taxonomists also prepare and disseminate information through manuals and monographs for further taxonomic studies. Taxonomic keys are tools that help in identification based on characteristics.

Exercises

1. Why are living organisms classified?
2. Why are the classification systems changing every now and then?
3. What different criteria would you choose to classify people that you meet often?
4. What do we learn from identification of individuals and populations?
5. Given below is the scientific name of Mango. Identify the correctly written name.

   Mangifera Indica

   Mangifera indica
6. Define a taxon. Give some examples of taxa at different hierarchical levels.
7. Can you identify the correct sequence of taxonomical categories?

   (a) Species → Order → Phylum → Kingdom

   (b) Genus → Species → Order → Kingdom

   (c) Species → Genus → Order → Phylum
8. Try to collect all the currently accepted meanings for the word 'species'. Discuss with your teacher the meaning of species in case of higher plants and animals on one hand, and bacteria on the other hand.
9. Define and understand the following terms:

   (i) Phylum (ii) Class (iii) Family (iv) Order (v) Genus
10. How is a key helpful in the identification and classification of an organism?
11. Illustrate the taxonomical hierarchy with suitable examples of a plant and an animal.

CHAPTER 2

BIOLOGICAL CLASSIFICATION

Since the dawn of civilisation, there have been many attempts to classify living organisms. It was done instinctively not using criteria that were scientific but borne out of a need to use organisms for our own use – for food, shelter and clothing. Aristotle was the earliest to attempt a more scientific basis for classification. He used simple morphological characters to classify plants into trees, shrubs and herbs. He also divided animals into two groups, those which had red blood and those that did not.

In Linnaeus' time a **Two Kingdom** system of classification with **Plantae** and **Animalia** kingdoms was developed that included all plants and animals respectively. This system was used till very recently. This system did not distinguish between the eukaryotes and prokaryotes, unicellular and multicellular organisms and photosynthetic (green algae) and non-photosynthetic (fungi) organisms. Classification of organisms into plants and animals was easily done and was easy to understand, inspite, a large number of organisms did not fall into either category. Hence the two kingdom classification used for a long time was found inadequate. A need was also felt for including, besides gross morphology, other characteristics like cell structure, nature of wall, mode of nutrition, habitat, methods of reproduction, evolutionary relationships, etc. Classification systems for the living organisms have hence, undergone several changes over time. Though plant and animal kingdoms have been a constant under all different systems, the understanding of what groups/organisms be included under these kingdoms have been changing; the number and nature of other kingdoms have also been understood differently by different scientists over time.

TABLE 2.1 **Characteristics of the Five Kingdoms**

Characters	**Five Kingdoms**				
	Monera	**Protista**	**Fungi**	**Plantae**	**Animalia**
Cell type	Prokaryotic	Eukaryotic	Eukaryotic	Eukaryotic	Eukaryotic
Cell wall	Noncellular (Polysaccharide + amino acid)	Present in some	Present (without cellulose)	Present (cellulose)	Absent
Nuclear membrane	Absent	Present	Present	Present	Present
Body organisation	Cellular	Cellular	Multiceullar/ loose tissue	Tissue/ organ	Tissue/organ/ organ system
Mode of nutrition	Autotrophic (chemosyn-thetic and photosynthetic) and Hetero-trophic (sapro-phyte/para-site)	Autotrophic (Photosyn-thetic) and Hetero-trophic	Heterotrophic (Saprophytic/ Parasitic)	Autotrophic (Photosyn-thetic)	Heterotrophic (Holozoic/ Saprophytic etc.)

R.H. Whittaker (1969) proposed a **Five Kingdom Classification.** The kingdoms defined by him were named **Monera**, **Protista**, **Fungi**, **Plantae** and **Animalia.** The main criteria for classification used by him include cell structure, thallus organisation, mode of nutrition, reproduction and phylogenetic relationships. Table 2.1 gives a comparative account of different characteristics of the five kingdoms.

Let us look at this five kingdom classification to understand the issues and considerations that influenced the classification system. Earlier classification systems included bacteria, blue green algae, fungi, mosses, ferns, gymnosperms and the angiosperms under 'Plants'. The character that unified this whole kingdom was that all the organisms included had a cell wall in their cells. This placed together groups which widely differed in other characterstics. It brought together the prokaryotic bacteria and the blue green algae with other groups which were eukaryotic. It also grouped together the unicellular organisms and the multicellular ones, say, for example, *Chlamydomonas* and *Spirogyra* were placed together under algae. The classification did not differentiate between the heterotrophic group – fungi, and the autotrophic green plants, though they also showed a characteristic difference in their walls composition – the fungi had chitin in their walls while the green plants had a cellulosic cell wall. When such characterstics were considered, the fungi were placed in a separate kingdom – Kingdom Fungi. All prokaryotic organisms were grouped together under Kingdom Monera and the unicellular eukaryotic organisms were placed in Kingdom Protista. Kingdom Protista has brought together *Chlamydomonas, Chlorella* (earlier placed in Algae within Plants and both having cell walls) with *Paramoecium* and *Amoeba* (which were earlier placed in the animal kingdom) which lack it. It has put together organisms which, in earlier classifications, were placed in different kingdoms. This happened because the criteria for classification changed. This kind of changes will take place in future too depending on the improvement in our understanding of characteristics and evolutionary relationships. Over time, an attempt has been made to evolve a classification system which reflects not only the morphological, physiological and reproductive similarities, but is also phylogenetic, i.e., is based on evolutionary relationships.

In this chapter we will study characteristics of Kingdoms Monera, Protista and Fungi of the Whittaker system of classification. The Kingdoms Plantae and Animalia, commonly referred to as plant and animal kingdoms, respectively, will be dealt with separately in chapters 3 and 4.

2.1 KINGDOM MONERA

Bacteria are the sole members of the Kingdom Monera. They are the most abundant micro-organisms. Bacteria occur almost everywhere. Hundreds of bacteria are present in a handful of soil. They also live in extreme habitats such as hot springs, deserts, snow and deep oceans where very few other life forms can survive. Many of them live in or on other organisms as parasites.

Bacteria are grouped under four categories based on their shape: the spherical Coccus (pl.: cocci), the rod-shaped Bacillus (pl.: bacilli), the comma-shaped Vibrium (pl.: vibrio) and the spiral Spirillum (pl.: spirilla) (Figure 2.1).

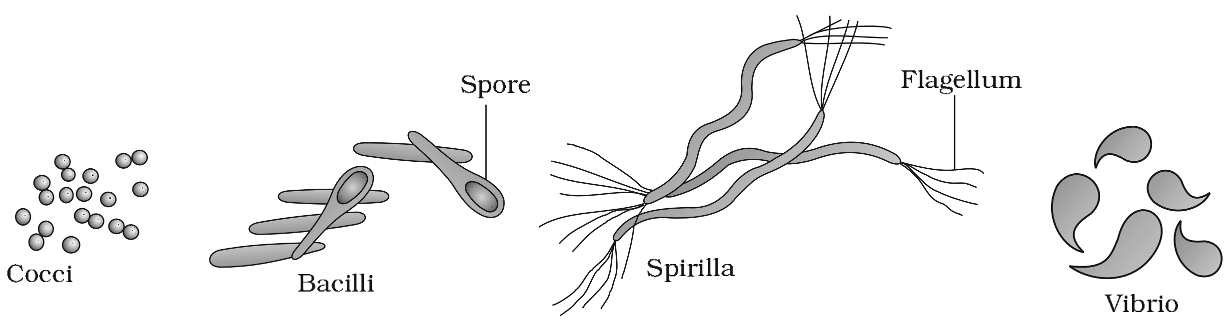


Figure 2.1 Bacteria of different shapes

Though the bacterial structure is very simple, they are very complex in behaviour. Compared to many other organisms, bacteria as a group show the most extensive metabolic diversity. Some of the bacteria are autotrophic, i.e., they synthesise their own food from inorganic substrates. They may be photosynthetic autotrophic or chemosynthetic autotrophic. The vast majority of bacteria are heterotrophs, i.e., they do not synthesise their own food but depend on other organisms or on dead organic matter for food.

2.1.1 Archaebacteria

These bacteria are special since they live in some of the most harsh habitats such as extreme salty areas (halophiles), hot springs (thermoacidophiles) and marshy areas (methanogens). Archaebacteria differ from other bacteria in having a different cell wall structure and this feature is responsible for their survival in extreme conditions. Methanogens are present in the guts of several ruminant animals such as cows and buffaloes and they are responsible for the production of methane (biogas) from the dung of these animals.

2.1.2 Eubacteria

There are thousands of different **eubacteria** or 'true bacteria'. They are characterised by the presence of a rigid cell wall, and if motile, a flagellum. The **cyanobacteria** (also referred to as blue-green algae) have chlorophyll *a* similar to green plants and are **photosynthetic autotrophs** (Figure 2.2). The cyanobacteria are unicellular, colonial or filamentous, marine or terrestrial algae. The colonies are generally surrounded by gelatinous sheath. They often form blooms in polluted water bodies. Some of these organisms can fix atmospheric nitrogen in specialised cells called **heterocysts,** e.g., *Nostoc* and *Anabaena*. **Chemosynthetic autotrophic** bacteria oxidise various inorganic substances such as nitrates, nitrites and ammonia and use the released energy for their ATP production. They play a great role in recycling nutrients like nitrogen, phosphorous, iron and sulphur.

Heterotrophic bacteria are the most abundant in nature. The majority are important decomposers. Many of them have a significant impact on human affairs. They are helpful in making curd from milk, production of antibiotics, fixing nitrogen in legume

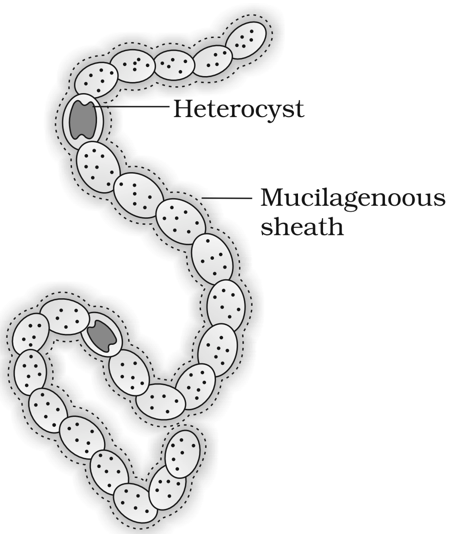


Figure 2.2 A filamentous blue-green algae – *Nostoc*

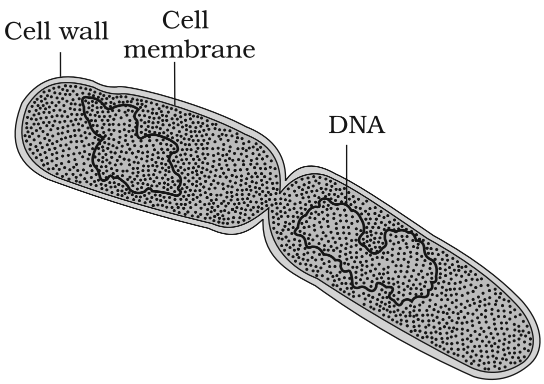


Figure 2.3 A dividing bacterium

roots, etc. Some are pathogens causing damage to human beings, crops, farm animals and pets. Cholera, typhoid, tetanus, citrus canker are well known diseases caused by different bacteria.

Bacteria reproduce mainly by fission (Figure 2.3). Sometimes, under unfavourable conditions, they produce spores. They also reproduce by a sort of sexual reproduction by adopting a primitive type of DNA transfer from one bacterium to the other.

The **Mycoplasmas** are organisms that completely lack a cell wall. They are the smallest living cells known and can survive without oxygen. Many mycoplasma are pathogenic in animals and plants.

2.2 Kingdom Protista

All single-celled eukaryotes are placed under **Protista**, but the boundaries of this kingdom are not well defined. What may be 'a photosynthetic protistan' to one biologist may be 'a plant' to another. In this book we include Chrysophytes, Dianoflagellates, Euglenoids, Slime moulds and Protozoans under Protista. Members of Protista are primarily aquatic. This kingdom forms a link with the others dealing with plants, animals and fungi. Being eukaryotes, the protistan cell body contains a well defined nucleus and other membrane-bound organelles. Some have flagella or cilia. Protists reproduce asexually and sexually by a process involving cell fusion and zygote formation.

2.2.1 Chrysophytes

This group includes diatoms and golden algae (desmids). They are found in fresh water as well as in marine environments. They are microscopic and float passively in water currents (plankton). Most of them are photosynthetic. In diatoms the cell walls form two thin overlapping shells, which fit together as in a soap box. The walls are embedded with silica and thus the walls are indestructible. Thus, diatoms have left behind large amount of cell wall deposits in their habitat; this accumulation over billions of years is referred to as 'diatomaceous earth'. Being gritty this soil is used in polishing, filtration of oils and syrups. Diatoms are the chief 'producers' in the oceans.

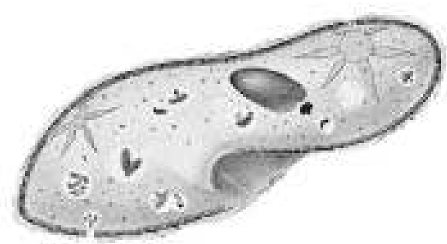
2.2.2 Dianoflagellates

These organisms are mostly marine and photosynthetic. They appear yellow, green, brown, blue or red depending on the main pigments present in their cells. The cell wall has stiff cellulose plates on the outer surface. Most of them have two flagella; one lies longitudinally and the other transversely in a furrow between the wall plates. Very often, red dianoflagellates (Example: *Gonyaulax)* undergo such rapid multiplication that they make the sea appear red (red tides). Toxins released by such large numbers may even kill other marine animals such as fishes.

2.2.3 Euglenoids

Majority of them are fresh water organisms found in stagnant water. Instead of a cell wall, they have a protein rich layer called pellicle which makes their body flexible. They have two flagella, a short and a long one. Though they are photosynthetic in the presence of sunlight, when deprived of sunlight they behave like heterotrophs by predating on other smaller organisms. Interestingly, the pigments of euglenoids are identical to those present in higher plants. Example: *Euglena* (Figure 2.4a).

(a)



(b)

Figure 2.4 (a) *Euglena*
(b) *Paramoecium*

2.2.4 Slime Moulds

Slime moulds are saprophytic protists. The body moves along decaying twigs and leaves engulfing organic material. Under suitable conditions, they form an aggregation called plasmodium which may grow and spread over several feet. During unfavourable conditions, the plasmodium differentiates and forms fruiting bodies bearing spores at their tips. The spores possess true walls. They are extremely resistant and survive for many years, even under adverse conditions. The spores are dispersed by air currents.

2.2.5 Protozoans

All protozoans are heterotrophs and live as predators or parasites. They are believed to be primitive relatives of animals. There are four major groups of protozoans.

Amoeboid protozoans: These organisms live in fresh water, sea water or moist soil. They move and capture their prey by putting out pseudopodia (false feet) as in *Amoeba*. Marine forms have silica shells on their surface. Some of them such as *Entamoeba* are parasites.

Flagellated protozoans: The members of this group are either free-living or parasitic. They have flagella. The parasitic forms cause diaseases such as sleeping sickness. Example: *Trypanosoma*.

Ciliated protozoans: These are aquatic, actively moving organisms because of the presence of thousands of cilia. They have a cavity (gullet) that opens to the outside of the cell surface. The coordinated movement of rows of cilia causes the water laden with food to be steered into the gullet. Example: *Paramoecium* (Figure 2.4b).

Sporozoans: This includes diverse organisms that have an infectious spore-like stage in their life cycle. The most notorious is *Plasmodium* (malarial parasite) which causes malaria which has a staggering effect on human population.

2.3 KINGDOM FUNGI

The fungi constitute a unique kingdom of heterotrophic organisms. They show a great diversity in morphology and habitat. When your bread develops a mould or your orange rots it is because of fungi. The common mushroom you eat and toadstools are also fungi. White spots seen on mustard leaves are due to a parasitic fungus. Some unicellular fungi, e.g., yeast are used to make bread and beer. Other fungi cause diseases in plants and animals; wheat rust-causing *Puccinia* is an important example. Some are the source of antibiotics, e.g., *Penicillium*. Fungi are cosmopolitan and occur in air, water, soil and on animals and plants. They prefer to grow in warm and humid places. Have you ever wondered why we keep food in the refrigerator ? Yes, it is to prevent food from going bad due to bacterial or fungal infections.

With the exception of yeasts which are unicellular, fungi are filamentous. Their bodies consist of long, slender thread-like structures called hyphae. The network of hyphae is known as mycelium. Some hyphae are continuous tubes filled with multinucleated cytoplasm – these are called coenocytic hyphae. Others have septae or cross walls in their hyphae. The cell walls of fungi are composed of chitin and polysaccharides.

Most fungi are heterotrophic and absorb soluble organic matter from dead substrates and hence are called **saprophytes**. Those that depend on living plants and animals are called **parasites**. They can also live as **symbionts** – in association with algae as **lichens** and with roots of higher plants as **mycorrhiza**.

Reproduction in fungi can take place by vegetative means – fragmentation, fission and budding. Asexual reproduction is by spores called conidia or sporangiospores or zoospores, and sexual reproduction is by oospores, ascospores and basidiospores. The various spores are produced in distinct structures called fruiting bodies. The sexual cycle involves the following three steps:

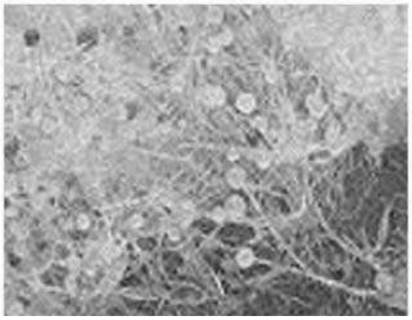
(i) Fusion of protoplasms between two motile or non-motile gametes called **plasmogamy.**

(ii) Fusion of two nuclei called **karyogamy.**

(iii) Meiosis in zygote resulting in haploid spores.

When a fungus reproduces sexually, two haploid hyphae of compatible mating types come together and fuse. In some fungi the fusion of two haploid cells immediately results in diploid cells (2n). However, in other fungi (ascomycetes and basidiomycetes), an intervening dikaryotic stage (n + n i.e. two nuclei per cell) occurs; such a condition is called a **dikaryon** and the phase is called **dikaryophase** of fungus. Later, the parental nuclei fuse and the cells become diploid. The fungi form fruiting bodies in which reduction division occurs, leading to formation of haploid spores.

The morphology of the mycelium, mode of spore formation and fruiting bodies form the basis for the division of the kingdom into various classes.



(a)

(b)

(c)

Figure 2.5 Fungi: (a) *Mucor* (b) *Aspergillus* (c) *Agaricus*

2.3.1 Phycomycetes

Members of phycomycetes are found in aquatic habitats and on decaying wood in moist and damp places or as obligate parasites on plants. The mycelium is aseptate and coenocytic. Asexual reproduction takes place by zoospores (motile) or by aplanospores (non-motile). These spores are endogeneously produced in sporangium. Zygospores are formed by fusion of two gametes. These gametes are similar in morphology (isogamous) or dissimilar (anisogamous or oogamous). Some common examples are *Mucor* (Figure 2.5a), *Rhizopus* (the bread mould mentioned earlier) and *Albugo* (the parasitic fungi on mustard).

2.3.2 Ascomycetes

Commonly known as sac-fungi, the ascomycetes are unicellular, e.g., yeast (*Sacharomyces*) or multicellular, e.g., *Penicillium.* They are saprophytic, decomposers, parasitic or coprophilous (growing on dung). Mycelium is branched and septate. The asexual spores are conidia produced exogenously on the special mycelium called conidiophores. Conidia on germination produce mycelium. Sexual spores are called ascospores which are produced endogenously in sac like asci (singular ascus). These asci are arranged in different types of fruiting bodies called ascocarps. Some examples are *Aspergillus* (Figure 2.5b), *Claviceps* and *Neurospora. Neurospora* is used extensively in biochemical and genetic work. Many members like morels and buffles are edible and are considered delicacies.

2.3.3 Basidiomycetes

Commonly known forms of basidiomycetes are mushrooms, bracket fungi or puffballs. They grow in soil, on logs and tree stumps and in living plant bodies as parasites, e.g., rusts and smuts. The mycelium is branched and septate. The asexual spores are generally not found, but vegetative reproduction by fragmentation is common. The sex organs are absent, but plasmogamy is brought about by fusion of two vegetative or somatic cells of different strains or genotypes. The resultant structure is dikaryotic which ultimately gives rise to basidium. Karyogamy and meiosis take place in the basidium producing four basidiospores. The basidiospores are exogenously produced on the basidium (pl.: basidia). The basidia are arranged in fruiting bodies called basidiocarps. Some common members are *Agaricus* (mushroom) (Figure 2.5c), *Ustilago* (smut) and *Puccinia* (rust fungus).

2.3.4 Deuteromycetes

Commonly known as imperfect fungi because only the asexual or vegetative phases of these fungi are known. When the sexual forms of these fungi were discovered they were moved into classes they rightly belong to. It is also possible that the asexual and vegetative stage have been given one name (and placed under deuteromycetes) and the sexual stage another (and placed under another class). Later when the linkages were established, the fungi were correctly identified and moved out of deuteromycetes. Once perfect (sexual) stages of members of dueteromycetes were discovered they were often moved to ascomycetes and basidiomycetes. The deuteromycetes reproduce only by asexual spores known as conidia. The mycelium is septate and branched. Some members are saprophytes or parasites while a large number of them are decomposers of litter and help in mineral cycling. Some examples are *Alternaria, Colletotrichum* and *Trichoderma.*

2.4 KINGDOM PLANTAE

Kingdom Plantae includes all eukaryotic chlorophyll-containing organisms commonly called plants. A few members are partially heterotrophic such as the insectivorous plants or parasites. Bladderwort and Venus fly trap are examples of insectivorous plants and *Cuscuta* is a parasite. The plant cells have an eukaryotic structure with prominent chloroplasts and cell wall mainly made of cellulose. You will study the eukaryotic cell structure in detail in Chapter 8. Plantae includes algae, bryophytes, pteridophytes, gymnosperms and angiosperms.

Life cycle of plants has two distinct phases – the diploid sporophytic and the haploid gametophytic – that alternate with each other. The lengths of the haploid and diploid phases, and whether these phases are free–living or dependent on others, vary among different groups in plants. This phenomenon is called **alternation of generation.** You will study further details of this kingdom in Chapter 3.

2.5 KINGDOM ANIMALIA

This kingdom is characterised by heterotrophic eukaryotic organisms that are multicellular and their cells lack cell walls. They directly or indirectly depend on plants for food. They digest their food in an internal cavity and store food reserves as glycogen or fat. Their mode of nutrition is holozoic – by ingestion of food. They follow a definite growth pattern and grow into adults that have a definite shape and size. Higher forms show elaborate sensory and neuromotor mechanism. Most of them are capable of locomotion.

The sexual reproduction is by copulation of male and female followed by embryological development. Salient features of various phyla are described in Chapter 4.

2.6 VIRUSES, VIROIDS AND LICHENS

In the five kingdom classification of Whittaker there is no mention of some acellular organisms like viruses and viroids, and lichens. These are briefly introduced here.

All of us who have suffered the illeffects of common cold or 'flu' know what effects viruses can have on us, even if we do not associate it with our condition. Viruses did not find a place in classification since they are not truly 'living', if we understand living as those organisms that have a cell structure. The viruses are non-cellular organisms that are characterised by having an inert crystalline structure outside the living cell. Once they

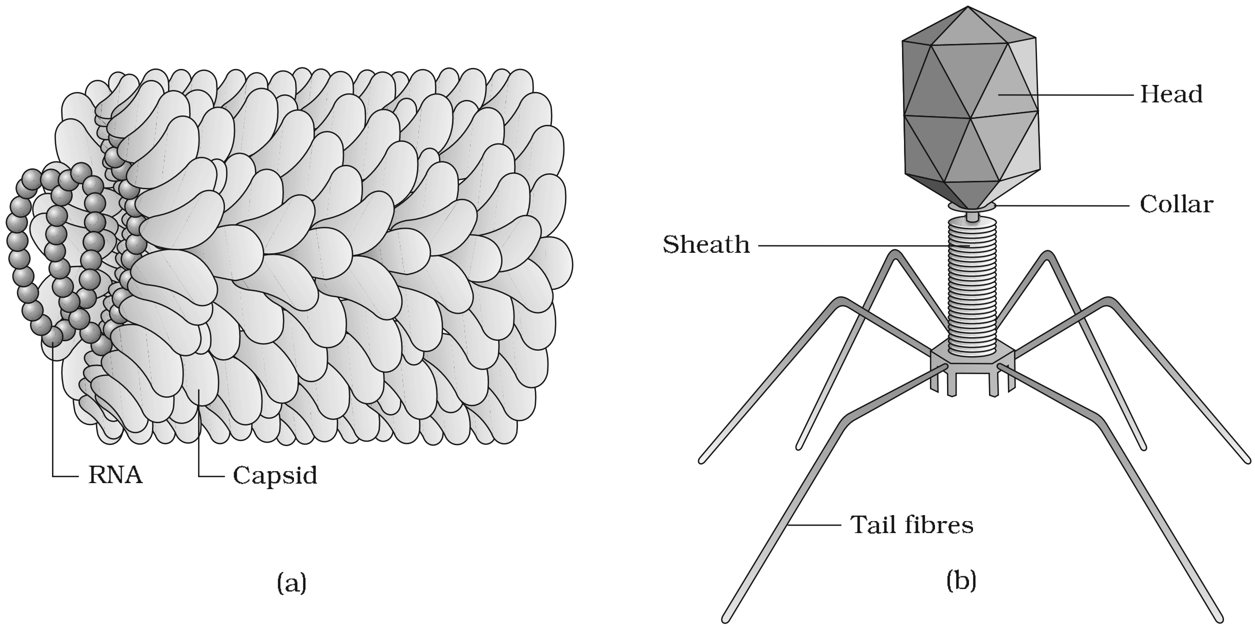


Figure 2.6 (a) Tobacco Mosaic Virus (TMV) (b) Bacteriophage

infect a cell they take over the machinery of the host cell to replicate themselves, killing the host. Would you call viruses living or non-living?

The name virus that means venom or poisonous fluid was given by Pasteur. D.J. Ivanowsky (1892) recognised certain microbes as causal organism of the mosaic disease of tobacco. These were found to be smaller than bacteria because they passed through bacteria-proof filters. M.W. Beijerinek (1898) demonstrated that the extract of the infected plants of tobacco could cause infection in healthy plants and called the fluid as *Contagium vivum fluidum* (infectious living fluid). W.M. Stanley (1935) showed that viruses could be crystallised and crystals consist largely of proteins. They are inert outside their specific host cell. Viruses are obligate parasites.

In addition to proteins viruses also contain genetic material, that could be either RNA or DNA. No virus contains both RNA and DNA. A virus is a nucleoprotein and the genetic material is infectious. In general, viruses that infect plants have single stranded RNA and viruses that infect animals have either single or double stranded RNA or double stranded DNA. Bacterial viruses or bacteriophages (viruses that infect the bacteria) are usually double stranded DNA viruses. The protein coat called capsid made of small subunits called capsomeres, protects the nucleic acid. These capsomeres are arranged in helical or polyhedral geometric forms. Viruses cause diseases like mumps, small pox, herpes and influenza. AIDS in humans is also caused by a virus. In plants, the symptoms can be mosaic formation, leaf rolling and curling, yellowing and vein clearing, dwarfing and stunted growth.

Viroids : In 1971 T.O. Diener discovered a new infectious agent that was smaller than viruses and caused potato spindle tuber disease. It was found to be a free RNA; it lacked the protein coat that is found in viruses, hence the name viroid. The RNA of the viroid was of low molecular weight.

Lichens : Lichens are symbiotic associations i.e. mutually useful associations, between algae and fungi. The algal component is known as **phycobiont** and fungal component as **mycobiont,** which are autotrophic and heterotrophic, respectively. Algae prepare food for fungi and fungi provide shelter and absorb mineral nutrients and water for its partner. So close is their association that if one saw a lichen in nature one would never imagine that they had two different organisms within them. Lichens are very good pollution indicators – they do not grow in polluted areas.

SUMMARY

Biological classification of plants and animals was first proposed by Aristotle on the basis of simple morphlogical characters. Linnaeus later classified all living organisms into two kingdoms – Plantae and Animalia. Whittaker proposed an elaborate five kindgom classification – Monera, Protista, Fungi, Plantae and Animalia. The main criteria of the five kingdom classification were cell structure, body organisation, mode of nutrition and reproduction, and phylogenetic relationships.

In the five kingdom classification, bacteria are included in Kingdom Monera. Bacteria are cosmopolitan in distribution. These organisms show the most extensive metabolic diversity. Bacteria may be autotrophic or heterotrophic in their mode of nutrition. Kingdom Protista includes all single-celled eukaryotes such as Chrysophytes, Dianoflagellates, Euglenoids, Slime-moulds and Protozoans. Protists have defined nucleus and other membrane bound organelles. They reproduce both asexually and sexually. Members of Kingdom Fungi show a great diversity in structures and habitat. Most fungi are saprophytic in their mode of nutrition. They show asexual and sexual reproduction. Phycomycetes, Ascomycetes, Basidiomycetes and Deuteromycetes are the four classes under this kingdom. The plantae includes all eukaryotic chlorophyll-containing organisms. Algae, bryophytes, pteridophytes, gymnosperms and angiosperms are included in this group. The life cycle of plants exhibit alternation of generations – gametophytic and sporophytic generations. The heterotrophic eukaryotic, multicellular organisms lacking a cell wall are included in the Kingdom Animalia. The mode of nutrition of these organisms is holozoic. They reproduce mostly by the sexual mode. Some acellular organisms like viruses and viroids as well as the lichens are not included in the five kingdom system of classification.

EXERCISES

1. Discuss how classification systems have undergone several changes over a period of time?
2. State two economically important uses of:

   (a) heterotrophic bacteria

   (b) archaebacteria
3. What is the nature of cell-walls in diatoms?
4. Find out what do the terms 'algal bloom' and 'red-tides' signify.
5. How are viroids different from viruses?
6. Describe briefly the four major groups of Protozoa.
7. Plants are autotrophic. Can you think of some plants that are partially heterotrophic?
8. What do the terms phycobiont and mycobiont signify?
9. Give a comparative account of the classes of Kingdom Fungi under the following:

   (i) mode of nutrition

   (ii) mode of reproduction
10. What are the characteristic features of Euglenoids?
11. Give a brief account of viruses with respect to their structure and nature of genetic material. Also name four common viral diseases.
12. Organise a discussion in your class on the topic – Are viruses living or non-living?

Chapter 3

Plant Kingdom

In the previous chapter, we looked at the broad classification of living organisms under the system proposed by Whittaker (1969) wherein he suggested the Five Kingdom classification viz. Monera, Protista, Fungi, Animalia and Plantae. In this chapter, we will deal in detail with further classification within Kingdom Plantae popularly known as the 'plant kingdom'.

We must stress here that our understanding of the plant kingdom has changed over time. Fungi, and members of the Monera and Protista having cell walls have now been excluded from Plantae though earlier classifications put them in the same kingdom. So, the cyanobacteria that are also referred to as blue green algae are not 'algae' any more. In this chapter, we will describe Plantae under Algae, Bryophytes, Pteridophytes, Gymnosperms and Angiosperms.

Let us also look at classification within angiosperms to understand some of the concerns that influenced the classification systems. The earliest systems of classification used only gross superficial morphological characters such as habit, colour, number and shape of leaves, etc. They were based mainly on vegetative characters or on the androecium structure (system given by Linnaeus). Such systems were **artificial;** they separated the closely related species since they were based on a few characteristics. Also, the artificial systems gave equal weightage to vegetative and sexual characteristics; this is not acceptable since we know that often the vegetative characters are more easily affected by environment. As against this, **natural classification systems** developed, which were based on natural affinities among the organisms and consider, not only the external features, but also internal features, like ultra-structure, anatomy, embryology and phytochemistry. Such a classification for flowering plants was given by George Bentham and Joseph Dalton Hooker.

At present **phylogenetic classification systems** based on evolutionary relationships between the various organisms are acceptable. This assumes that organisms belonging to the same taxa have a common ancestor. We now use information from many other sources too to help resolve difficulties in classification. These become more important when there is no supporting fossil evidence. **Numerical Taxonomy** which is now easily carried out using computers is based on all observable characteristics. Number and codes are assigned to all the characters and the data are then processed. In this way each character is given equal importance and at the same time hundreds of characters can be considered. **Cytotaxonomy** that is based on cytological information like chromosome number, structure, behaviour and **chemotaxonomy** that uses the chemical constituents of the plant to resolve confusions, are also used by taxonomists these days.

3.1 ALGAE

Algae are chlorophyll-bearing, simple, thalloid, autotrophic and largely aquatic (both fresh water and marine) organisms. They occur in a variety of other habitats: moist stones, soils and wood. Some of them also occur in association with fungi (lichen) and animals (e.g., on sloth bear).

The form and size of algae is highly variable (Figure 3.1). The size ranges from the microscopic unicellular forms like *Chlamydomonas,* to colonial forms like *Volvox* and to the filamentous forms like *Ulothrix* and *Spirogyra.* A few of the marine forms such as kelps, form massive plant bodies.

The algae reproduce by vegetative, asexual and sexual methods. Vegetative reproduction is by fragmentation. Each fragment develops into a thallus. Asexual reproduction is by the production of different types of spores, the most common being the **zoospores**. They are flagellated (motile) and on germination gives rise to new plants. Sexual reproduction takes place through fusion of two gametes. These gametes can be flagellated and similar in size (as in *Chlamydomonas*) or non-flagellated (non-motile) but similar in size (as in *Spirogyra*). Such reproduction is called **isogamous**. Fusion of two gametes dissimilar in size, as in some species of *Chlamydomonas* is termed as **anisogamous**. Fusion between one large, non-motile (static) female gamete and a smaller, motile male gamete is termed **oogamous**, e.g., *Volvox, Fucus.*

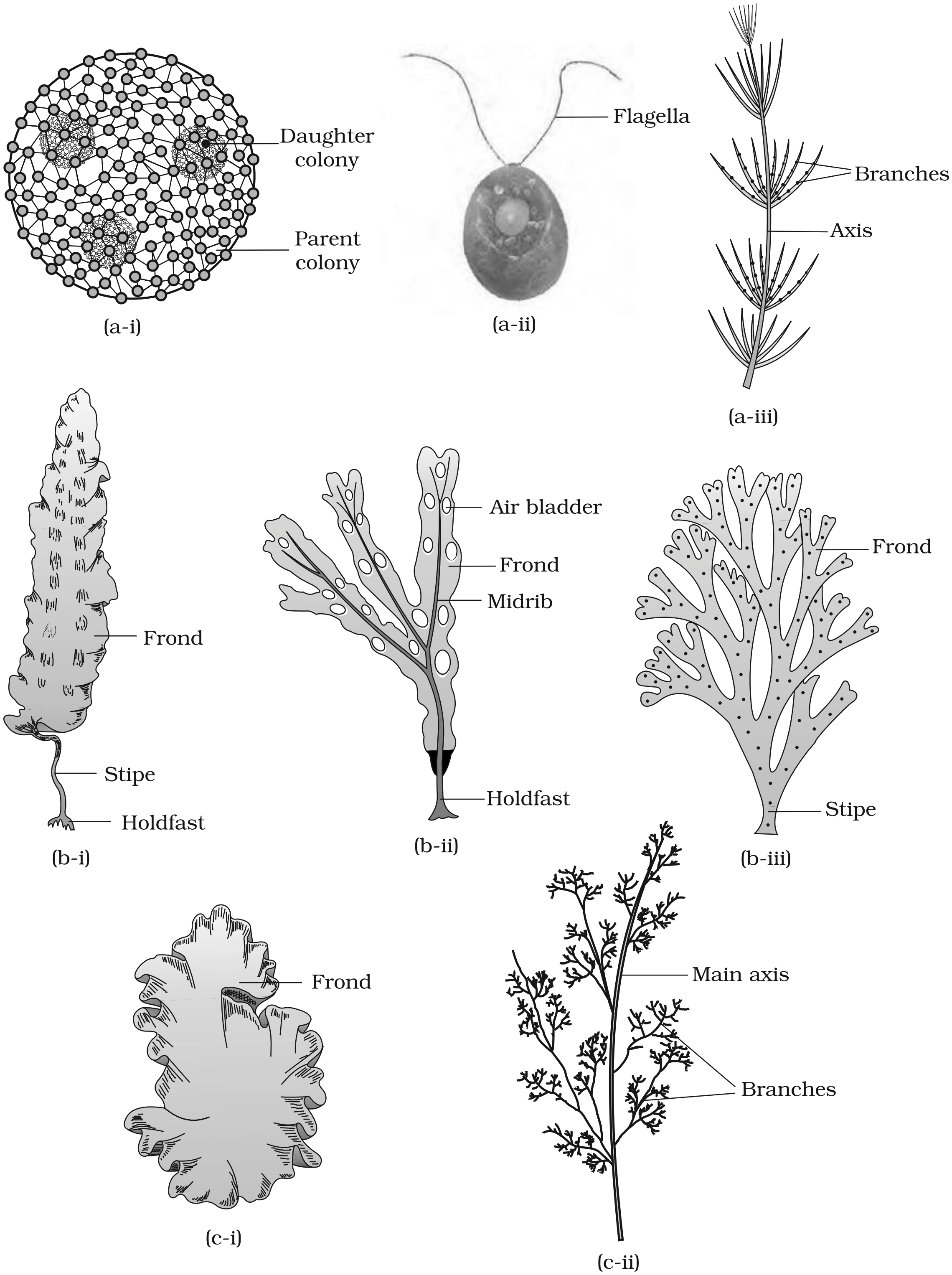


Figure 3.1 Algae : (a) Green algae (i) *Volvox* (ii) *Chlamydomonas* (iii) *Chara*
(b) Brown algae (i) *Laminaria* (ii) *Fucus* (iii) *Dictyota*
(c) Red algae (i) *Porphyra* (ii) *Polysiphonia*

Algae are useful to man in a variety of ways. At least a half of the total carbon dioxide fixation on earth is carried out by algae through photosynthesis. Being photosynthetic they increase the level of dissolved oxygen in their immediate environment. They are of paramount importance as primary producers of energy-rich compounds which form the basis of the food cycles of all aquatic animals. Many species of *Porphyra, Laminaria* and *Sargassum* are among the 70 species of marine algae used as food. Certain marine brown and red algae produce large amounts of hydrocolloids (water holding substances), e.g., **algin** (brown algae) and **carrageen** (red algae) are used commercially. Agar, one of the commercial products obtained from *Gelidium* and *Gracilaria* are used to grow microbes and in preparations of ice-creams and jellies. *Chlorella* and *Spirullina* are unicellular algae, rich in proteins and are used as food supplements even by space travellers. The algae are divided into three main classes: **Chlorophyceae, Phaeophyceae** and **Rhodophyceae**.

3.1.1 Chlorophyceae

The members of chlorophyceae are commonly called **green algae**. The plant body may be unicellular, colonial or filamentous. They are usually grass green due to the dominance of pigments chlorophyll *a* and *b*. The pigments are localised in definite chloroplasts. The chloroplasts may be discoid, plate-like, reticulate, cup-shaped, spiral or ribbon-shaped in different species. Most of the members have one or more storage bodies called pyrenoids located in the chloroplasts. Pyrenoids contain protein besides starch. Some algae may store food in the form of oil droplets. Green algae usually have a rigid cell wall made of an inner layer of cellulose and an outer layer of pectose.

Vegetative reproduction usually takes place by fragmentation or by formation of different types of spores. Asexual reproduction is by flagellated zoospores produced in zoosporangia. The sexual reproduction shows considerable variation in the type and formation of sex cells and it may be isogamous, anisogamous or oogamous. Some commonly found green algae are: *Chlamydomonas, Volvox, Ulothrix, Spirogyra* and *Chara* (Figure 3.1a).

3.1.2 Phaeophyceae

The members of phaeophyceae or **brown algae** are found primarily in marine habitats. They show great variation in size and form. They range from simple branched, filamentous forms (*Ectocarpus*) to profusely branched forms as represented by kelps, which may reach a height of 100 metres. They possess chlorophyll *a*, *c*, carotenoids and xanthophylls. They vary in colour from olive green to various shades of brown depending upon the amount of the xanthophyll pigment, fucoxanthin present in them. Food is stored as complex carbohydrates, which may be in the form of laminarin or mannitol. The vegetative cells have a cellulosic wall usually covered on the outside by a gelatinous coating of **algin**. The protoplast contains, in addition to plastids, a centrally located vacuole and nucleus. The plant body is usually attached to the substratum by a **holdfast**, and has a stalk, the **stipe** and leaf like photosynthetic organ – the **frond**. Vegetative reproduction takes place by fragmentation. Asexual reproduction in most brown algae is by biflagellate zoospores that are pear-shaped and have two unequal laterally attached flagella.

Sexual reproduction may be isogamous, anisogamous or oogamous. Union of gametes may take place in water or within the oogonium (oogamous species). The gametes are pyriform (pear-shaped) and bear two laterally attached flagella. The common forms are *Ectocarpus, Dictyota, Laminaria, Sargassum* and *Fucus* (Figure 3.1b).

3.1.3 Rhodophyceae

Rhodophyta are commonly called **red algae** because of the predominance of the red pigment, r-phycoerythrin in their body. Majority of the red algae are marine with greater concentrations found in the warmer areas. They occur in both well-lighted regions close to the surface of water and also at great depths in oceans where relatively little light penetrates.

The red thalli of most of the red algae are multicellular. Some of them have complex body organisation. The food is stored as floridean starch which is very similar to amylopectin and glycogen in structure.

The red algae usually reproduce vegetatively by fragmentation. They reproduce asexually by non-motile spores and sexually by non-motile

TABLE 3.1 Divisions of Algae and their Main Characteristics

Classes	Common Name	Major Pigments	Stored Food	Cell Wall	Flagellar Number and Position of Insertions	Habitat
Chlorophyceae	Green algae	Chlorophyll *a*, *b*	Starch	Cellulose	2-8, equal, apical	Fresh water, brackish water, salt water
Phaeophyceae	Brown algae	Chlorophyll *a*, *c*, fucoxanthin	Mannitol, laminarin	Cellulose and algin	2, unequal, lateral	Fresh water (rare) brackish water, salt water
Rhodophyceae	Red algae	Chlorophyll *a*, *d*, phycoerythrin	Floridean starch	Cellulose	Absent	Fresh water (some), brackish water, salt water (most)

gametes. Sexual reproduction is oogamous and accompanied by complex post fertilisation developments. The common members are: *Polysiphonia*, *Porphyra* (Figure 3.1c), *Gracilaria* and *Gelidium.*

3.2 Bryophytes

Bryophytes include the various mosses and liverworts that are found commonly growing in moist shaded areas in the hills (Figure 3.2).

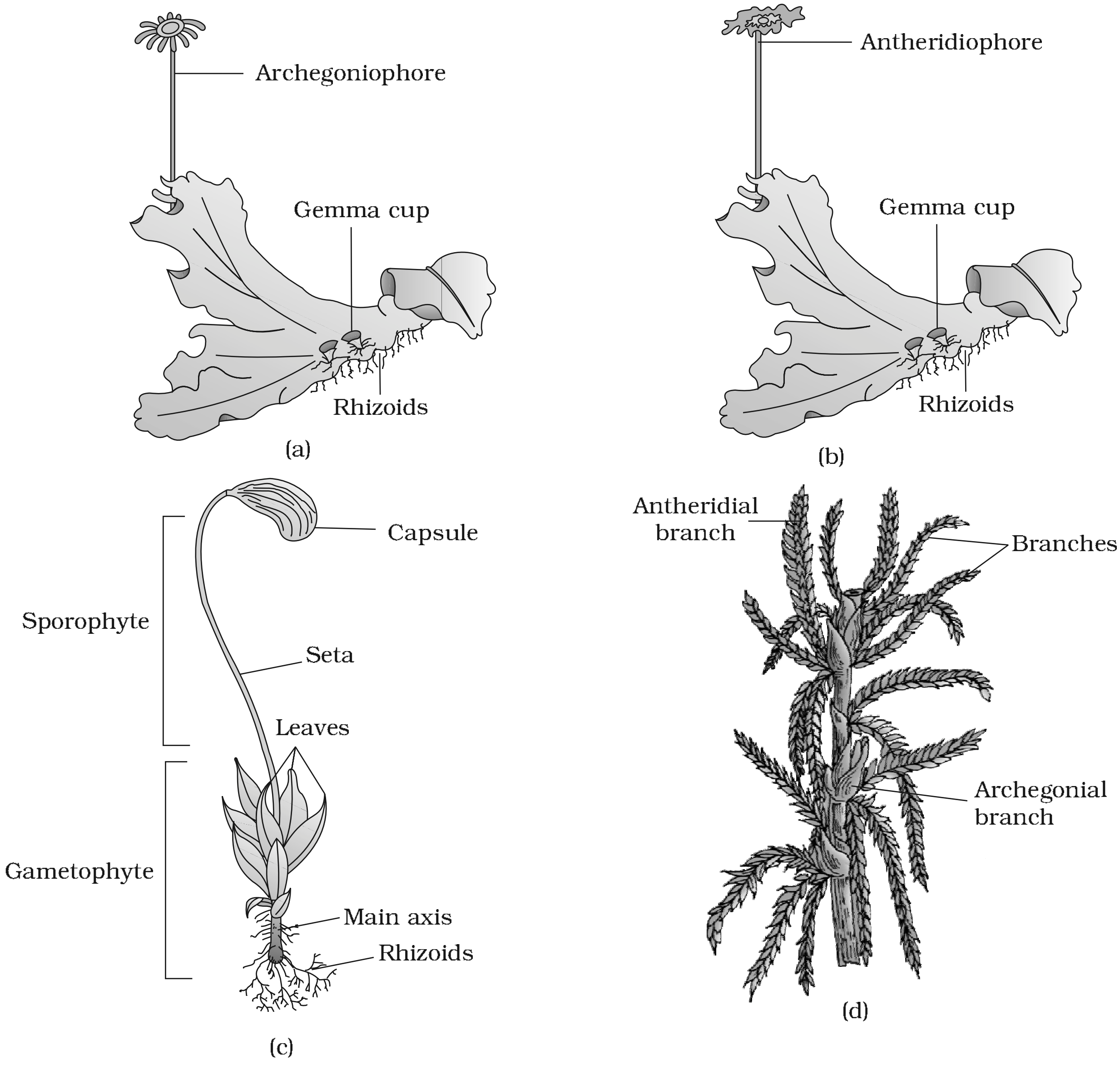


Figure 3.2 Bryophytes: A liverwort – *Marchantia* (a) Female thallus (b) Male thallus Mosses – (c) *Funaria*, gametophyte and sporophyte (d) *Sphagnum* gametophyte

Bryophytes are also called amphibians of the plant kingdom because these plants can live in soil but are dependent on water for sexual reproduction. They usually occur in damp, humid and shaded localities. They play an important role in plant succession on bare rocks/soil.

The plant body of bryophytes is more differentiated than that of algae. It is thallus-like and prostrate or erect, and attached to the substratum by unicellular or multicellular rhizoids. They lack true roots, stem or leaves. They may possess root-like, leaf-like or stem-like structures. The main plant body of the bryophyte is haploid. It produces gametes, hence is called a **gametophyte**. The sex organs in bryophytes are multicellular. The male sex organ is called **antheridium.** They produce biflagellate **antherozoids**. The female sex organ called **archegonium** is flask-shaped and produces a single egg. The antherozoids are released into water where they come in contact with archegonium. An antherozoid fuses with the egg to produce the zygote. Zygotes do not undergo reduction division immediately. They produce a multicellular body called a **sporophyte**. The sporophyte is not free-living but attached to the photosynthetic gametophyte and derives nourishment from it. Some cells of the sporophyte undergo reduction division (meiosis) to produce haploid spores. These spores germinate to produce gametophyte.

Bryophytes in general are of little economic importance but some mosses provide food for herbaceous mammals, birds and other animals. Species of *Sphagnum*, a moss, provide peat that have long been used as fuel, and because of their capacity to hold water as packing material for trans-shipment of living material. Mosses along with lichens are the first organisms to colonise rocks and hence, are of great ecological importance. They decompose rocks making the substrate suitable for the growth of higher plants. Since mosses form dense mats on the soil, they reduce the impact of falling rain and prevent soil erosion. The bryophytes are divided into **liverworts** and **mosses**.

3.2.1 Liverworts

The liverworts grow usually in moist, shady habitats such as banks of streams, marshy ground, damp soil, bark of trees and deep in the woods. The plant body of a liverwort is thalloid, e.g., *Marchantia*. The thallus is dorsiventral and closely appressed to the substrate. The leafy members have tiny leaf-like appendages in two rows on the stem-like structures.

Asexual reproduction in liverworts takes place by fragmentation of thalli, or by the formation of specialised structures called **gemmae** (sing. gemma). Gemmae are green, multicellular, asexual buds, which develop in small receptacles called gemma cups located on the thalli. The gemmae become detached from the parent body and germinate to form new individuals. During sexual reproduction, male and female sex organs are produced either on the same or on different thalli. The sporophyte is differentiated into a foot, seta and capsule. After meiosis, spores are produced within the capsule. These spores germinate to form free-living gametophytes.

3.2.2 Mosses

The predominant stage of the life cycle of a moss is the gametophyte which consists of two stages. The first stage is the **protonema** stage, which develops directly from a spore. It is a creeping, green, branched and frequently filamentous stage. The second stage is the **leafy stage**, which develops from the secondary protonema as a lateral bud. They consist of upright, slender axes bearing spirally arranged leaves. They are attached to the soil through multicellular and branched rhizoids. This stage bears the sex organs.

Vegetative reproduction in mosses is by fragmentation and budding in the secondary protonema. In sexual reproduction, the sex organs antheridia and archegonia are produced at the apex of the leafy shoots. After fertilisation, the zygote develops into a sporophyte, consisting of a foot, seta and capsule. The sporophyte in mosses is more elaborate than that in liverworts. The capsule contains spores. Spores are formed after meiosis. The mosses have an elaborate mechanism of spore dispersal. Common examples of mosses are *Funaria, Polytrichum* and *Sphagnum* (Figure 3.2).

3.3 Pteridophytes

The Pteridophytes include horsetails and ferns. Pteridophytes are used for medicinal purposes and as soil-binders. They are also frequently grown as ornamentals. Evolutionarily, they are the first terrestrial plants to possess vascular tissues – xylem and phloem. You shall study more about these tissues in Chapter 6. The pteridophytes are found in cool, damp, shady places though some may flourish well in sandy-soil conditions.

You may recall that in bryophytes the dominant phase in the life cycle is the gametophytic plant body. However, in pteridophytes, the main plant body is a sporophyte which is differentiated into true root, stem and leaves (Figure 3.3). These organs possess well-differentiated vascular tissues. The leaves in pteridophyta are small (microphylls) as in *Selaginella* or large (macrophylls) as in ferns. The sporophytes bear sporangia that are subtended by leaf-like appendages called **sporophylls**. In some cases sporophylls may form distinct compact structures called strobili or cones (*Selaginella, Equisetum*). The sporangia produce spores by meiosis in spore mother cells. The spores germinate to give rise to inconspicuous, small but multicellular,

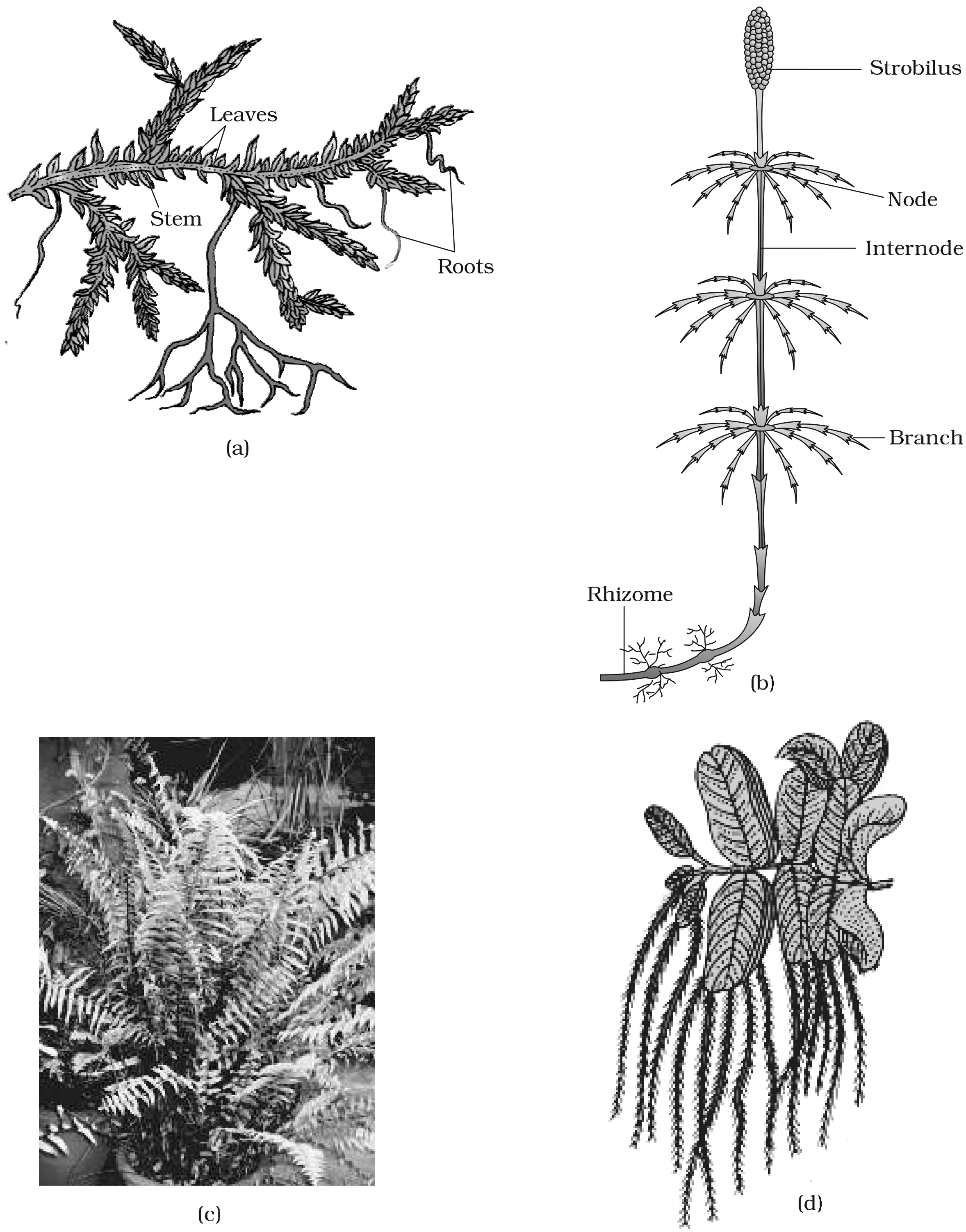


Figure 3.3 Pteridophytes : (a) *Selaginella* (b) *Equisetum* (c) Fern (d) *Salvinia*

free-living, mostly photosynthetic thalloid gametophytes called **prothallus**. These gametophytes require cool, damp, shady places to grow. Because of this specific restricted requirement and the need for water for fertilisation, the spread of living pteridophytes is limited and restricted to narrow geographical regions. The gametophytes bear male and female sex organs called antheridia and archegonia, respectively. Water is required for transfer of antherozoids – the male gametes released from the antheridia, to the mouth of archegonium. Fusion of male gamete with the egg present in the archegonium result in the formation of zygote. Zygote thereafter produces a multicellular well-differentiated sporophyte which is the dominant phase of the pteridophytes. In majority of the pteridophytes all the spores are of similar kinds; such plants are called **homosporous**. Genera like *Selaginella* and *Salvinia* which produce two kinds of spores, macro (large) and micro (small) spores, are known as **heterosporous**. The megaspores and microspores germinate and give rise to female and male gametophytes, respectively. The female gametophytes in these plants are retained on the parent sporophytes for variable periods. The development of the zygotes into young embryos take place within the female gametophytes. This event is a precursor to the **seed habit** considered an important step in evolution.

The pteridophytes are further classified into four classes: Psilopsida *(Psilotum);* Lycopsida *(Selaginella, Lycopodium)*, Sphenopsida *(Equisetum)* and Pteropsida *(Dryopteris, Pteris, Adiantum)*.

3.4 GYMNOSPERMS

The gymnosperms (*gymnos* : naked, *sperma* : seeds) are plants in which the ovules are not enclosed by any ovary wall and remain exposed, both before and after fertilisation. The seeds that develop post-fertilisation, are not covered, i.e., are naked. Gymnosperms include medium-sized trees or tall trees and shrubs (Figure 3.4). One of the gymnosperms, the giant redwood tree *Sequoia* is one of the tallest tree species. The roots are generally tap roots. Roots in some genera have fungal association in the form of **mycorrhiza** *(Pinus)*, while in some others *(Cycas)* small specialised roots called coralloid roots are associated with N_2- fixing cyanobacteria. The stems are unbranched (*Cycas*) or branched (*Pinus, Cedrus*). The leaves may be simple or compound. In *Cycas* the pinnate leaves persist for a few years. The leaves in gymnosperms are well-adapted to withstand extremes of temperature, humidity and wind. In conifers, the needle-like leaves reduce the surface area. Their thick cuticle and sunken stomata also help to reduce water loss.

The gymnosperms are heterosporous; they produce haploid microspores and megaspores. The two kinds of spores are produced within sporangia that are borne on sporophylls which are arranged spirally along an axis to form lax or compact strobili or **cones**. The strobili bearing **microsporophylls** and **microsporangia** are called microsporangiate or **male strobili**. The microspores develop into a male gametophytic generation which is highly reduced and is confined to only a limited number of cells. This reduced gametophyte is called a **pollen grain**. The development of pollen grains take place within the microsporangia. The cones bearing megasporophylls with ovules or **megasporangia** are called macrosporangiate or **female strobili**. The male or female cones or strobili may be borne on the same tree (*Pinus*) or on different trees (*Cycas*). The megaspore mother cell is differentiated from one of the cells of the nucellus. The nucellus is protected by envelopes and the composite structure is called an **ovule**. The ovules are borne on megasporophylls which may be clustered to form the female cones. The megaspore mother cell divides meiotically to form four megaspores. One of the megaspores enclosed within the **megasporangium** (nucellus) develops into a multicellular female gametophyte that bears two or more **archegonia** or female sex organs. The multicellular female gametophyte is also retained within megasporangium.

Unlike bryophytes and pteridophytes, in gymnosperms the male and the female gametophytes do not have an independent free-living existence. They remain within the sporangia retained on the sporophytes. The pollen grain is released from the microsporangium. They are carried in air currents and come in contact with the opening of the ovules borne on megasporophylls. The pollen tube carrying the male gametes grows towards archegonia in the ovules and discharge their contents near the mouth of the archegonia. Following fertilisation, zygote develops into an embryo and the ovules into seeds. These seeds are not covered.

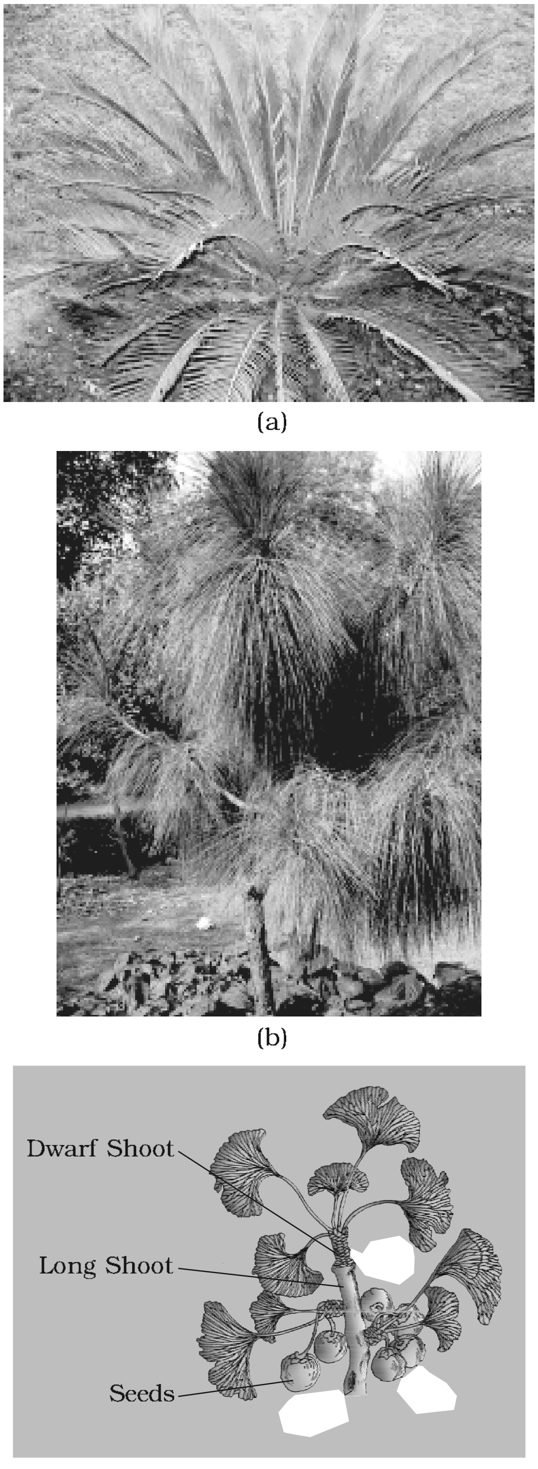


Figure 3.4 Gymnosperms: (a) *Cycas* (b) *Pinus* (c) *Ginkgo*

3.5 Angiosperms

Unlike the gymnosperms where the ovules are naked, in the angiosperms or flowering plants, the pollen grains and ovules are developed in specialised structures called **flowers**. In angiosperms, the seeds are enclosed by fruits. The angiosperms are an exceptionally large group of plants occurring in wide range of habitats. They range in size from tiny, almost microscopic *Wolfia* to tall trees of *Eucalyptus* (over 100 metres). They provide us with food, fodder, fuel, medicines and several other commercially important products. They are divided into two classes : the **dicotyledons** and the **monocotyledons** (Figure 3.5). The dicotyledons are characterised by having two cotyledons in their seeds while the monocolyledons have only one. The male sex organs in a flower is the stamen. Each stamen consists of a slender filament with an anther at the tip. The anthers, following meiosis, produce pollen grains. The female sex organs in a flower is the pistil or the carpel. Pistil consists of an ovary enclosing one to many ovules. Within ovules are present highly reduced female gametophytes termed **embryo-sacs**. The embryo-sac formation is preceded by meiosis. Hence, each of the cells of an embryo-sac is haploid. Each embryo-sac has a three-celled **egg apparatus** – one **egg cell** and two **synergids**, three **antipodal** cells and two **polar nuclei**. The polar nuclei eventually fuse to produce a diploid secondary nucleus. Pollen grain, after dispersal from the anthers, are carried by wind or various other agencies to the stigma of a pistil. This is termed as

(a)

(b)

Figure 3.5 Angiosperms : (a) A dicotyledon (b) A monocotyledon pollination. The pollen grains germinate on the stigma and the resulting pollen tubes grow through the tissues of stigma and style and reach the ovule. The pollen tubes enter the embryo-sac where two male gametes are discharged. One of the male gametes fuses with the egg cell to form a zygote (syngamy). The other male gamete fuses with the diploid secondary nucleus to produce the triploid primary endosperm nucleus (PEN). Because of the involvement of two fusions, this event is termed as **double fertilisation**, an event unique to angiosperms. The zygote develops into an embryo (with one or two cotyledons) and the PEN develops into endosperm which provides nourishment to the developing embryo. The synergids and antipodals degenerate after fertilisation. During these events the ovules develop into seeds and the ovaries develop into fruit. The life cycle of an angiosperm is shown in Figure 3.6.

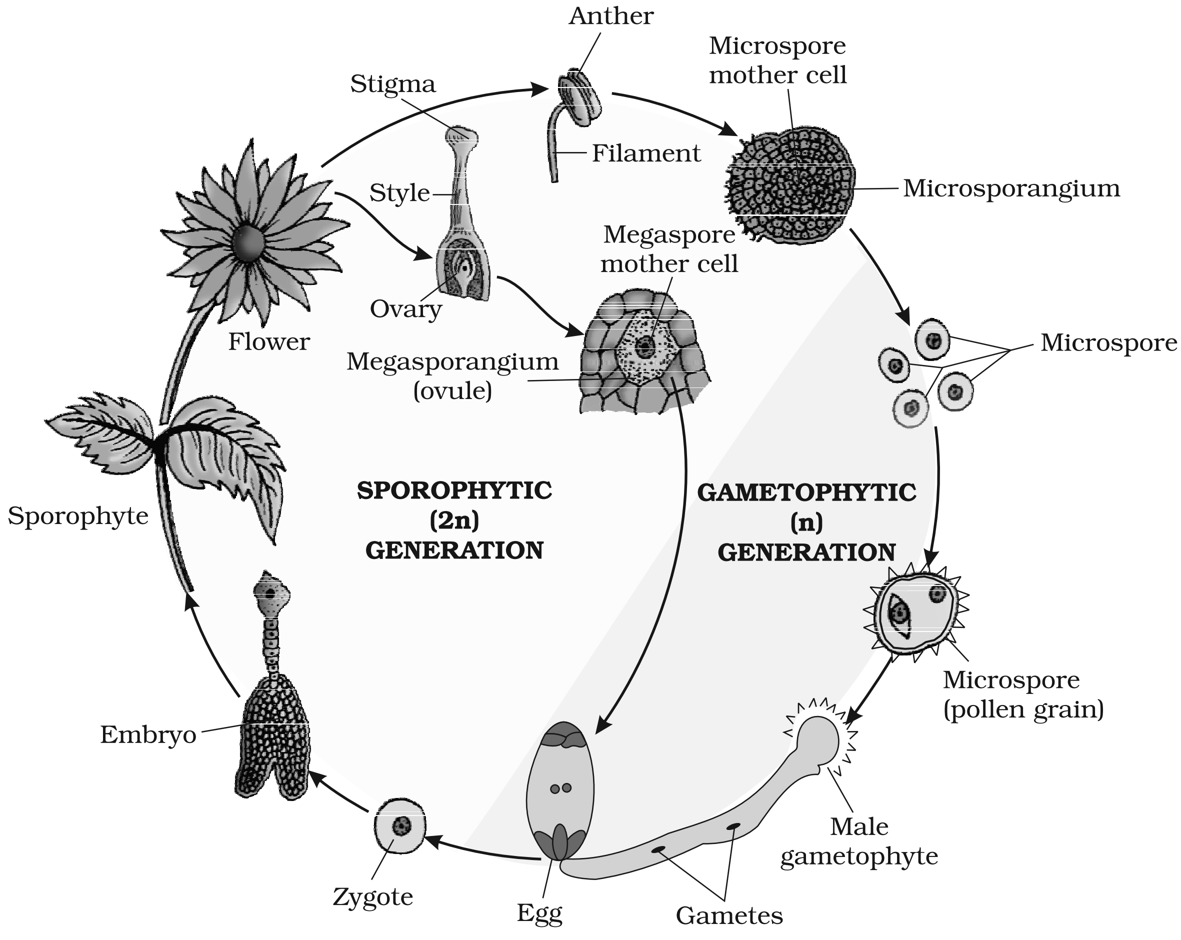


Figure 3.6 Life cycle of an angiosperm

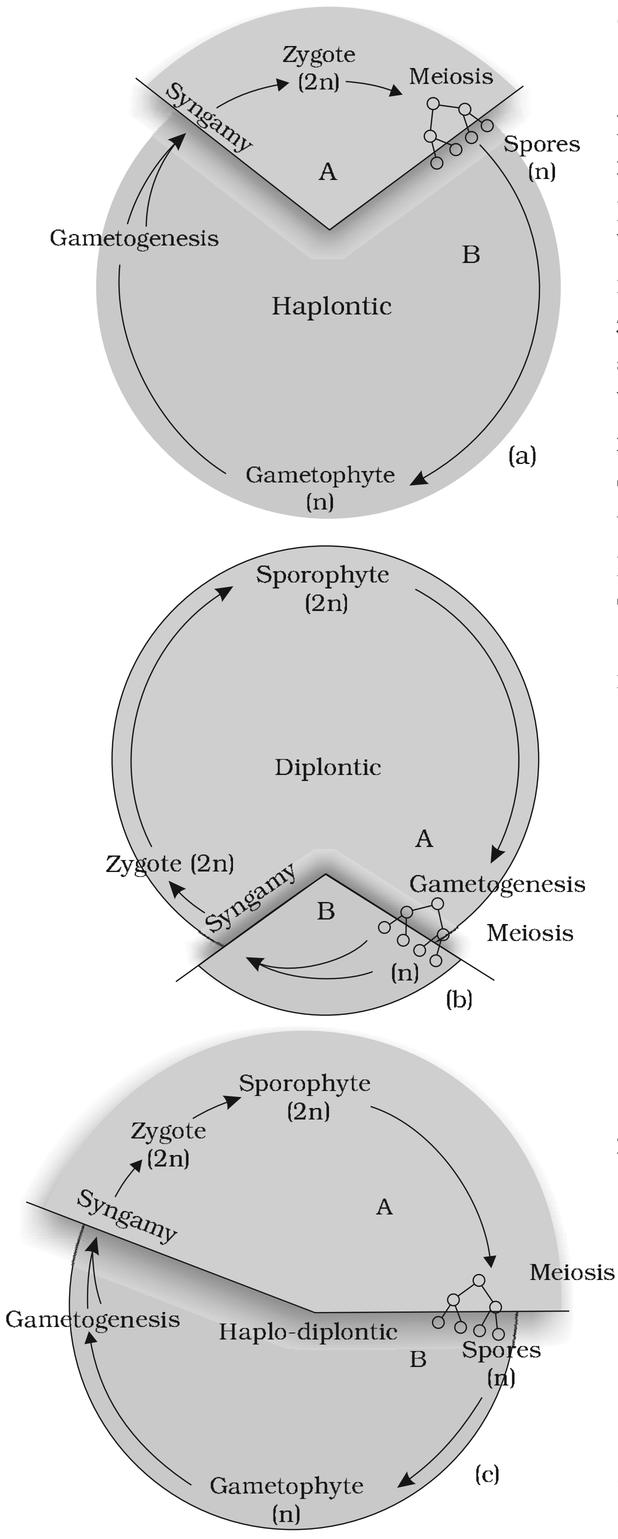


Figure 3.7 Life cycle patterns : (a) Haplontic (b) Diplontic (c) Haplo-diplontic

3.6 PLANT LIFE CYCLES AND ALTERNATION OF GENERATIONS

In plants, both haploid and diploid cells can divide by mitosis. This ability leads to the formation of different plant bodies - haploid and diploid. The haploid plant body produces gametes by mitosis. This plant body represents a gametophyte. Following fertilisation the zygote also divides by mitosis to produce a diploid sporophytic plant body. Haploid spores are produced by this plant body by meiosis. These in turn, divide by mitosis to form a haploid plant body once again. Thus, during the life cycle of any sexually reproducing plant, there is an alternation of generations between gamete producing haploid gametophyte and spore producing diploid sporophyte.

However, different plant groups, as well as individuals representing them, differ in the following patterns:

1. Sporophytic generation is represented only by the one-celled zygote. There are no free-living sporophytes. Meiosis in the zygote results in the formation of haploid spores. The haploid spores divide mitotically and form the gametophyte. The dominant, photosynthetic phase in such plants is the free-living gametophyte. This kind of life cycle is termed as **haplontic**. Many algae such as *Volvox, Spirogyra* and some species of *Chlamydomomas* represent this pattern (Figure 3.7 a).

2. On the other extreme, is the type wherein the diploid sporophyte is the dominant, photosynthetic, independent phase of the plant. The gametophytic phase is represented by the single to few-celled haploid gametophyte. This kind of lifecycle is termed as **diplontic**. All seed-bearing plants i.e. gymnosperms and angiosperms, follow this pattern (Figure 3.7 b).

3. Bryophytes and pteridophytes, interestingly, exhibit an intermediate condition **(Haplo-diplontic)**; both phases are multicellular and often free-living. However, they differ in their dominant phases.

A dominant, independent, photosynthetic, thalloid or erect phase is represented by a haploid gametophyte and it alternates with the short-lived multicelluler sporophyte totally or partially dependent on the gametophyte for its anchorage and nutrition. All bryophytes represent this pattern.

The diploid sporophyte is represented by a dominant, independent, photosynthetic, vascular plant body. It alternates with multicellular, saprophytic/autotrophic, independent but short-lived haploid gametophyte. Such a pattern is known as haplo-diplontic life cycle. All pteridophytes exhibit this pattern (Figure 3.7 c).

Interestingly, while most algal genera are haplontic, some of them such as *Ectocarpus*, *Polysiphonia*, kelps are haplo-diplontic. *Fucus*, an alga is diplontic.

SUMMARY

Plant kingdom includes algae, bryophytes, pteridophytes, gymnosperms and angiosperms. Algae are chlorophyll-bearing simple, thalloid, autotrophic and largely aquatic organisms. Depending on the type of pigment possesed and the type of stored food, algae are classfied into three classes, namely Chlorophyceae, Phaeophyceae and Rhodophyceae. Algae usually reproduce vegetatively by fragmentation, asexually by formation of different types of spores and sexually by formation of gametes which may show isogamy, anisogamy or oogamy.

Bryophytes are plants which can live in soil but are dependent on water for sexual reproduction. Their plant body is more differentiated than that of algae. It is thallus-like and prostrate or erect and attached to the substratum by rhizoids. They possess root-like, leaf-like and stem-like structures. The bryophytes are divided into liverworts and mosses. The plant body of liverworts is thalloid and dorsiventral whereas mosses have upright, slender axes bearing spirally arranged leaves. The main plant body of a bryophyte is gamete-producing and is called a gametophyte. It bears the male sex organs called antheridia and female sex organs called archegonia. The male and female gametes produced fuse to form zygote which produces a multicellular body called a sporophyte. It produces haploid spores. The spores germinate to form gametophytes.

In pteridophytes the main plant is a sporophyte which is differentiated into true root, stem and leaves. These organs possess well-differentiated vascular tissues. The sporophytes bear sporangia which produce spores. The spores germinate to form gametophytes which require cool, damp places to grow. The gametophytes bear male and female sex organs called antheridia and archegonia, respectively. Water is required for transfer of male gametes to archegonium where zygote is formed after fertilisation. The zygote produces a sporophyte.

The gymnosperms are the plants in which ovules are not enclosed by any ovary wall. After fertilisation the seeds remain exposed and therefore these plants are called naked-seeded plants. The gymnosperms produce microspores and megaspores which are produced in microsporangia and megasporangia borne on the sporophylls. The sporophylls – microsporophylls and megasporophylls – are arranged spirally on axis to form male and female cones, respectively. The pollen grain germinates and pollen tube releases the male gamete into the ovule, where it fuses with the egg cell in archegonia. Following fertilisation, the zygote develops into embryo and the ovules into seeds.

In angiosperms, the male sex organs (stamen) and female sex organs (pistil) are borne in a flower. Each stamen consists of a filament and an anther. The anther produces pollen grains (male gametophyte) after meiosis. The pistil consists of an ovary enclosing one to many ovules. Within the ovule is the female gametophyte or embryo sac which contains the egg cell. The pollen tube enters the embryo-sac where two male gametes are discharged. One male gamete fuses with egg cell (syngamy) and other fuses with diploid secondary nucleus (triple fusion). This phenomenon of two fusions is called double fertilisation and is unique to angiosperms. The angiosperms are divided into two classes – the dictyledons and the monocotyledons.

During the life cycle of any sexually reproducing plant, there is alternation of generations between gamete producing haploid gametophyte and spore producing diploid sporophyte. However, different plant groups as well as individuals may show different patterns of life cycles – haplontic, diplontic or intermediate.

EXERCISES

1. What is the basis of classification of algae?
2. When and where does reduction division take place in the life cycle of a liverwort, a moss, a fern, a gymnosperm and an angiosperm?
3. Name three groups of plants that bear archegonia. Briefly describe the life cycle of any one of them.
4. Mention the ploidy of the following: protonemal cell of a moss; primary endosperm nucleus in dicot, leaf cell of a moss; prothallus cell of a ferm; gemma cell in *Marchantia*; meristem cell of monocot, ovum of a liverwort, and zygote of a fern.
5. Write a note on economic importance of algae and gymnosperms.
6. Both gymnosperms and angiosperms bear seeds, then why are they classified separately?
7. What is heterospory? Briefly comment on its significance. Give two examples.

8. Explain briefly the following terms with suitable examples:-
   (i) protonema
   (ii) antheridium
   (iii) archegonium
   (iv) diplontic
   (v) sporophyll
   (vi) isogamy
9. Differentiate between the following:-
   (i) red algae and brown algae
   (ii) liverworts and moss
   (iii) homosporous and heterosporous pteridophyte
   (iv) syngamy and triple fusion
10. How would you distinguish monocots from dicots?
11. Match the followings (column I with column II)

Column I	Column II
(a) *Chlamydomonas*	(i) Moss
(b) *Cycas*	(ii) Pteridophyte
(c) *Selaginella*	(iii) Algae
(d) *Sphagnum*	(iv) Gymnosperm

12. Describe the important characteristics of gymnosperms.

Chapter 4

Animal Kingdom

When you look around, you will observe different animals with different structures and forms. As over a million species of animals have been described till now, the need for classification becomes all the more important. The classification also helps in assigning a systematic position to newly described species.

4.1 Basis of Classification

Inspite of differences in structure and form of different animals, there are fundamental features common to various individuals in relation to the arrangement of cells, body symmetry, nature of coelom, patterns of digestive, circulatory or reproductive systems. These features are used as the basis of animal classification and some of them are discussed here.

4.1.1 Levels of Organisation

Though all members of Animalia are multicellular, all of them do not exhibit the same pattern of organisation of cells. For example, in sponges, the cells are arranged as loose cell aggregates, i.e., they exhibit **cellular level** of organisation. Some division of labour (activities) occur among the cells. In coelenterates, the arrangement of cells is more complex. Here the cells performing the same function are arranged into tissues, hence is called **tissue level** of organisation. A still higher level of organisation, i.e., **organ level** is exhibited by members of Platyhelminthes and other higher phyla where tissues are grouped together to form organs, each specialised for a particular function. In animals like Annelids, Arthropods, Molluscs, Echinoderms and Chordates, organs have associated to form functional systems, each system concerned with a specific physiological function. This pattern is called **organ system** level of organisation. Organ systems in different groups of animals exhibit various patterns of complexities. For example, the digestive system in Platyhelminthes has only a single opening to the outside of the body that serves as both mouth and anus, and is hence called incomplete. A complete digestive system has two openings, mouth and anus. Similarly, the circulatory system may be of two types:

(i) **open type** in which the blood is pumped out of the heart and the cells and tissues are directly bathed in it or

(ii) **closed type** in which the blood is circulated through a series of vessels of varying diameters (arteries, veins and capillaries).

4.1.2 Symmetry

Animals can be categorised on the basis of their symmetry. Sponges are mostly **asymmetrical,** i.e., any plane that passes through the centre does not divide them into equal halves. When any plane passing through the central axis of the body divides the organism into two identical halves, it is called **radial symmetry**. Coelenterates, ctenophores and echinoderms have this kind of body plan (Figure 4.1a). Animals like annelids, arthropods, etc., where the body can be divided into identical left and right halves in only one plane, exhibit **bilateral symmetry** (Figure 4.1b).

4.1.3 Diploblastic and Triploblastic Organisation

Animals in which the cells are arranged in two embryonic layers, an external **ectoderm** and an internal **endoderm**, are called **diploblastic** animals, e.g., coelenterates. An undifferentiated layer, mesoglea, is present in between the ectoderm and the endoderm (Figure 4.2a).

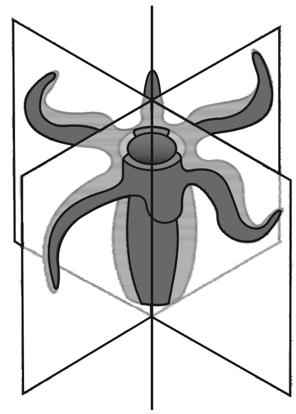


Figure 4.1 (a) Radial symmetry

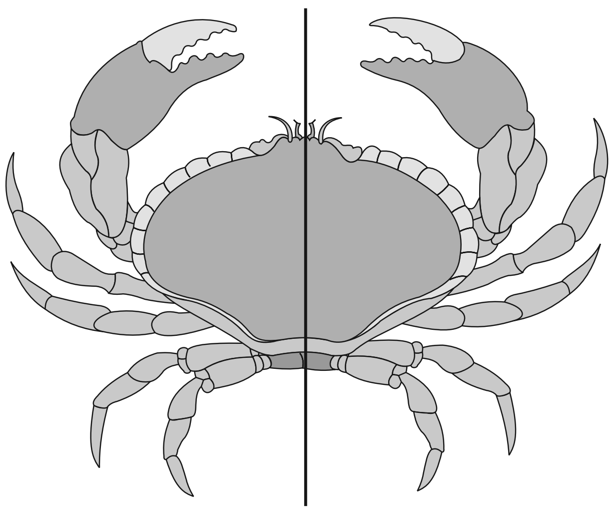


Figure 4.1 (b) Bilateral symmetry

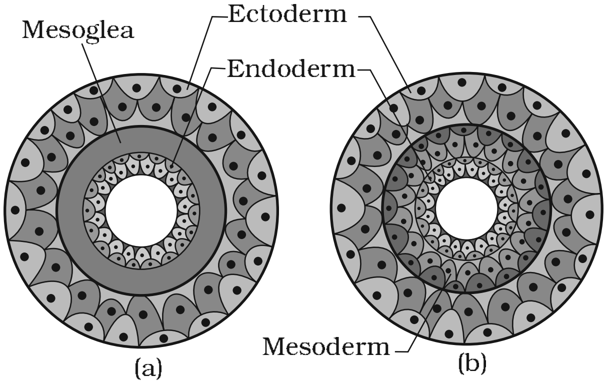


Figure 4.2 Showing germinal layers : (a) Diploblastic (b) Triploblastic

Those animals in which the developing embryo has a third germinal layer, **mesoderm**, in between the ectoderm and endoderm, are called **triploblastic** animals (platyhelminthes to chordates, Figure 4.2b).

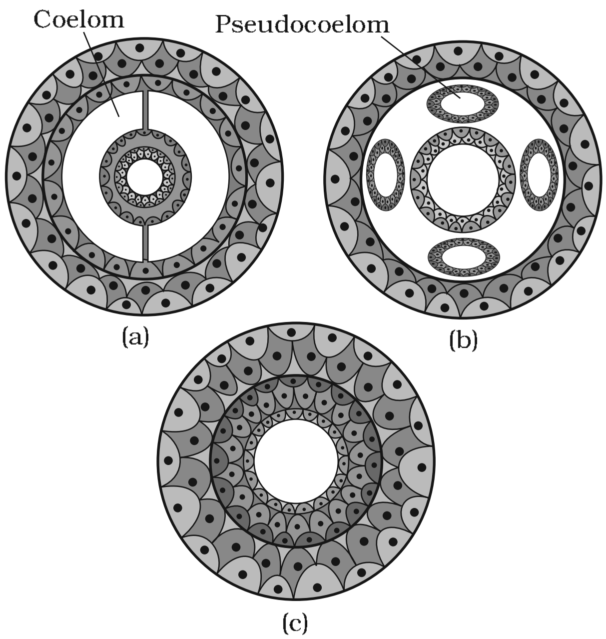


Figure 4.3 Diagrammatic sectional view of : (a) Coelomate (b) Pseudocoelomate (c) Acoelomate

4.1.4 Coelom

Presence or absence of a cavity between the body wall and the gut wall is very important in classification. The body cavity, which is lined by mesoderm is called **coelom**. Animals possessing coelom are called **coelomates,** e.g., annelids, molluscs, arthropods, echinoderms, hemichordates and chordates (Figure 4.3a). In some animals, the body cavity is not lined by mesoderm, instead, the mesoderm is present as scattered pouches in between the ectoderm and endoderm. Such a body cavity is called pseudocoelom and the animals possessing them are called **pseudocoelomates,** e.g., aschelminthes (Figure 4.3b). The animals in which the body cavity is absent are called **acoelomates,** e.g., platyhelminthes (Figure 4.3c).

4.1.5 Segmentation

In some animals, the body is externally and internally divided into segments with a serial repetition of at least some organs. For example, in earthworm, the body shows this pattern called metameric segmentation and the phenomenon is known as **metamerism**.

4.1.6 Notochord

Notochord is a mesodermally derived rod-like structure formed on the dorsal side during embryonic development in some animals. Animals with notochord are called chordates and those animals which do not form this structure are called non-chordates, e.g., porifera to echinoderms.

4.2 Classification of Animals

The broad classification of Animalia based on common fundamental features as mentioned in the preceding sections is given in Figure 4.4.

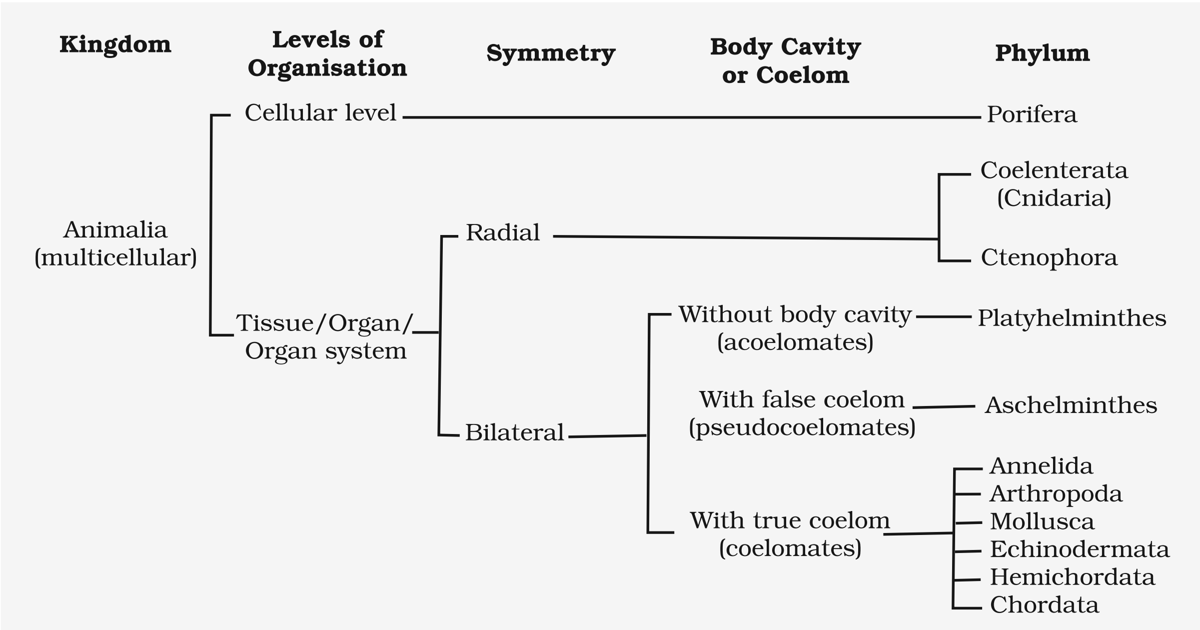


Figure 4.4 Broad classification of Kingdom Animalia based on common fundamental features

The important characteristic features of the different phyla are described.

4.2.1 Phylum – Porifera

Members of this phylum are commonly known as sponges. They are generally marine and mostly asymmetrical animals (Figure 4.5). These are primitive multicellular animals and have cellular level of organisation. Sponges have a water transport or canal system. Water enters through minute pores (**ostia**) in the body wall into a central cavity, **spongocoel**, from where it goes out through the **osculum**. This pathway of water transport is helpful in food gathering, respiratory exchange and removal of waste. **Choanocytes** or collar cells line the spongocoel and the canals. Digestion is intracellular. The body is supported by a skeleton made up of **spicules** or **spongin fibres**. Sexes are not separate (**hermaphrodite**), i.e., eggs and sperms are produced by the same individual. Sponges reproduce asexually by fragmentation and sexually by formation of gametes. Fertilisation is internal and development is indirect having a larval stage which is morphologically distinct from the adult.

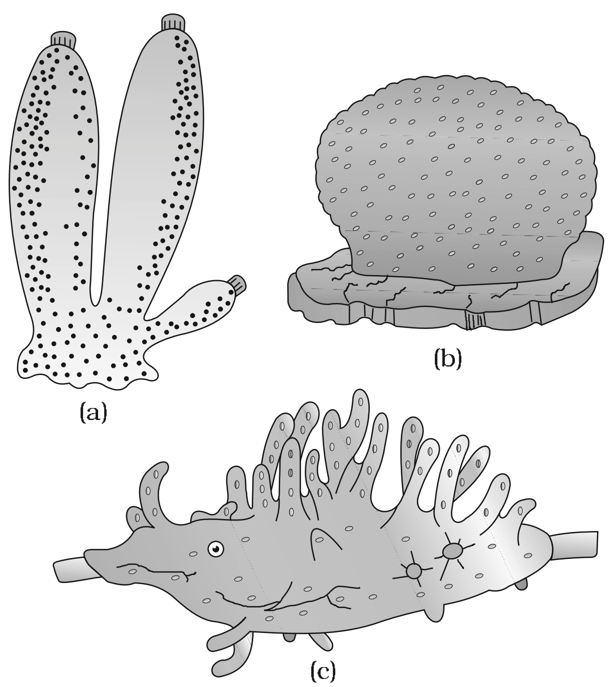


Figure 4.5 Examples for Porifera : (a) *Sycon* (b) *Euspongia* (c) *Spongilla*

Examples: *Sycon* (Scypha), *Spongilla* (Fresh water sponge) and *Euspongia* (Bath sponge).

4.2.2 Phylum – Coelenterata (Cnidaria)

They are aquatic, mostly marine, sessile or free-swimming, radially symmetrical animals (Figure 4.6). The name cnidaria is derived from the cnidoblasts or cnidocytes (which contain the stinging capsules or nematocytes) present on the tentacles and the body. Cnidoblasts are used for anchorage, defense and for the capture of prey (Figure 4.7). Cnidarians exhibit tissue level of organisation and are diploblastic. They have a central gastro-vascular cavity with a single opening, **hypostome**. Digestion is extracellular and intracellular. Some of the cnidarians, e.g., **corals** have a skeleton composed of calcium carbonate. Cnidarians exhibit two basic body forms called **polyp** and **medusa** (Figure 4.6). The former is a sessile and cylindrical form like Hydra, Adamsia, etc. whereas, the latter is umbrella-shaped and free-swimming like *Aurelia* or jelly fish. Those cnidarians which exist in both forms exhibit alternation of generation (Metagenesis), i.e., polyps produce medusae asexually and medusae form the polyps sexually (e.g., *Obelia*).

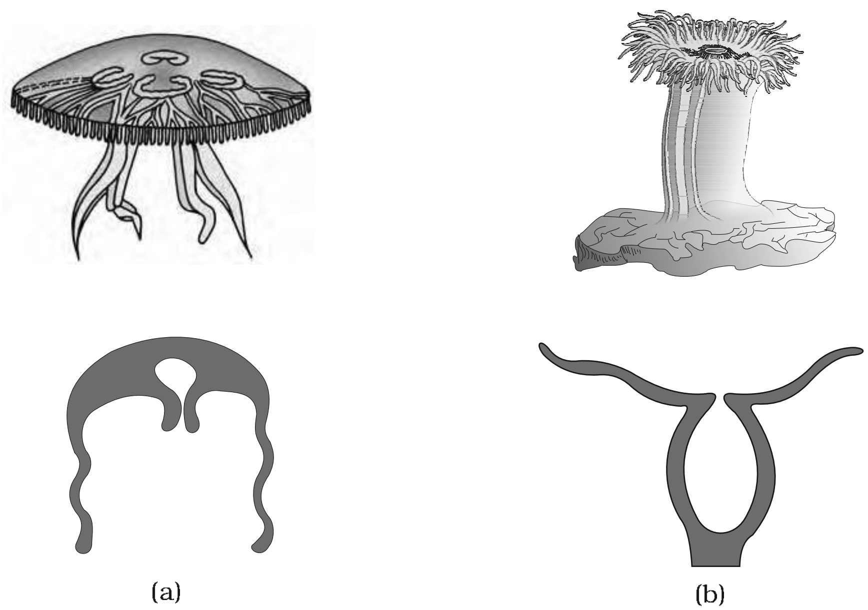


Figure 4.6 Examples of Coelenterata indicating outline of their body form : (a) *Aurelia* (Medusa) (b) *Adamsia* (Polyp)

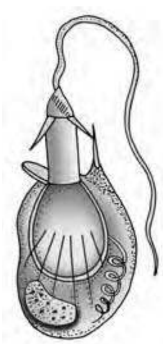


Figure 4.7 Diagrammatic view of Cnidoblast

Examples: *Physalia* (Portuguese man-of-war), *Adamsia* (Sea anemone), *Pennatula* (Sea-pen), *Gorgonia* (Sea-fan) and *Meandrina* (Brain coral).

4.2.3 Phylum – Ctenophora

Ctenophores, commonly known as **sea walnuts** or **comb jellies** are exclusively marine, radially symmetrical, diploblastic organisms with tissue level of organisation. The body bears eight external rows of ciliated **comb plates**, which help in locomotion (Figure 4.8). Digestion is both extracellular and intracellular. **Bioluminescence** (the property of a living organism to emit light) is well-marked in ctenophores. Sexes are not separate. Reproduction takes place only by sexual means. Fertilisation is external with indirect development.

Examples: *Pleurobrachia* and *Ctenoplana*.

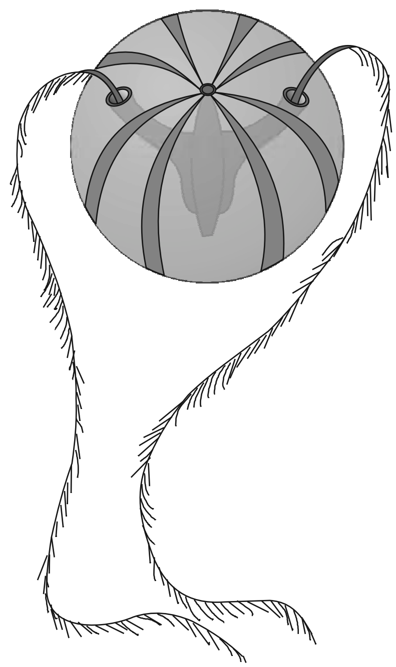


Figure 4.8 Example of Ctenophora (*Pleurobrachia*)

4.2.4 Phylum – Platyhelminthes

They have dorso-ventrally flattened body, hence are called **flatworms** (Figure 4.9). These are mostly endoparasites found in animals including human beings. Flatworms are bilaterally symmetrical, triploblastic and acoelomate animals with organ level of organisation. Hooks and suckers are present in the parasitic forms. Some of them absorb nutrients from the host directly through their body surface. Specialised cells called flame cells help in osmoregulation and excretion. Sexes are not separate. Fertilisation is internal and development is through many larval stages. Some members like *Planaria* possess high regeneration capacity.

Examples: *Taenia* (Tapeworm), *Fasciola* (Liver fluke).

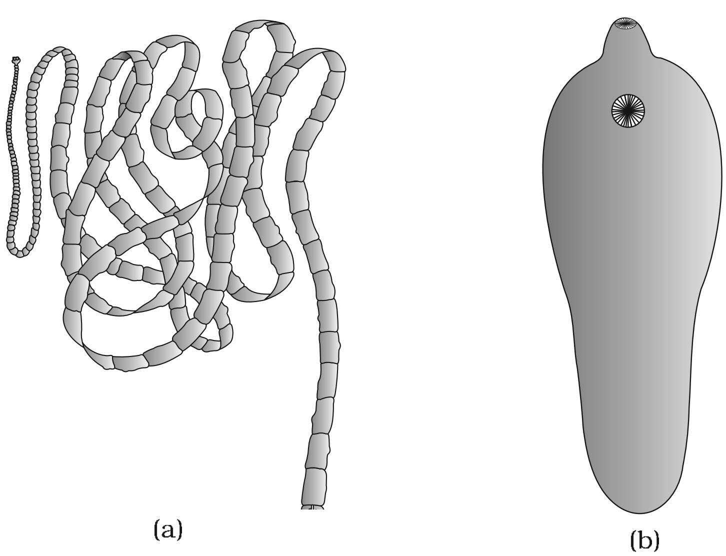


Figure 4.9 Examples of Platyhelminthes : (a) Tape worm (b) Liver fluke

4.2.5 Phylum – Aschelminthes

The body of the aschelminthes is circular in cross-section, hence, the name **roundworms** (Figure 4.10). They may be freeliving, aquatic and terrestrial or parasitic in plants and animals. Roundworms have organ-system level of body organisation. They are bilaterally symmetrical, triploblastic and pseudocoelomate animals. Alimentary canal is complete with a well-developed **muscular pharynx.** An excretory tube removes body wastes from the body cavity through the excretory pore. Sexes are separate (**dioecious**), i.e., males and females are distinct. Often females are longer than males. Fertilisation is internal and development may be direct (the young ones resemble the adult) or indirect.

Examples : *Ascaris* (Round Worm), *Wuchereria* (Filaria worm), *Ancylostoma* (Hookworm).

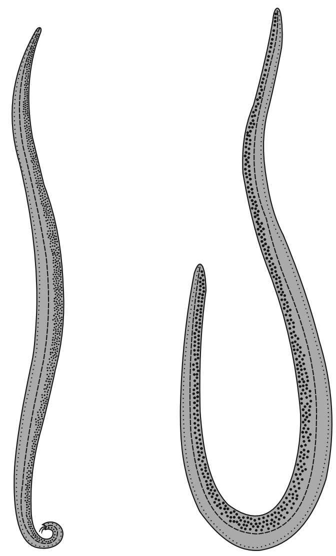


Figure 4.10 Aschelminthes – Roundworm

4.2.6 Phylum – Annelida

They may be aquatic (marine and fresh water) or terrestrial; free-living, and sometimes parasitic. They exhibit organ-system level of body organisation and bilateral symmetry. They are triploblastic, metamerically segmented and coelomate animals. Their body surface is distinctly marked out into **segments** or **metameres** (Latin, *annulus* : little ring) and, hence, the phylum name Annelida (Figure 4.11). They possess longitudinal and circular muscles which help in locomotion. Aquatic annelids like *Nereis* possess lateral appendages, **parapodia**, which help in swimming. A closed circulatory system is present. **Nephridia** (sing. nephridium) help in osmoregulation and excretion. Neural system consists of paired ganglia (sing. ganglion) connected by lateral nerves to a double ventral nerve cord. *Nereis,* an aquatic form, is dioecious, but earthworms and leeches are monoecious. Reproduction is sexual.

Examples : *Nereis*, *Pheretima* (Earthworm) and *Hirudinaria* (Blood sucking leech).

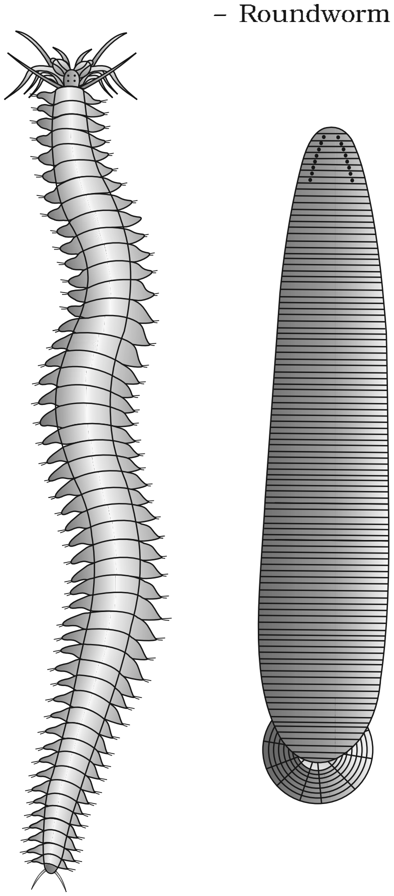


Figure 4.11 Examples of Annelida : (a) *Nereis* (b) *Hirudinaria*

4.2.7 Phylum – Arthropoda

This is the **largest phylum** of Animalia which includes insects. Over two-thirds of all named species on earth are arthropods (Figure 4.12). They have organ-system level of organisation. They are bilaterally symmetrical, triploblastic, segmented and coelomate animals. The body of arthropods is covered by chitinous exoskeleton. The body consists of **head**, **thorax** and **abdomen**. They have **jointed appendages** (arthros-joint, poda-appendages). Respiratory organs are gills, book gills, book lungs or tracheal system. Circulatory system is of open type. Sensory organs like antennae, eyes (compound and simple), statocysts or balance organs are present. Excretion takes place through **malpighian tubules**. They are mostly dioecious. Fertilisation is usually internal. They are mostly oviparous. Development may be direct or indirect.

Examples: Economically important insects – *Apis* (Honey bee), *Bombyx* (Silkworm), *Laccifer* (Lac insect)

Vectors – *Anopheles*, *Culex* and *Aedes* (Mosquitoes)

Gregarious pest – *Locusta* (Locust)

Living fossil – *Limulus* (King crab).

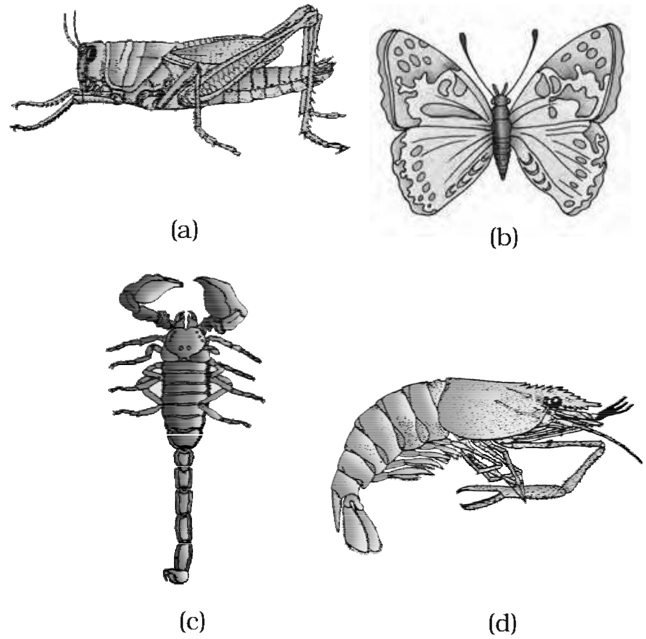


Figure 4.12 Examples of Arthropoda : (a) Locust (b) Butterfly (c) Scorpion (d) Prawn

4.2.8 Phylum – Mollusca

This is the **second largest** animal phylum (Figure 4.13). Molluscs are terrestrial or aquatic (marine or fresh water) having an organ-system level of organisation. They are bilaterally symmetrical, triploblastic and coelomate animals. Body is covered by a calcareous shell and is unsegmented with a distinct **head**, **muscular foot** and **visceral hump**. A soft and spongy layer of skin forms a mantle over the visceral hump. The space between the hump and the mantle is called the mantle cavity in which feather like gills are present. They have respiratory and excretory functions. The anterior head region has sensory tentacles. The mouth contains a file-like rasping organ for feeding, called **radula**.

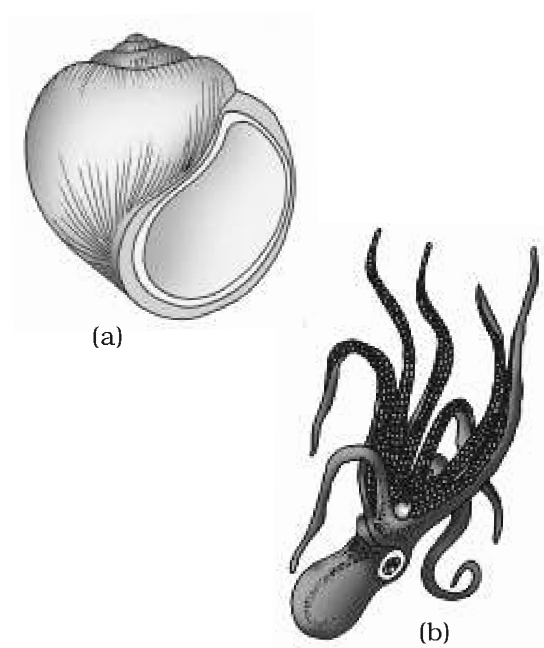


Figure 4.13 Examples of Mollusca : (a) *Pila* (b) *Octopus*

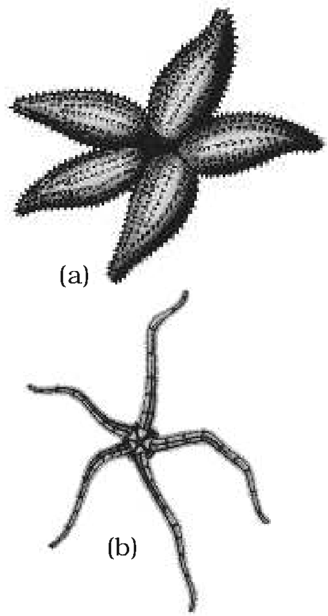


Figure 4.14 Examples for Echinodermata : (a) *Asterias* (b) *Ophiura*

They are usually dioecious and oviparous with indirect development.
Examples: *Pila* (Apple snail), *Pinctada* (Pearl oyster), *Sepia* (Cuttlefish), *Loligo* (Squid), *Octopus* (Devil fish), *Aplysia* (Sea-hare), *Dentalium* (Tusk shell) and *Chaetopleura* (Chiton).

4.2.9 Phylum – Echinodermata

These animals have an endoskeleton of calcareous ossicles and, hence, the name Echinodermata (Spiny bodied, Figure 4.14). All are marine with organ-system level of organisation. The adult echinoderms are radially symmetrical but larvae are bilaterally symmetrical. They are triploblastic and coelomate animals. Digestive system is complete with mouth on the lower (ventral) side and anus on the upper (dorsal) side. The most distinctive feature of echinoderms is the presence of **water vascular system** which helps in locomotion, capture and transport of food and respiration. An excretory system is absent. Sexes are separate. Reproduction is sexual. Fertilisation is usually external. Development is indirect with free-swimming larva.
Examples: *Asterias* (Star fish), *Echinus* (Sea urchin), *Antedon* (Sea lily), *Cucumaria* (Sea cucumber) and *Ophiura* (Brittle star).

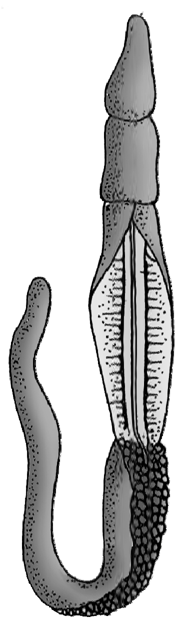


Figure 4.15 *Balanoglossus*

4.2.10 Phylum – Hemichordata

Hemichordata was earlier considered as a sub-phylum under phylum Chordata. But now it is placed as a separate phylum under non-chordata.

This phylum consists of a small group of **worm-like** marine animals with organ-system level of organisation. They are bilaterally symmetrical, triploblastic and coelomate animals. The body is cylindrical and is composed of an anterior **proboscis**, a **collar** and a long **trunk** (Figure 4.15). Circulatory system is of open type. Respiration takes place through gills. Excretory organ is proboscis gland. Sexes are separate. Fertilisation is external. Development is indirect.

Examples: *Balanoglossus* and *Saccoglossus.*

4.2.11 Phylum – Chordata

Animals belonging to phylum Chordata are fundamentally characterised by the presence of a **notochord**, a **dorsal**

hollow nerve cord and **paired pharyngeal gill slits** (Figure 4.16). These are bilaterally symmetrical, triploblastic, coelomate with organ-system level of organisation. They possess a post anal tail and a closed circulatory system.

Table 4.1 presents a comparison of salient features of chordates and non-chordates.

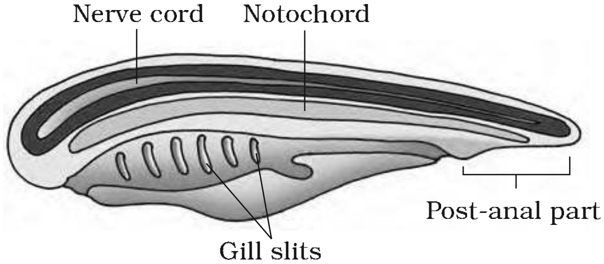


Figure 4.16 Chordata characteristics

TABLE 4.1 Comparison of Chordates and Non-chordates

S.No.	Chordates	Non-chordates
1.	Notochord present.	Notochord absent.
2.	Central nervous system is dorsal, hollow and single.	Central nervous system is ventral, solid and double.
3.	Pharynx perforated by gill slits.	Gill slits are absent.
4.	Heart is ventral.	Heart is dorsal (if present).
5.	A post-anal part (tail) is present.	Post-anal tail is absent.

Phylum Chordata is divided into three subphyla: **Urochordata** or **Tunicata**, **Cephalochordata** and **Vertebrata**.

Subphyla Urochordata and Cephalochordata are often referred to as **protochordates** (Figure 4.17) and are exclusively marine. In Urochordata, notochord is present only in larval tail, while in Cephalochordata, it extends from head to tail region and is persistent throughout their life.

Examples: Urochordata – *Ascidia, Salpa, Doliolum;* Cephalochordata – *Branchiostoma* (Amphioxus or Lancelet).

Figure 4.17 *Ascidia*

The members of subphylum Vertebrata possess notochord during the embryonic period. The notochord is replaced by a cartilaginous or bony **vertebral column** in the adult. Thus all vertebrates are chordates but all chordates are not vertebrates. Besides the basic chordate characters, vertebrates have a ventral muscular heart with two, three or four chambers, kidneys for excretion and osmoregulation and paired appendages which may be fins or limbs.

The subphylum Vertebrata is further divided as follows:

Vertebrata
- Division
  - Agnatha (lacks jaw)
    - Class
      1. Cyclostomata
  - Gnathostomata (bears jaw)
    - Super Class
      - Pisces (bear fins)
        - Class
          1. Chondrichthyes
          2. Osteichthyes
      - Tetrapoda (bear limbs)
        - Class
          1. Amphibia
          2. Reptilia
          3. Aves
          4. Mammals

4.2.11.1 Class – Cyclostomata

All living members of the class Cyclostomata are ectoparasites on some fishes. They have an elongated body bearing 6-15 pairs of **gill slits** for respiration. Cyclostomes have a sucking and circular mouth without jaws (Fig. 4.18). Their body is devoid of scales and paired fins. Cranium and vertebral column are cartilaginous. Circulation is of closed type. Cyclostomes are marine but migrate for spawning to fresh water. After spawning, within a few days, they die. Their larvae, after metamorphosis, return to the ocean.

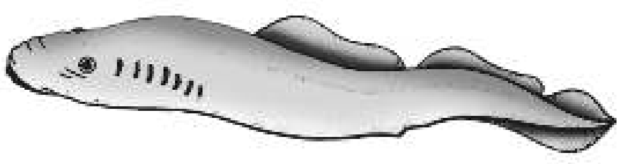


Figure 4.18 A jawless vertebrate - *Petromyzon*

Examples: *Petromyzon* (Lamprey) and *Myxine* (Hagfish).

4.2.11.2 Class – Chondrichthyes

They are marine animals with streamlined body and have cartilaginous endoskeleton (Figure 4.19). Mouth is located ventrally. **Notochord** is **persistent** throughout life. Gill slits are separate and without **operculum** (gill cover). The skin is tough, containing minute **placoid scales**. Teeth are modified placoid scales which are backwardly directed. Their jaws are very powerful. These animals are predaceous. Due to the absence of air bladder, they have to swim constantly to avoid sinking.

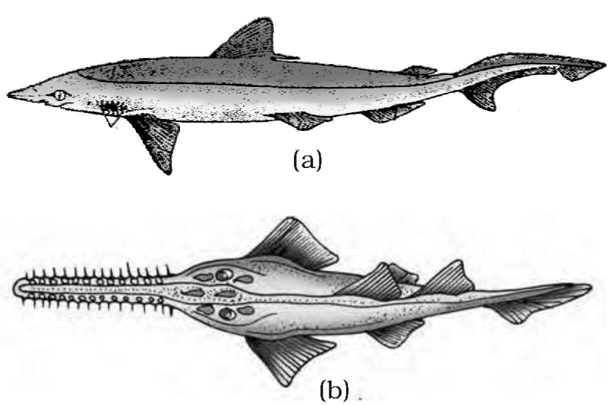


Figure 4.19 Example of Cartilaginous fishes : (a) *Scoliodon* (b) *Pristis*

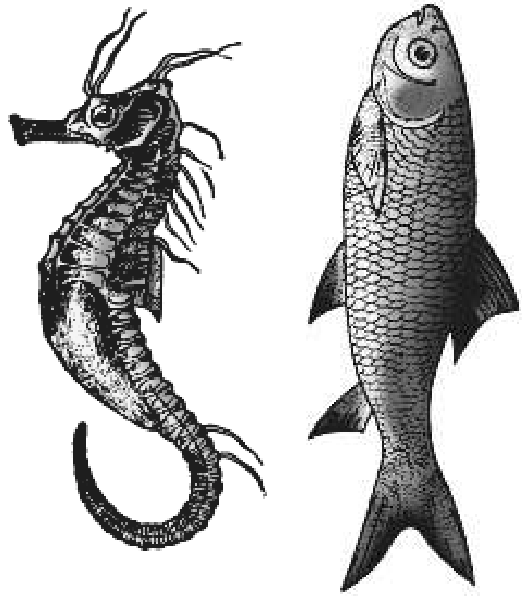
Heart is two-chambered (one auricle and one ventricle). Some of them have **electric organs** (e.g., *Torpedo*) and some possess **poison sting** (e.g., *Trygon*). They are cold-blooded (**poikilothermous**) animals, i.e., they lack the capacity to regulate their body temperature. Sexes are separate. In males pelvic fins bear claspers. They have internal fertilisation and many of them are viviparous.

Examples: *Scoliodon* (Dog fish), *Pristis* (Saw fish), *Carcharodon* (Great white shark), *Trygon* (Sting ray).

4.2.11.3 Class – Osteichthyes

It includes both marine and fresh water fishes with bony endoskeleton. Their body is streamlined. Mouth is mostly terminal (Figure 4.20). They have four pairs of gills which are covered by an **operculum** on each side. Skin is covered with cycloid/ctenoid scales. **Air bladder** is present which regulates buoyancy. Heart is two-chambered (one auricle and one ventricle). They are cold-blooded animals. Sexes are separate. Fertilisation is usually external. They are mostly oviparous and development is direct.

Examples: Marine – *Exocoetus* (Flying fish), *Hippocampus* (Sea horse); Freshwater – *Labeo* (Rohu), *Catla* (Katla), *Clarias* (Magur); Aquarium – *Betta* (Fighting fish), *Pterophyllum* (Angel fish).



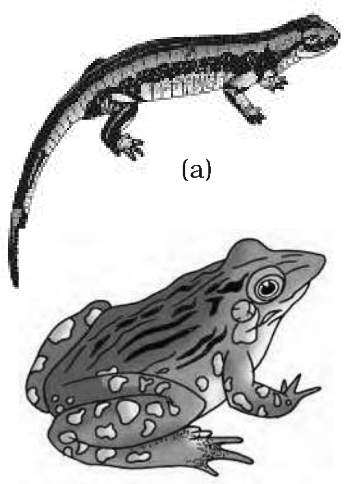
(a) (b)

Figure 4.20 Examples of Bony fishes : (a) *Hippocampus* (b) *Catla*

4.2.11.4 Class – Amphibia

As the name indicates (*Gr., Amphi* : dual, *bios*, life), amphibians can live in aquatic as well as terrestrial habitats (Figure 4.21). Most of them have two pairs of limbs. Body is divisible into **head** and **trunk.** Tail may be present in some. The amphibian skin is moist (without scales). The eyes have eyelids. A **tympanum** represents the ear. Alimentary canal, urinary and reproductive tracts open into a common chamber called **cloaca** which opens to the exterior. Respiration is by gills, lungs and through skin. The heart is three-chambered (two auricles and one ventricle). These are cold-blooded animals. Sexes are separate. Fertilisation is external. They are oviparous and development is direct or indirect.

Examples: *Bufo* (Toad), *Rana* (Frog), *Hyla* (Tree frog), *Salamandra* (Salamander), *Ichthyophis* (Limbless amphibia).



(a)

(b)

Figure 4.21 Examples of Amphibia :
(a) *Salamandra*
(b) *Rana*

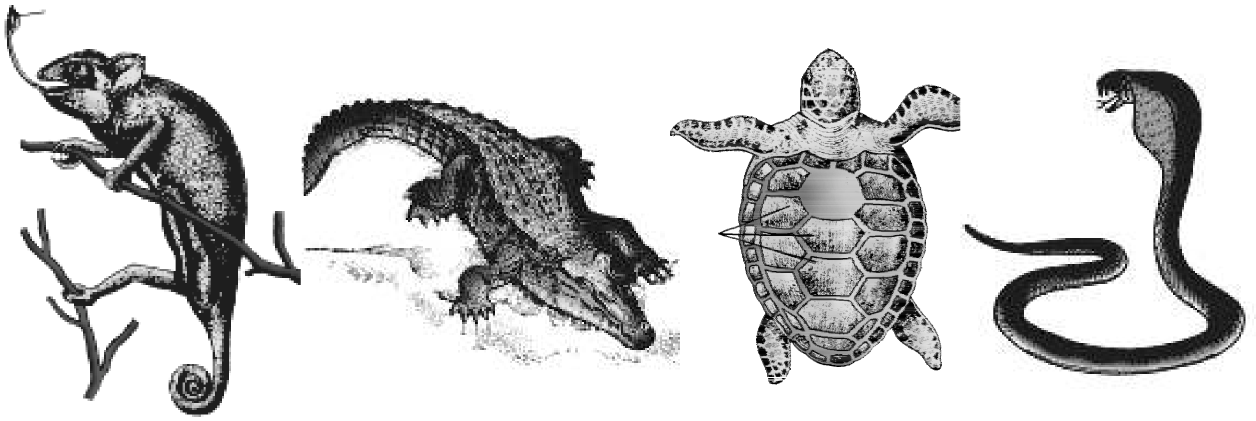


Figure 4.22 Reptiles : (a) *Chameleon* (b) *Crocodilus* (c) *Chelone* (d) *Naja*

4.2.11.5 Class – Reptilia

The class name refers to their creeping or crawling mode of locomotion (*Latin*, *repere* or *reptum*, to creep or crawl). They are mostly terrestrial animals and their body is covered by dry and cornified skin, epidermal **scales** or **scutes** (Fig. 4.22). They do not have external ear openings. Tympanum represents ear. Limbs, when present, are two pairs. Heart is usually three-chambered, but four-chambered in crocodiles. Reptiles are poikilotherms. Snakes and lizards shed their scales as skin cast. Sexes are separate. Fertilisation is internal. They are oviparous and development is direct.

Examples: *Chelone* (Turtle), *Testudo* (Tortoise), *Chameleon* (Tree lizard), *Calotes* (Garden lizard), *Crocodilus* (Crocodile), *Alligator* (Alligator). *Hemidactylus* (Wall lizard), Poisonous snakes – *Naja* (Cobra), *Bangarus* (Krait), *Vipera* (Viper).

4.2.11.6 Class – Aves

The characteristic features of Aves (birds) are the presence of **feathers** and most of them can fly except flightless birds (e.g., Ostrich). They possess **beak** (Figure 4.23). The forelimbs are modified into **wings**. The hind limbs generally have scales and are modified for walking, swimming or clasping the tree branches. Skin is dry without glands except the oil gland at the base of the tail. Endoskeleton is fully ossified (bony) and the long bones are hollow with **air cavities** (pneumatic). The digestive tract of birds has additional chambers, the crop and gizzard. Heart is completely four-chambered. They are warm-blooded (**homoiothermous**) animals, i.e., they are able to maintain a constant body temperature. Respiration is by

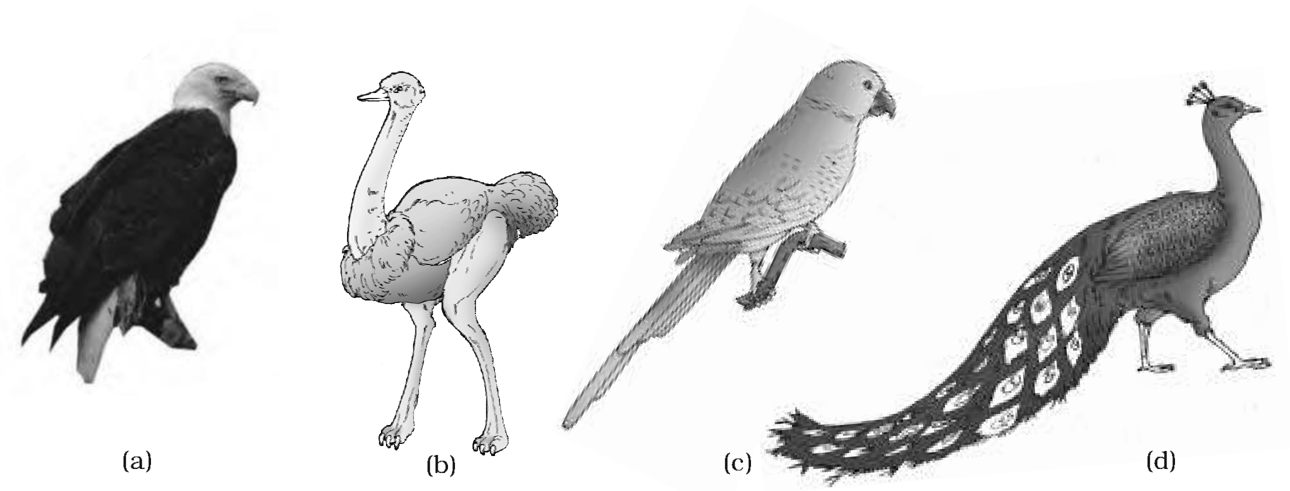


Figure 4.23 Some birds : (a) *Neophron* (b) *Struthio* (c) *Psittacula* (d) *Pavo*

lungs. Air sacs connected to lungs supplement respiration. Sexes are separate. Fertilisation is internal. They are oviparous and development is direct.

Examples : *Corvus* (Crow), *Columba* (Pigeon), *Psittacula* (Parrot), *Struthio* (Ostrich), *Pavo* (Peacock), *Aptenodytes* (Penguin), *Neophron* (Vulture).

4.2.11.7 Class – Mammalia

They are found in a variety of habitats – polarice caps, deserts, mountains, forests, grasslands and dark caves. Some of them have adapted to fly or live in water. The most unique mammalian characteristic is the presence of milk producing glands (**mammary glands**) by which the young ones are nourished. They have two pairs of limbs, adapted for walking, running, climbing, burrowing, swimming or flying (Figure 4.24). The skin of

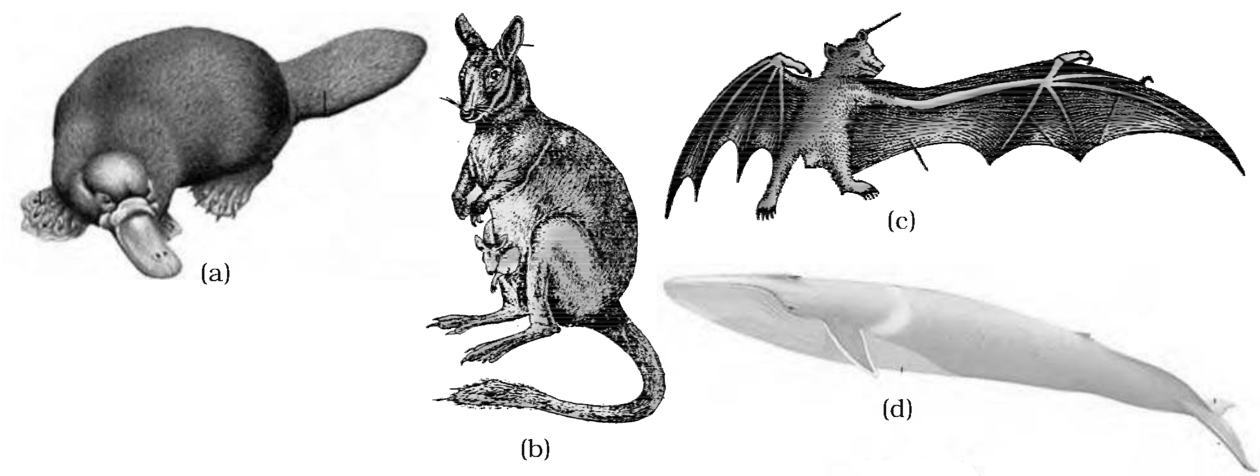


Figure 4.24 Some mammals : (a) *Ornithorhynchus* (b) *Macropus* (c) *Pteropus* (d) *Balaenoptera*

mammals is unique in possessing **hair**. External ears or **pinnae** are present. Different types of teeth are present in the jaw. Heart is four-chambered. They are homoiothermous. Respiration is by lungs. Sexes are separate and fertilisation is internal. They are viviparous with few exceptions and development is direct.

Examples: Oviparous-*Ornithorhynchus* (Platypus); Viviparous - *Macropus* (Kangaroo), *Pteropus* (Flying fox), *Camelus* (Camel), *Macaca* (Monkey), *Rattus* (Rat), *Canis* (Dog), *Felis* (Cat), *Elephas* (Elephant), *Equus* (Horse), *Delphinus* (Common dolphin), *Balaenoptera* (Blue whale), *Panthera tigris* (Tiger), *Panthera leo* (Lion).

The salient distinguishing features of all phyla under animal kingdom is comprehensively given in the Table 4.2.

TABLE 4.2 Salient Features of Different Phyla in the Animal Kingdom

Phylum	Level of Organisation	Symmetry	Coelom	Segmentation	Digestive System	Circulatory System	Respiratory System	Distinctive Features
Porifera	Cellular	Many	Absent	Absent	Absent	Absent	Absent	Body with pores and canals in walls.
Coelenterata (Cnidaria)	Tissue	Radial	Absent	Absent	Incomplete	Absent	Absent	Cnidoblasts present.
Ctenophora	Tissue	Radial	Absent	Absent	Incomplete	Absent	Absent	Comb plates for locomotion.
Platyhelminthes	Organ & Organ-system	Bilateral	Absent	Absent	Incomplete	Absent	Absent	Flat body, suckers.
Aschelminthes	Organ-system	Bilateral	Pseudo coelomate	Absent	Complete	Absent	Absent	Often worm-shaped, elongated.
Annelida	Organ-system	Bilateral	Coelomate	Present	Complete	Present	Present	Body segmentation like rings.
Arthropoda	Organ-system	Bilateral	Coelomate	Present	Complete	Present	Present	Exoskeleton of cuticle, jointed appendages.
Mollusca	Organ-system	Bilateral	Coelomate	Absent	Complete	Present	Present	External skeleton shell usually present.
Echinodermata	Organ-system	Radial	Coelomate	Absent	Complete	Present	Present	Water vascular system, radial symmetry.
Hemichordata	Organ-system	Bilateral	Coelomate	Absent	Complete	Present	Present	Worm-like with proboscis, collar and trunk.
Chordata	Organ-system	Bilateral	Coelomate	Present	Complete	Present	Present	Notochord, dorsal hollow nerve cord, gill slits with limbs or fins.

SUMMARY

The basic fundamental features such as level of organisation, symmetry, cell organisation, coelom, segmentation, notochord, etc., have enabled us to broadly classify the animal kingdom. Besides the fundamental features, there are many other distinctive characters which are specific for each phyla or class.

Porifera includes multicellular animals which exhibit cellular level of organisation and have characteristic flagellated choanocytes. The coelenterates have tentacles and bear cnidoblasts. They are mostly aquatic, sessile or free-floating. The ctenophores are marine animals with comb plates. The platyhelminthes have flat body and exhibit bilateral symmetry. The parasitic forms show distinct suckers and hooks. Aschelminthes are pseudocoelomates and include parasitic as well as non-parasitic round worms.

Annelids are metamerically segmented animals with a true coelom. The arthropods are the most abundant group of animals characterised by the presence of jointed appendages. The molluscs have a soft body surrounded by an external calcareous shell. The body is covered with external skeleton made of chitin. The echinoderms possess a spiny skin. Their most distinctive feature is the presence of water vascular system. The hemichordates are a small group of worm-like marine animals. They have a cylindrical body with proboscis, collar and trunk.

Phylum Chordata includes animals which possess a notochord either throughout or during early embryonic life. Other common features observed in the chordates are the dorsal, hollow nerve cord and paired pharyngeal gill slits. Some of the vertebrates do not possess jaws (Agnatha) whereas most of them possess jaws (Gnathostomata). Agnatha is represented by the class, Cyclostomata. They are the most primitive chordates and are ectoparasites on fishes. Gnathostomata has two super classes, Pisces and Tetrapoda. Classes Chondrichthyes and Osteichthyes bear fins for locomotion and are grouped under Pisces. The Chondrichthyes are fishes with cartilaginous endoskeleton and are marine. Classes, Amphibia, Reptilia, Aves and Mammalia have two pairs of limbs and are thus grouped under Tetrapoda. The amphibians have adapted to live both on land and water. Reptiles are characterised by the presence of dry and cornified skin. Limbs are absent in snakes. Fishes, amphibians and reptiles are poikilothermous (cold-blooded). Aves are warm-blooded animals with feathers on their bodies and forelimbs modified into wings for flying. Hind limbs are adapted for walking, swimming, perching or clasping. The unique features of mammals are the presence of mammary glands and hairs on the skin. They commonly exhibit viviparity.

EXERCISES

1. What are the difficulties that you would face in classification of animals, if common fundamental features are not taken into account?
2. If you are given a specimen, what are the steps that you would follow to classify it?
3. How useful is the study of the nature of body cavity and coelom in the classification of animals?
4. Distinguish between intracellular and extracellular digestion?
5. What is the difference between direct and indirect development?
6. What are the peculiar features that you find in parasitic platyhelminthes?
7. What are the reasons that you can think of for the arthropods to constitute the largest group of the animal kingdom?
8. Water vascular system is the characteristic of which group of the following:

   (a) Porifera (b) Ctenophora (c) Echinodermata (d) Chordata
9. "All vertebrates are chordates but all chordates are not vertebrates". Justify the statement.
10. How important is the presence of air bladder in Pisces?
11. What are the modifications that are observed in birds that help them fly?
12. Could the number of eggs or young ones produced by an oviparous and viviparous mother be equal? Why?
13. Segmentation in the body is first observed in which of the following:

    (a) Platyhelminthes (b) Aschelminthes (c) Annelida (d) Arthropoda
14. Match the following:

(i)	Operculum	(a)	Ctenophora
(ii)	Parapodia	(b)	Mollusca
(iii)	Scales	(c)	Porifera
(iv)	Comb plates	(d)	Reptilia
(v)	Radula	(e)	Annelida
(vi)	Hairs	(f)	Cyclostomata and Chondrichthyes
(vii)	Choanocytes	(g)	Mammalia
(viii)	Gill slits	(h)	Osteichthyes

15. Prepare a list of some animals that are found parasitic on human beings.

UNIT 2

STRUCTURAL ORGANISATION IN PLANTS AND ANIMALS

The description of the diverse forms of life on earth was made only by observation – through naked eyes or later through magnifying lenses and microscopes. This description is mainly of gross structural features, both external and internal. In addition, observable and perceivable living phenomena were also recorded as part of this description. Before experimental biology or more specifically, physiology, was established as a part of biology, naturalists described only biology. Hence, biology remained as a natural history for a long time. The description, by itself, was amazing in terms of detail. While the initial reaction of a student could be boredom, one should keep in mind that the detailed description, was utilised in the later day reductionist biology where living processes drew more attention from scientists than the description of life forms and their structure. Hence, this description became meaningful and helpful in framing research questions in physiology or evolutionary biology. In the following chapters of this unit, the structural organisation of plants and animals, including the structural basis of physiologial or behavioural phenomena, is described. For convenience, this description of morphological and anatomical features is presented separately for plants and animals.

Katherine Esau
(1898 – 1997)

KATHERINE ESAU was born in Ukraine in 1898. She studied agriculture in Russia and Germany and received her doctorate in 1931 in United States. She reported in her early publications that the curly top virus spreads through a plant via the food-conducting or phloem tissue. Dr Esau's *Plant Anatomy* published in 1954 took a dynamic, developmental approach designed to enhance one's understanding of plant structure and an enormous impact worldwide, literally bringing about a revival of the discipline. The *Anatomy of Seed Plants* by Katherine Esau was published in 1960. It was referred to as Webster's of plant biology – it is encyclopediac. In 1957 she was elected to the National Academy of Sciences, becoming the sixth woman to receive that honour. In addition to this prestigious award, she received the National Medal of Science from President George Bush in 1989.

When Katherine Esau died in the year 1997, Peter Raven, director of Anatomy and Morphology, Missouri Botanical Garden, remembered that she 'absolutely dominated' the field of plant biology even at the age of 99.

Chapter 5

Morphology of Flowering Plants

The wide range in the structure of higher plants will never fail to fascinate us. Even though the angiosperms show such a large diversity in external structure or **morphology**, they are all characterised by presence of roots, stems, leaves, flowers and fruits.

In chapters 2 and 3, we talked about classification of plants based on morphological and other characteristics. For any successful attempt at classification and at understanding any higher plant (or for that matter any living organism) we need to know standard technical terms and standard definitions. We also need to know about the possible variations in different parts, found as adaptations of the plants to their environment, e.g., adaptions to various habitats, for protection, climbing, storage, etc.

If you pull out any weed you will see that all of them have roots, stems and leaves. They may be bearing flowers and fruits. The underground part of the flowering plant is the root system while the portion above the ground forms the shoot system (Figure 5.1).

5.1 The Root

In majority of the dicotyledonous plants, the direct elongation of the radicle leads to the formation of **primary root** which grows inside the soil. It bears lateral roots of several orders that are referred to as **secondary, tertiary,** etc. **roots.** The primary roots and its branches constitute the

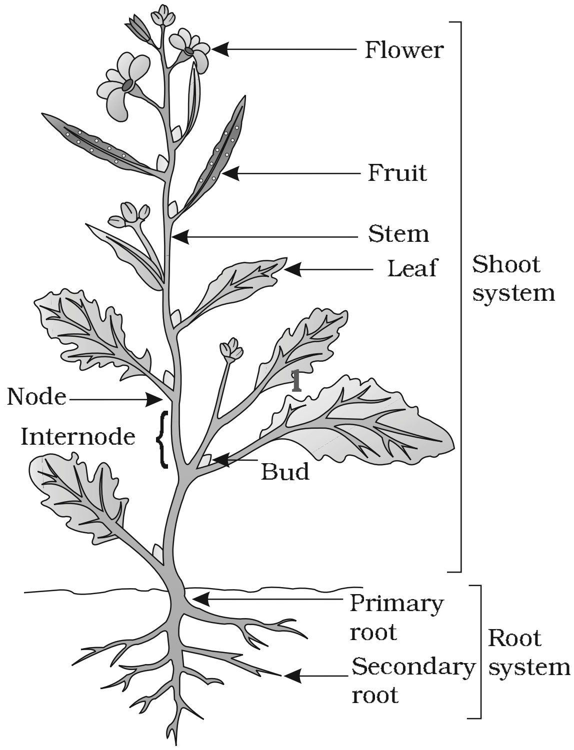


Figure 5.1 Parts of a flowering plant

tap root system, as seen in the mustard plant (Figure 5.2a). In monocotyledonous plants, the primary root is short lived and is replaced by a large number of roots. These roots originate from the base of the stem and constitute the **fibrous root system**, as seen in the wheat plant (Figure 5.2b). In some plants, like grass, *Monstera* and the banyan tree, roots arise from parts of the plant other than the radicle and are called **adventitious roots** (Figure 5.2c). The main functions of the root system are absorption of water and minerals from the soil, providing a proper anchorage to the plant parts, storing reserve food material and synthesis of plant growth regulators.

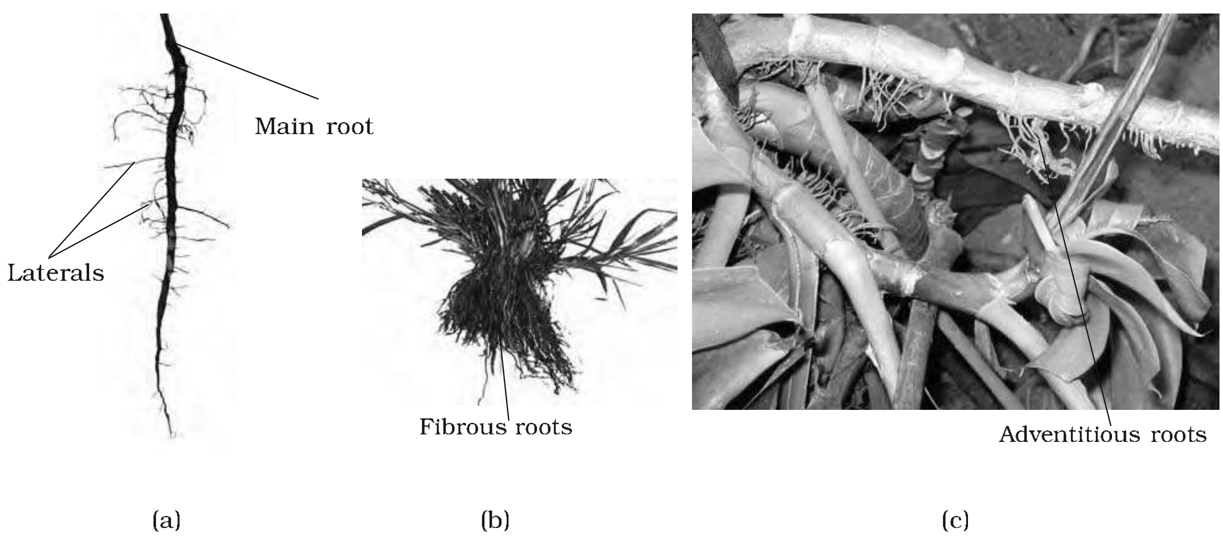


Figure 5.2 Different types of roots : (a) Tap (b) Fibrous (c) Adventitious

5.1.1 Regions of the Root

The root is covered at the apex by a thimble-like structure called the **root cap** (Figure 5.3). It protects the tender apex of the root as it makes its way through the soil. A few millimetres above the root cap is the **region of meristematic activity**. The cells of this region are very small, thin-walled and with dense protoplasm. They divide repeatedly. The cells proximal to this region undergo rapid elongation and enlargement and are responsible for the growth of the root in length. This region is called the **region of elongation**. The cells of the elongation zone gradually differentiate and mature. Hence, this zone, proximal to region of elongation, is called the **region of maturation**. From this region some of the epidermal cells form very fine and delicate, thread-like structures called **root hairs**. These root hairs absorb water and minerals from the soil.

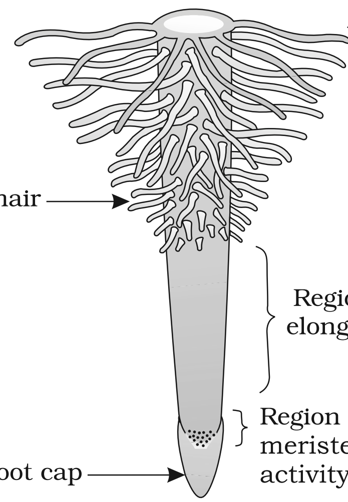


Figure 5.3 The regions of the root-tip

5.1.2 Modifications of Root

Roots in some plants change their shape and structure and become modified to perform functions other than absorption and conduction of water and minerals. They are modified for support storage of food and respiration (Figure 5.4 and 5.5). Tap roots of carrot, turnips and adventitious roots of sweet potato, get swollen and store food. Can you give some more such examples? Have you ever wondered what those hanging structures are that support a banyan tree? These are called **prop** roots. Similarly, the stems of maize and sugarcane have supporting roots coming out of the lower nodes of the stem. These are called **stilt** roots. In some plants such as *Rhizophora* growing in swampy areas, many roots come out of the ground and grow vertically upwards. Such roots, called **pneumatophores**, help to get oxygen for respiration.

Figure 5.4 Modification of root for support: Banyan tree

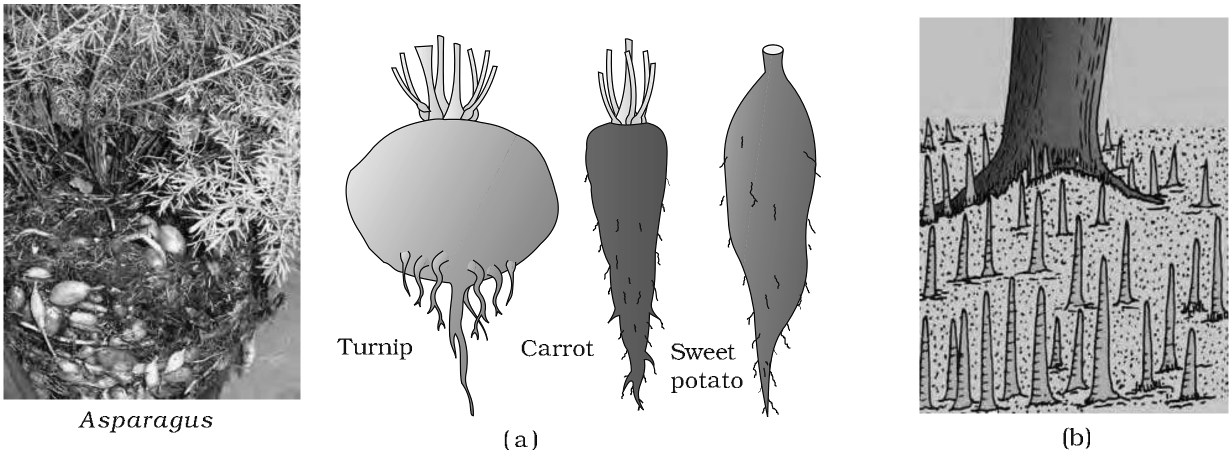


Figure 5.5 Modification of root for : (a) storage (b) respiration: pneumatophore in *Rhizophora*

5.2 THE STEM

What are the features that distinguish a stem from a root? The stem is the ascending part of the axis bearing branches, leaves, flowers and fruits. It develops from the plumule of the embryo of a germinating seed. The stem bears **nodes** and **internodes**. The region of the stem where leaves are born are called nodes while internodes are the portions between two nodes. The stem bears buds, which may be terminal or axillary. Stem is generally green when young and later often become woody and dark brown.

The main function of the stem is spreading out branches bearing leaves, flowers and fruits. It conducts water, minerals and photosynthates. Some stems perform the function of storage of food, support, protection and of vegetative propagation.

5.2.1 Modifications of Stem

The stem may not always be typically like what they are expected to be. They are modified to perform different functions (Figure 5.6). Underground stems of potato, ginger, turmeric, *zaminkand, Colocasia* are modified to store food in them. They also act as organs of perenation to tide over conditions unfavourable for growth. Stem **tendrils** which develop from axillary buds, are slender and spirally coiled and help plants to climb such as in gourds (cucumber, pumpkins, watermelon) and grapevines. Axillary buds of stems may also get modified into woody, straight and pointed **thorns**. Thorns are found in many plants such as *Citrus*, *Bougainvillea*. They protect plants from browsing animals. Some plants of arid regions modify their stems into flattened (*Opuntia*), or fleshy cylindrical *(Euphorbia)* structures. They contain chlorophyll and carry

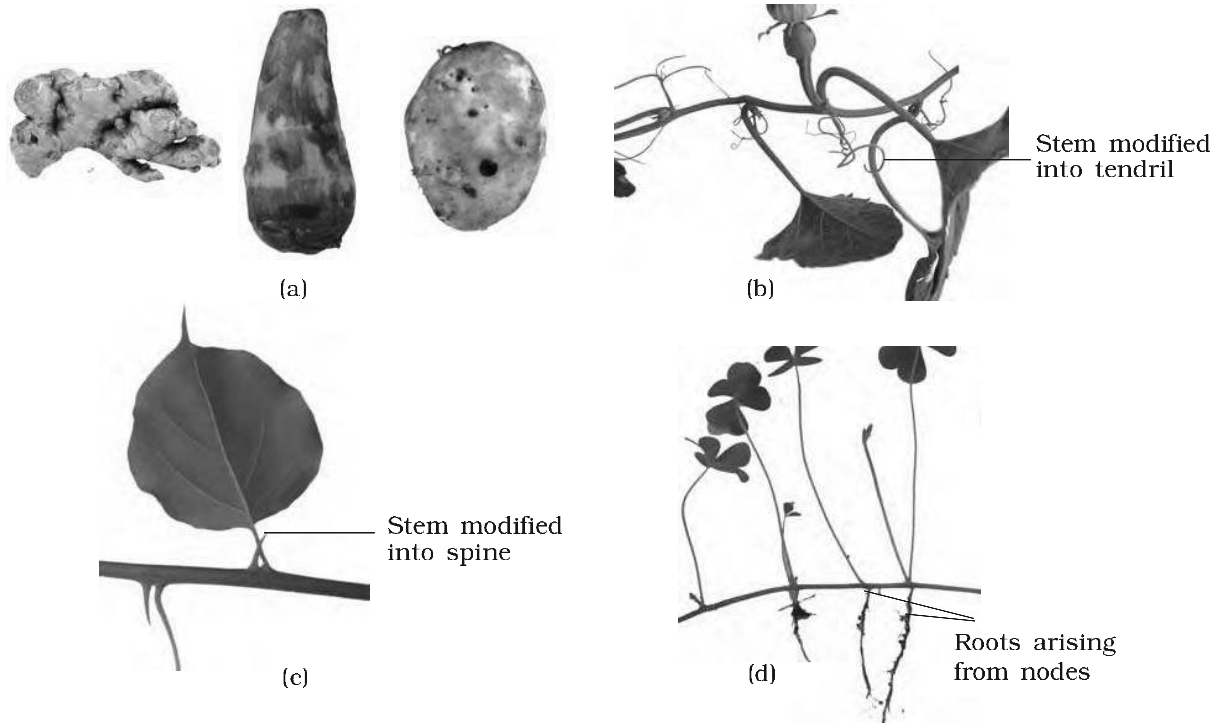


Figure 5.6 Modifications of stem for : (a) storage (b) support (c) protection (d) spread and vegetative propagation

out photosynthesis. Underground stems of some plants such as grass and strawberry, etc., spread to new niches and when older parts die new plants are formed. In plants like mint and jasmine a slender lateral branch arises from the base of the main axis and after growing aerially for some time arch downwards to touch the ground. A lateral branch with short internodes and each node bearing a rosette of leaves and a tuft of roots is found in aquatic plants like *Pistia* and *Eichhornia*. In banana, pineapple and *Chrysanthemum*, the lateral branches originate from the basal and underground portion of the main stem, grow horizontally beneath the soil and then come out obliquely upward giving rise to leafy shoots.

5.3 THE LEAF

The leaf is a lateral, generally flattened structure borne on the stem. It develops at the node and bears a bud in its axil. The **axillary bud** later develops into a branch. Leaves originate from shoot apical meristems and are arranged in an acropetal order. They are the most important vegetative organs for photosynthesis.

A typical leaf consists of three main parts: leaf base, petiole and lamina (Figure 5.7 a). The leaf is attached to the stem by the **leaf base** and may

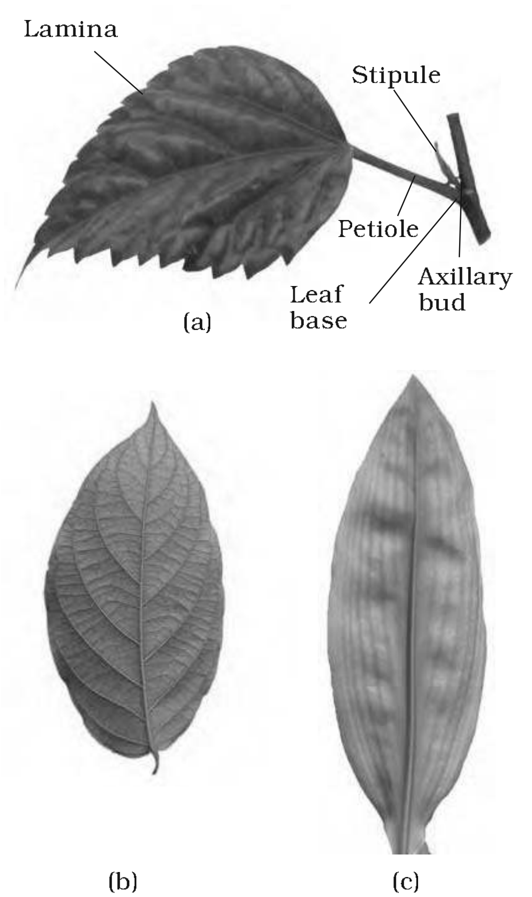


Figure 5.7 Structure of a leaf :
(a) Parts of a leaf
(b) Reticulate venation
(c) Parallel venation

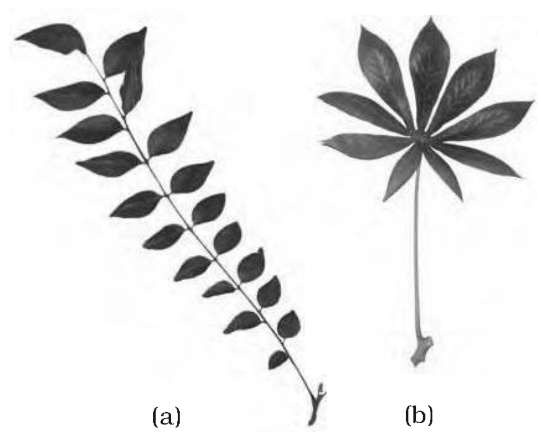


Figure 5.8 Compound leaves :
(a) pinnately compound leaf
(b) palmately compound leaf

bear two lateral small leaf like structures called stipules. In monocotyledons, the leaf base expands into a sheath covering the stem partially or wholly. In some leguminous plants the leafbase may become swollen, which is called the **pulvinus**. The **petiole** help hold the blade to light. Long thin flexible petioles allow leaf blades to flutter in wind, thereby cooling the leaf and bringing fresh air to leaf surface. The **lamina** or the **leaf blade** is the green expanded part of the leaf with veins and veinlets. There is, usually, a middle prominent vein, which is known as the midrib. Veins provide rigidity to the leaf blade and act as channels of transport for water, minerals and food materials. The shape, margin, apex, surface and extent of incision of lamina varies in different leaves.

5.3.1 Venation

The arrangement of veins and the veinlets in the lamina of leaf is termed as **venation**. When the veinlets form a network, the venation is termed as **reticulate** (Figure 5.7 b). When the veins run parallel to each other within a lamina, the venation is termed as **parallel** (Figure 5.7 c). Leaves of dicotyledonous plants generally possess reticulate venation, while parallel venation is the characteristic of most monocotyledons.

5.3.2 Types of Leaves

A leaf is said to be **simple**, when its lamina is entire or when incised, the incisions do not touch the midrib. When the incisions of the lamina reach up to the midrib breaking it into a number of leaflets, the leaf is called **compound**. A bud is present in the axil of petiole in both simple and compound leaves, but not in the axil of leaflets of the compound leaf.

The compound leaves may be of two types (Figure 5.8). In a **pinnately compound leaf** a number of leaflets are present on a common axis, the **rachis**, which represents the midrib of the leaf as in neem.

In **palmately compound leaves,** the leaflets are attached at a common point, i.e., at the tip of petiole, as in silk cotton.

5.3.3 Phyllotaxy

Phyllotaxy is the pattern of arrangement of leaves on the stem or branch**.** This is usually of three types – alternate, opposite and whorled (Figure 5.9). In **alternate** type of phyllotaxy**,** a single leaf arises at each node in alternate manner, as in china rose, mustard and sun flower plants. In **opposite** type, a pair of leaves arise at each node and lie opposite to each other as in *Calotropis* and guava plants. If more than two leaves arise at a node and form a whorl, it is called **whorled,** as in *Alstonia.*

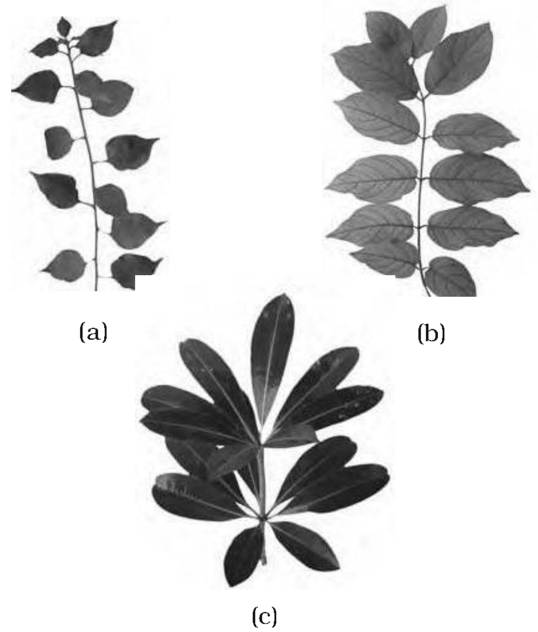


Figure 5.9 Different types of phyllotaxy : (a) Alternate (b) Opposite (c) Whorled

5.3.4 Modifications of Leaves

Leaves are often modified to perform functions other than photosynthesis. They are converted into **tendrils** for climbing as in peas or into **spines** for defence as in cacti (Figure 5.10 a, b). The fleshy leaves of onion and garlic store food (Figure 5.10c). In some plants such as Australian acacia, the leaves are small and short-lived. The petioles in these plants expand, become green and synthesise food. Leaves of certain insectivorous plants such as pitcher plant, venus-fly trap are also modified leaves.

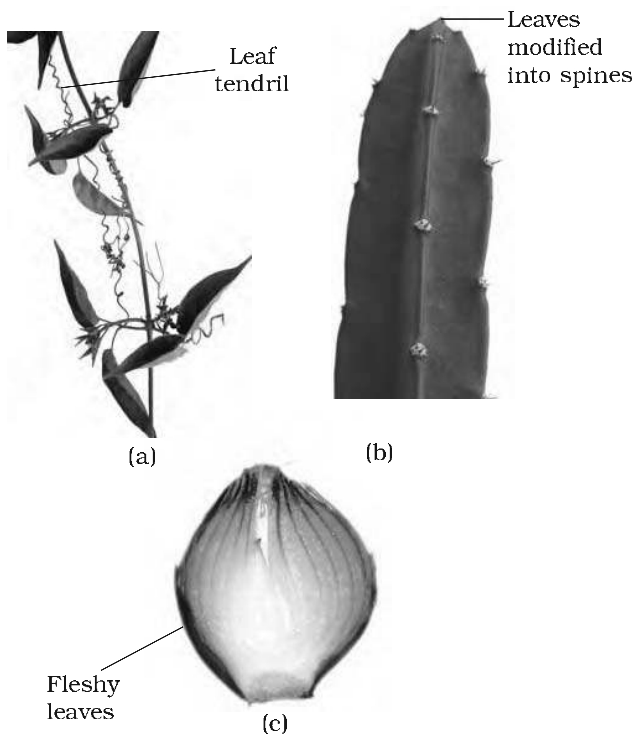


Figure 5.10 Modifications of leaf for : (a) support: tendril (b) protection: spines (c) storage: fleshy leaves

5.4 THE INFLORESCENCE

A flower is a modified shoot wherein the shoot apical meristem changes to floral meristem. Internodes do not elongate and the axis gets condensed. The apex produces different kinds of floral appendages laterally at successive nodes instead of leaves. When a shoot tip transforms into a flower, it is always solitary. The arrangement of flowers on the

Figure 5.11 Racemose inflorescence

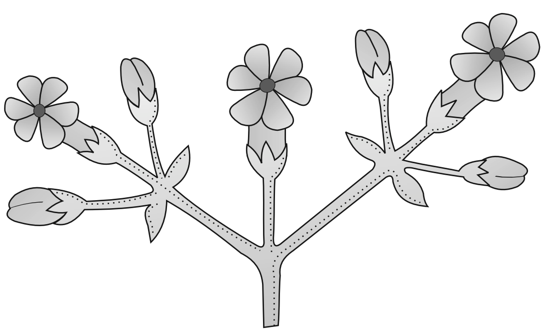


Figure 5.12 Cymose inflorescence

floral axis is termed as **inflorescence**. Depending on whether the apex gets converted into a flower or continues to grow, two major types of inflorescences are defined – racemose and cymose. In **racemose** type of inflorescences the main axis continues to grow, the flowers are borne laterally in an acropetal succession (Figure 5.11).

In **cymose** type of inflorescence the main axis terminates in a flower, hence is limited in growth.The flowers are borne in a basipetal order (Figure 5.12).

5.5 The Flower

The flower is the reproductive unit in the angiosperms. It is meant for sexual reproduction. A typical flower has four different kinds of whorls arranged successively on the swollen end of the stalk or pedicel, called **thalamus or receptacle**. These are calyx, corolla, androecium and gynoecium. Calyx and corolla are accessory organs, while androecium and gynoecium are reproductive organs. In some flowers like lily, the calyx and corolla are not distinct and are termed as perianth. When a flower has both androecium and gynoecium, it is **bisexual**. A flower having either only stamens or only carpels is **unisexual.**

In symmetry, the flower may be **actinomorphic** (radial symmetry) or **zygomorphic** (bilateral symmetry). When a flower can be divided into two equal radial halves in any radial plane passing through the centre, it is said to be **actinomorphic,** e.g., mustard, *datura*, chilli. When it can be divided into two similar halves only in one particular vertical plane, it is **zygomorphic,** e.g., pea, gulmohur, bean, *Cassia*. A flower is **asymmetric** (irregular) if it cannot be divided into two similar halves by any vertical plane passing through the centre, as in canna.

A flower may be **trimerous, tetramerous** or **pentamerous** when the floral appendages are in multiple of 3, 4 or 5, respectively. Flowers with bracts, reduced leaf found at the base of the pedicel, are called **bracteate** and those without bracts, **ebracteate**.

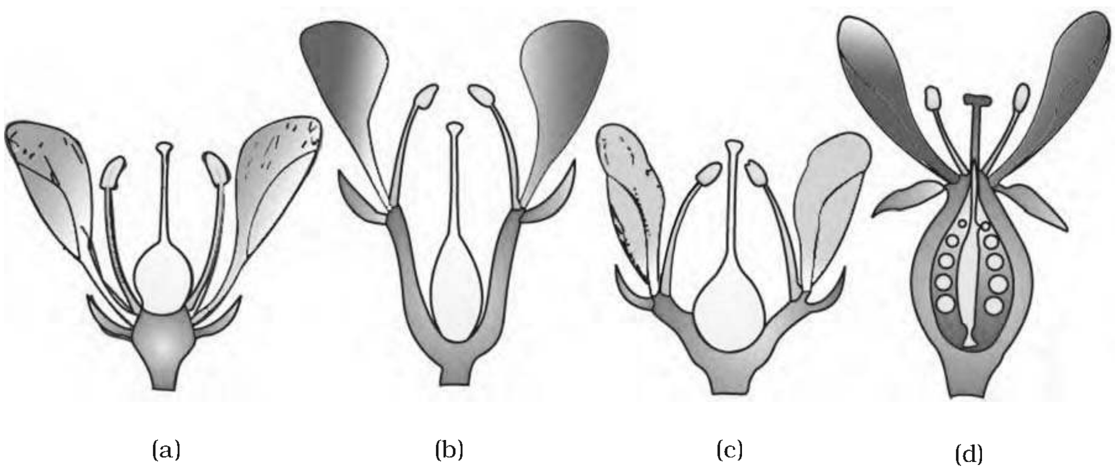


Figure 5.13 Position of floral parts on thalamus : (a) Hypogynous (b) and (c) Perigynous (d) Epigynous

Based on the position of calyx, corolla and androecium in respect of the ovary on thalamus, the flowers are described as hypogynous perigynous and epigynous (Figure 5.13). In the **hypogynous** flower the gynoecium occupies the highest position while the other parts are situated below it. The ovary in such flowers is said to be **superior,** e.g., mustard, china rose and brinjal. If gynoecium is situated in the centre and other parts of the flower are located on the rim of the thalamus almost at the same level, it is called **perigynous.** The ovary here is said to be **half inferior,** e.g., plum, rose, peach. In **epigynous flowers,** the margin of thalamus grows upward enclosing the ovary completely and getting fused with it, the other parts of flower arise above the ovary. Hence, the ovary is said to be **inferior** as in flowers of guava and cucumber, and the ray florets of sunflower.

5.5.1 Parts of a Flower

Each flower normally has four floral whorls, viz., calyx, corolla, androecium and gynoecium (Figure 5.14).

5.5.1.1 Calyx

The calyx is the outermost whorl of the flower and the members are called sepals. Generally, sepals are green, leaf like and protect the flower in the bud stage. The calyx may be **gamosepalous** (sepals united) or **polysepalous** (sepals free).

5.5.1.2 Corolla

Corolla is composed of petals. Petals are usually brightly coloured to attract insects for pollination. Like calyx, corolla may be also free

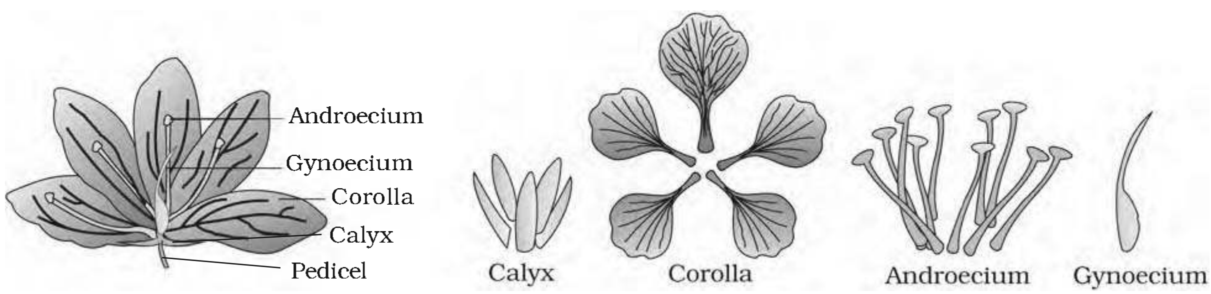
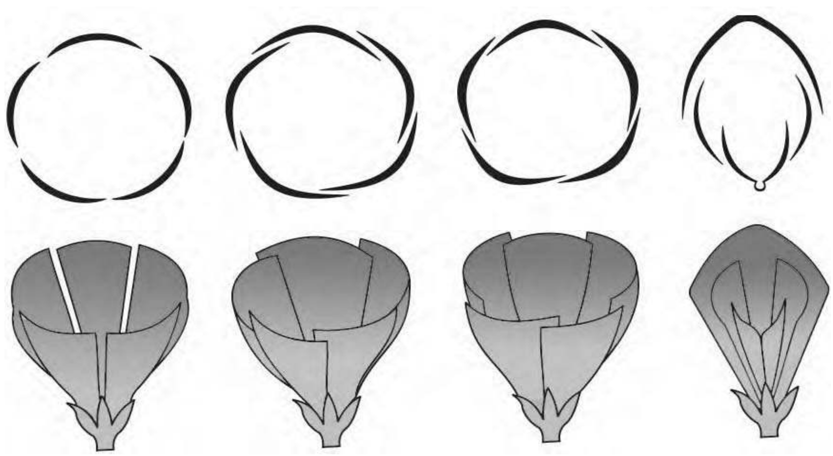


Figure 5.14 Parts of a flower

(gamopetalous) or united **(polypetalous)**. The shape and colour of corolla vary greatly in plants. Corolla may be tubular, bell-shaped, funnel-shaped or wheel-shaped.

Aestivation: The mode of arrangement of sepals or petals in floral bud with respect to the other members of the same whorl is known as aestivation. The main types of aestivation are valvate, twisted, imbricate and vexillary (Figure 5.15). When sepals or petals in a whorl just touch one another at the margin, without overlapping, as in *Calotropis*, it is said to be **valvate.** If one margin of the appendage overlaps that of the next one and so on as in china rose, lady's finger and cotton, it is called **twisted**. If the margins of sepals or petals overlap one another but not in any particular direction as in *Cassia* and gulmohur, the aestivation is called **imbricate**. In pea and bean flowers, there are five petals, the largest (standard) overlaps the two lateral petals (wings) which in turn overlap the two smallest anterior petals (keel); this type of aestivation is known as **vexillary** or papilionaceous.



(a) (b) (c) (d)

Figure 5.15 Types of aestivation in corolla : (a) Valvate (b) Twisted (c) Imbricate (d) Vexillary

5.5.1.3 Androecium

Androecium is composed of stamens. Each stamen which represents the male reproductive organ consists of a stalk or a filament and an anther. Each anther is usually bilobed and each lobe has two chambers, the pollen-sacs. The pollen grains are produced in pollen-sacs. A sterile stamen is called **staminode**.

Stamens of flower may be united with other members such as petals or among themselves. When stamens are attached to the petals, they are **epipetalous** as in brinjal, or **epiphyllous** when attached to the perianth as in the flowers of lily. The stamens in a flower may either remain free (polyandrous) or may be united in varying degrees. The stamens may be united into one bunch or one bundle **(monoadelphous)** as in china rose, or two bundles **(diadelphous)** as in pea, or into more than two bundles **(polyadelphous)** as in citrus. There may be a variation in the length of filaments within a flower, as in *Salvia* and mustard.

5.5.1.4 Gynoecium

Gynoecium is the female reproductive part of the flower and is made up of one or more carpels. A carpel consists of three parts namely stigma, style and ovary. **Ovary** is the enlarged basal part, on which lies the elongated tube, the style. The style connects the ovary to the stigma. The **stigma** is usually at the tip of the **style** and is the receptive surface for pollen grains. Each ovary bears one or more ovules attached to a flattened, cushion-like **placenta**. When more than one carpel is present, they may be free (as in lotus and rose) and are called **apocarpous**. They are termed **syncarpous** when carpels are fused, as in mustard and tomato. After fertilisation, the ovules develop into seeds and the ovary matures into a fruit.

Placentation: The arrangement of ovules within the ovary is known as placentation. The placentation are of different types namely, marginal, axile, parietal, basal, central and free central (Figure 5.16). In **marginal** placentation the placenta forms a ridge along the ventral suture of the ovary and the ovules are borne on this ridge forming two rows, as in pea. When the placenta is axial and the ovules are attached to it in a multilocular ovary, the placentaion is said to be **axile**, as in china rose, tomato and lemon. In **parietal** placentation, the ovules develop on the inner wall of the ovary or on peripheral part. Ovary is one-chambered but it becomes two-chambered due to the formation of the false septum, e.g., mustard and *Argemone*. When the ovules are borne on central axis and septa are absent, as in *Dianthus* and *Primrose* the placentation is

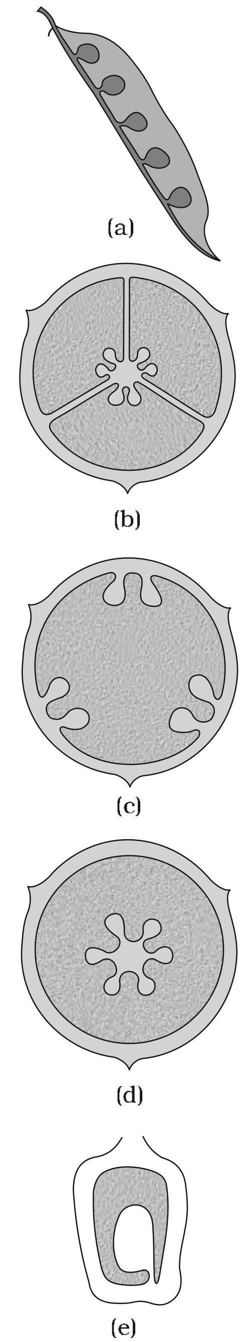


Figure 5.16 Types of placentation : (a) Marginal (b) Axile (c) Parietal (d) Free central (e) Basal

called **free central.** In **basal** placentation, the placenta develops at the base of ovary and a single ovule is attached to it, as in sunflower, marigold.

5.6 THE FRUIT

The fruit is a characteristic feature of the flowering plants. It is a mature or ripened ovary, developed after fertilisation. If a fruit is formed without fertilisation of the ovary, it is called a **parthenocarpic** fruit.

Generally, the fruit consists of a wall or **pericarp** and seeds. The pericarp may be dry or fleshy. When pericarp is thick and fleshy, it is differentiated into the outer **epicarp,** the middle **mesocarp** and the inner **endocarp**.

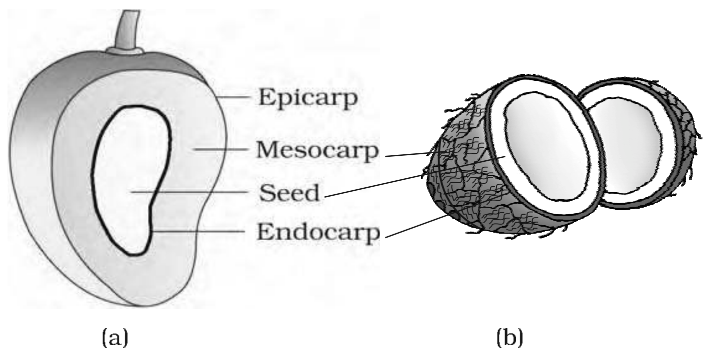


Figure 5.17 Parts of a fruit : (a) Mango (b) Coconut

In mango and coconut, the fruit is known as a drupe (Figure 5.17). They develop from monocarpellary superior ovaries and are one seeded. In mango the pericarp is well differentiated into an outer thin epicarp, a middle fleshy edible mesocarp and an inner stony hard endocarp. In coconut which is also a drupe, the mesocarp is fibrous.

5.7 THE SEED

The ovules after fertilisation, develop into seeds. A seed is made up of a seed coat and an embryo. The embryo is made up of a radicle, an embryonal axis and one (as in wheat, maize) or two cotyledons (as in gram and pea).

5.7.1 Structure of a Dicotyledonous Seed

The outermost covering of a seed is the seed coat. The seed coat has two layers, the outer **testa** and the inner **tegmen**. The **hilum** is a scar on the seed coat through which the developing seeds were attached to the fruit. Above the hilum is a small pore called the **micropyle**. Within the seed coat is the embryo, consisting of an embryonal axis and two cotyledons. The cotyledons are often fleshy and full of reserve food materials. At the two ends of the embryonal axis are present the radicle and the plumule (Figure 5.18). In some seeds such as castor the **endosperm** formed as a result of double fertilisation, is a food storing tissue. In plants such as bean, gram and pea, the endosperm is not present in mature seeds and such seeds are called non-endospermous.

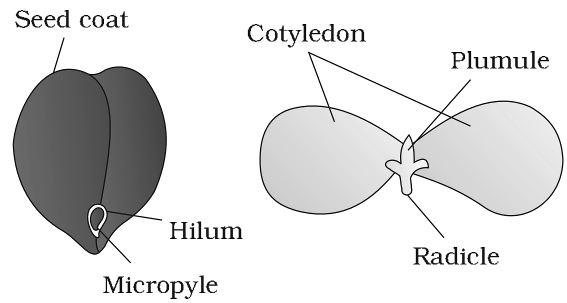


Figure 5.18 Structure of dicotyledonous seed

5.7.2 Structure of Monocotyledonous Seed

Generally, monocotyledonous seeds are endospermic but some as in orchids are non-endospermic. In the seeds of cereals such as maize the seed coat is membranous and generally fused with the fruit wall. The endosperm is bulky and stores food. The outer covering of endosperm separates the embryo by a proteinous layer called **aleurone layer**. The embryo is small and situated in a groove at one end of the endosperm. It consists of one large and shield shaped cotyledon known as **scutellum** and a short axis with a **plumule** and a **radicle**. The plumule and radicle are enclosed in sheaths which are called **coleoptile** and **coleorhiza** respectively (Figure 5.19).

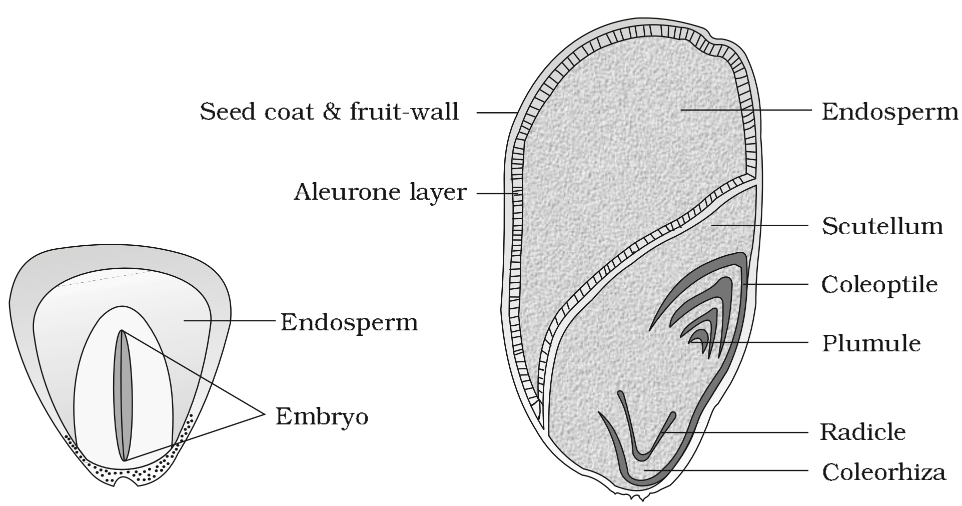
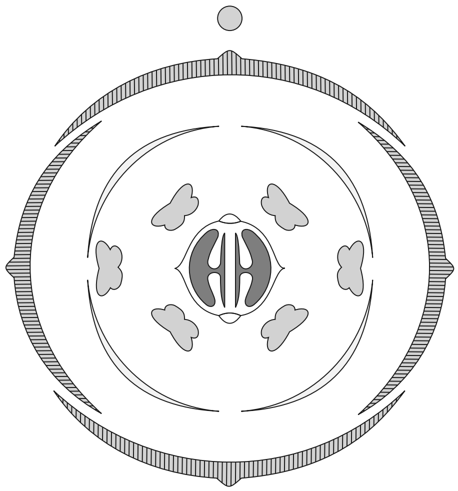


Figure 5.19 Structure of a monocotyledonous seed



$\oplus ⚥ K_{2+2} C_4 A_{2+4} \underline{G}_{(2)}$

Figure 5.20 Floral diagram with floral formula

5.8 Semi-Technical Description of a Typical Flowering Plant

Various morphological features are used to describe a flowering plant. The description has to be brief, in a simple and scientific language and presented in a proper sequence. The plant is described beginning with its habit, vegetative characters – roots, stem and leaves and then floral characters inflorescence and flower parts. After describing various parts of plant, a floral diagram and a floral formula are presented. The floral formula is represented by some symbols. In the floral formula, **Br** stands for bracteate **K** stands for calyx , **C** for corolla, **P** for perianth, **A** for androecium and **G** for Gynoecium, $\underline{\mathbf{G}}$ for superior ovary and $\overline{\mathbf{G}}$ for inferior ovary, ♂ for male, ♀ for female ⚥, for bisexual plants, $\oplus$ for actinomorphic and % for zygomorphic nature of flower. Fusion is indicated by enclosing the figure within bracket and adhesion by a line drawn above the symbols of the floral parts. A floral diagram provides information about the number of parts of a flower, their arrangement and the relation they have with one another (Figure 5.20). The position of the mother axis with respect to the flower is represented by a dot on the top of the floral diagram. Calyx, corolla, androecium and gynoecium are drawn in successive whorls, calyx being the outermost and the gynoecium being in the centre. Floral formula also shows cohesion and adhesion within parts of whorls and in between whorls. The floral diagram and floral formula in Figure 5.20 represents the mustard plant (Family: Brassicaceae).

5.9 Description of Some Important Families

5.9.1 Fabaceae

This family was earlier called Papilonoideae, a subfamily of family Leguminosae. It is distributed all over the world (Figure 5.21).

Vegetative Characters

Trees, shrubs, herbs; root with root nodules
Stem: erect or climber
Leaves: alternate, pinnately compound or simple; leaf base, pulvinate; stipulate; venation reticulate.

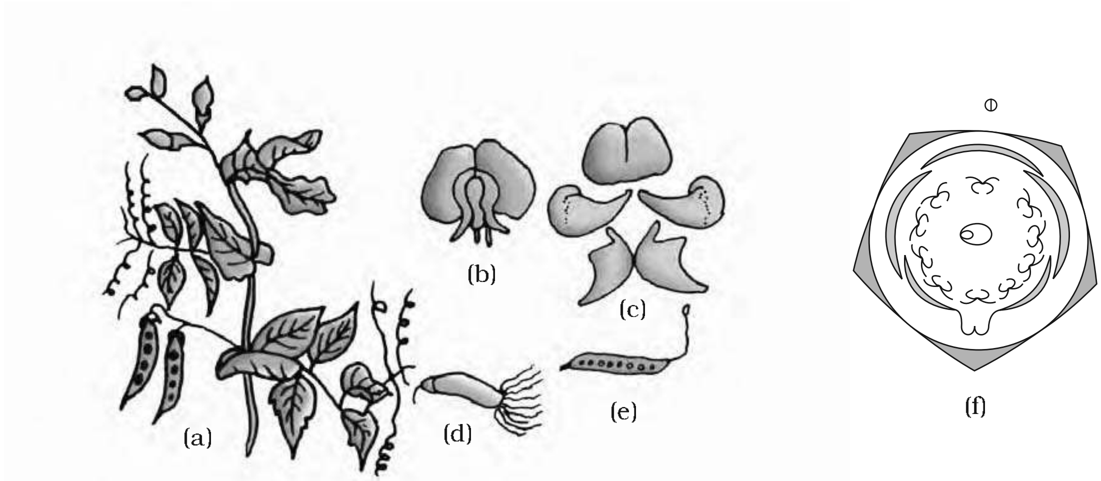


Figure 5.21 *Pisum sativum* (pea) plant : (a) Flowering twig (b) Flower (c) Petals (d) Reproductive parts (e) L.S.carpel (f) Floral diagram

Floral characters

Inflorescence: racemose
Flower: bisexual, zygomorphic
Calyx: sepals five, gamosepalous; imbricate aestivation
Corolla: petals five, polypetalous, papilionaceous, consisting of a posterior standard, two lateral wings, two anterior ones forming a keel (enclosing stamens and pistil), vexillary aestivation
Androecium: ten, diadelphous, anther dithecous
Gynoecium: ovary superior, mono carpellary, unilocular with many ovules, style single
Fruit: legume; seed: one to many, non-endospermic
Floral Formula: $\oplus ⚥ K_{(5)}\ C_{1+2+(2)}\ A_{(9)+1}\ \underline{G}_1$

Economic importance

Many plants belonging to the family are sources of pulses (gram, *arhar, sem, moong*, soyabean; edible oil (soyabean, groundnut); dye (indigofera); fibres (sunhemp); fodder *(Sesbania, Trifolium)*, ornamentals (lupin, sweet pea); medicine (*muliathi*).

5.9.2 Solanaceae

It is a large family, commonly called as the 'potato family'. It is widely distributed in tropics, subtropics and even temperate zones (Figure 5.22).

Vegetative Characters

Plants mostly, herbs, shrubs and small trees
Stem: herbaceous rarely woody, aerial; erect, cylindrical, branched, solid

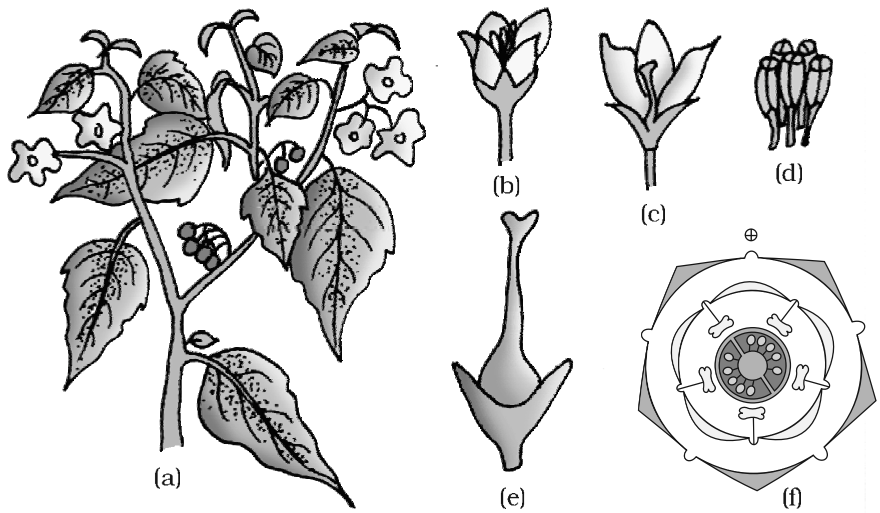


Figure 5.22 *Solanum nigrum* (makoi) plant : (a) Flowering twig (b) Flower (c) L.S. of flower (d) Stamens (e) Carpel (f) Floral diagram

or hollow, hairy or glabrous, underground stem in potato (*Solanum tuberosum*)

Leaves: alternate, simple, rarely pinnately compound, exstipulate; venation reticulate

Floral Characters

Inflorescence : Solitary, axillary or cymose as in *Solanum*
Flower: bisexual, actinomorphic
Calyx: sepals five, united, persistent, valvate aestivation
Corolla: petals five, united; valvate aestivation
Androecium: stamens five, epipetalous
Gynoecium: bicarpellary, syncarpous; ovary superior, bilocular, placenta swollen with many ovules
Fruits: berry or capsule
Seeds: many, endospermous
Floral Formula: $\oplus \text{⚥} K_{(5)} \overset{\frown}{C_{(5)} A_{(5)}} \underline{G}_{(2)}$

Economic Importance

Many plants belonging to this family are source of food (tomato, brinjal, potato), spice (chilli); medicine (belladonna, *ashwagandha*); fumigatory (tobacco); ornamentals (petunia).

5.9.3 Lilaceae

Commonly called the 'Lily family' is a characteristic representative of monocotyledonous plants. It is distributed world wide (Figure 5.23).

Vegetative characters: Perennial herbs with underground bulbs/corms/ rhizomes

Leaves mostly basal, alternate, linear, exstipulate with parallel venation

Floral characters

Inflorescence: solitary / cymose; often umbellate clusters

Flower: bisexual; actinomorphic
Perianth tepal six (3+3), often united into tube; valvate aestivation
Androcium: stamen six, (3+3)
Gynoecium: tricarpellary, syncarpous, ovary superior, trilocular with many ovules; axile placentation
Fruit: capsule, rarely berry
Seed: endospermous
Floral Formula: $\oplus ⚥ P_{3+3}\, A_{3+3}\, \underline{G}_{(3)}$

Economic Importance

Many plants belonging to this family are good ornamentals (tulip, *Gloriosa*), source of medicine (*Aloe*), vegetables (*Asparagus*), and colchicine (*Colchicum autumnale*).

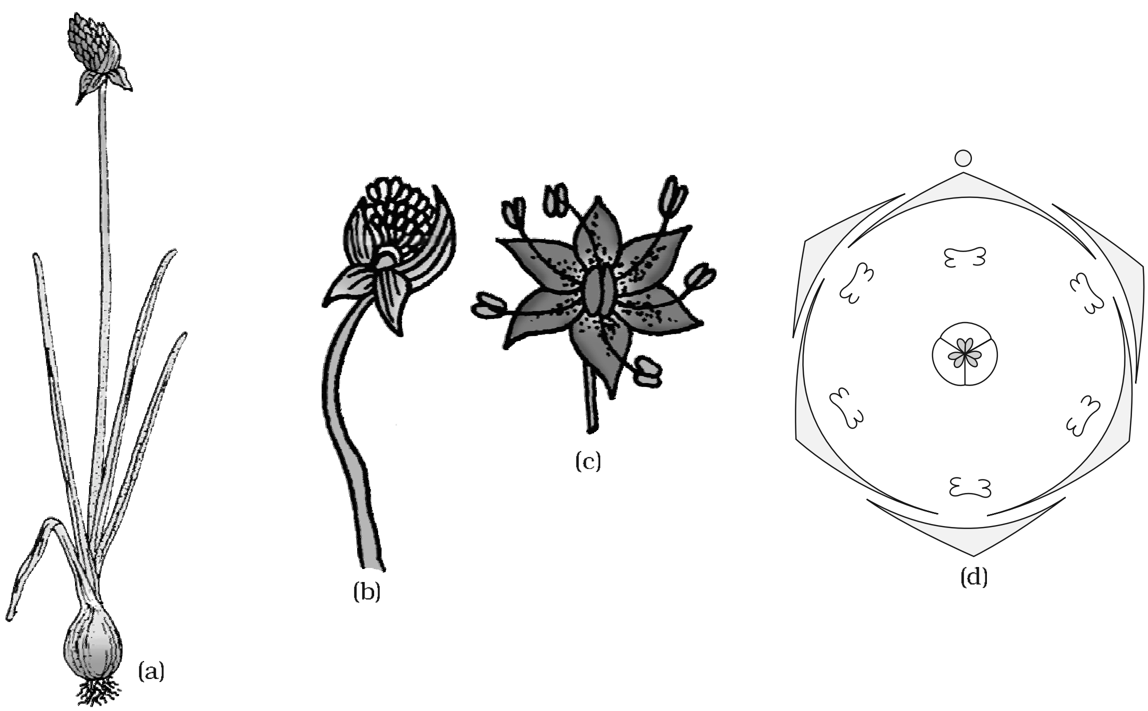


Figure 5.23 *Allium cepa* (onion) plant : (a) Plant (b) Inflorescence (c) Flower (d) Floral diagram

SUMMARY

Flowering plants exhibit enormous variation in shape, size, structure, mode of nutrition, life span, habit and habitat. They have well developed root and shoot systems. Root system is either tap root or fibrous. Generally, dicotyledonous plants have tap roots while monocotyledonous plants have fibrous roots. The roots in some plants get modified for storage of food, mechanical support and respiration. The shoot system is differentiated into stem, leaves, flowers and fruits. The morphological features of stems like the presence of nodes and internodes, multicellular hair and positively phototropic nature help to differentiate the stems from roots. Stems also get modified to perform diverse functions such as storage of food, vegetative propagation and protection under different conditions. Leaf is a lateral outgrowth of stem developed exogeneously at the node. These are green in colour to perform the function of photosynthesis. Leaves exhibit marked variations in their shape, size, margin, apex and extent of incisions of leaf blade (lamina). Like other parts of plants, the leaves also get modified into other structures such as tendrils, spines for climbing and protection respectively.

The flower is a modified shoot, meant for sexual reproduction. The flowers are arranged in different types of inflorescences. They exhibit enormous variation in structure, symmetry, position of ovary in relation to other parts, arrangement of petals, sepals, ovules etc. After fertilisation, the ovary is converted into fruits and ovules into seeds. Seeds either may be monocotyledonous or dicotyledonous. They vary in shape, size and period of viability. The floral characteristics form the basis of classification and identification of flowering plants. This can be illustrated through semi-technical descriptions of families. Hence, a flowering plant is described in a definite sequence by using scientific terms. The floral features are represented in the summarised form as floral diagrams and floral formula.

EXERCISES

1. What is meant by modification of root? What type of modification of root is found in the:

   (a) Banyan tree (b) Turnip (c) Mangrove trees

2. Justify the following statements on the basis of external features:

   (i) Underground parts of a plant are not always roots.
   (ii) Flower is a modified shoot.

3. How is a pinnately compound leaf different from a palmately compound leaf?

4. Explain with suitable examples the different types of phyllotaxy.

5. Define the following terms:
   (a) aestivation (b) placentation (c) actinomorphic
   (d) zygomorphic (e) superior ovary (f) perigynous flower
   (g) epipetalous stamen
6. Differentiate between
   (a) Racemose and cymose inflorescence
   (b) Fibrous root and adventitious root
   (c) Apocarpous and syncarpous ovary
7. Draw the labelled diagram of the following:
   (i) gram seed (ii) V.S. of maize seed
8. Describe modifications of stem with suitable examples.
9. Take one flower each of the families Fabaceae and Solanaceae and write its semi-technical description. Also draw their floral diagram after studying them.
10. Describe the various types of placentations found in flowering plants.
11. What is a flower? Describe the parts of a typical angiosperm flower.
12. How do the various leaf modifications help plants?
13. Define the term inflorescence. Explain the basis for the different types inflorescence in flowering plants.
14. Write the floral formula of a actinomorphic, bisexual, hypogynous flower with five united sepals, five free petals, five free stamens and two united carples with superior ovary and axile placentation.
15. Describe the arrangement of floral members in relation to their insertion on thalamus.

CHAPTER 6

ANATOMY OF FLOWERING PLANTS

You can very easily see the structural similarities and variations in the external morphology of the larger living organism, both plants and animals. Similarly, if we were to study the internal structure, one also finds several similarities as well as differences. This chapter introduces you to the internal structure and functional organisation of higher plants. Study of internal structure of plants is called anatomy. Plants have cells as the basic unit, cells are organised into tissues and in turn the tissues are organised into organs. Different organs in a plant show differences in their internal structure. Within angiosperms, the monocots and dicots are also seen to be anatomically different. Internal structures also show adaptations to diverse environments.

6.1 THE TISSUES

A tissue is a group of cells having a common origin and usually performing a common function. A plant is made up of different kinds of tissues. Tissues are classified into two main groups, namely, meristematic and permanent tissues based on whether the cells being formed are capable of dividing or not.

6.1.1 Meristematic Tissues

Growth in plants is largely restricted to specialised regions of active cell division called **meristems** (*Gk. meristos*: divided). Plants have different kinds of meristems. The meristems which occur at the tips of roots and shoots and produce primary tissues are called **apical meristems** (Figure 6.1).

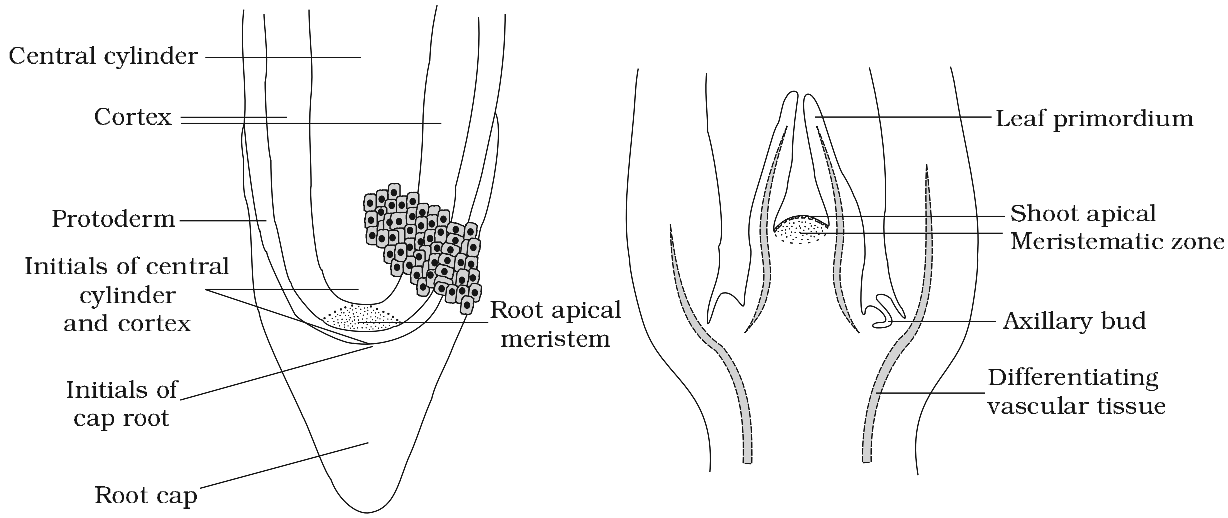


Figure 6.1 Apical meristem: (a) Root (b) Shoot

Root apical meristem occupies the tip of a root while the shoot apical meristem occupies the distant most region of the stem axis. During the formation of leaves and elongation of stem, some cells 'left behind' from shoot apical meristem, constitute the **axillary bud**. Such buds are present in the axils of leaves and are capable of forming a branch or a flower. The meristem which occurs between mature tissues is known as **intercalary meristem**. They occur in grasses and regenerate parts removed by the grazing herbivores. Both apical meristems and intercalary meristems are **primary meristems** because they appear early in life of a plant and contribute to the formation of the primary plant body.

The meristem that occurs in the mature regions of roots and shoots of many plants, particularly those that produce woody axis and appear later than primary meristem is called the **secondary** or **lateral meristem.** They are cylindrical meristems. Fascicular vascular cambium, interfascicular cambium and cork-cambium are examples of lateral meristems. These are responsible for producing the secondary tissues.

Following divisions of cells in both primary and as well as secondary meristems, the newly formed cells become structurally and functionally specialised and lose the ability to divide. Such cells are termed **permanent** or **mature cells** and constitute the permanent tissues. During the formation of the primary plant body, specific regions of the apical meristem produce dermal tissues, ground tissues and vascular tissues.

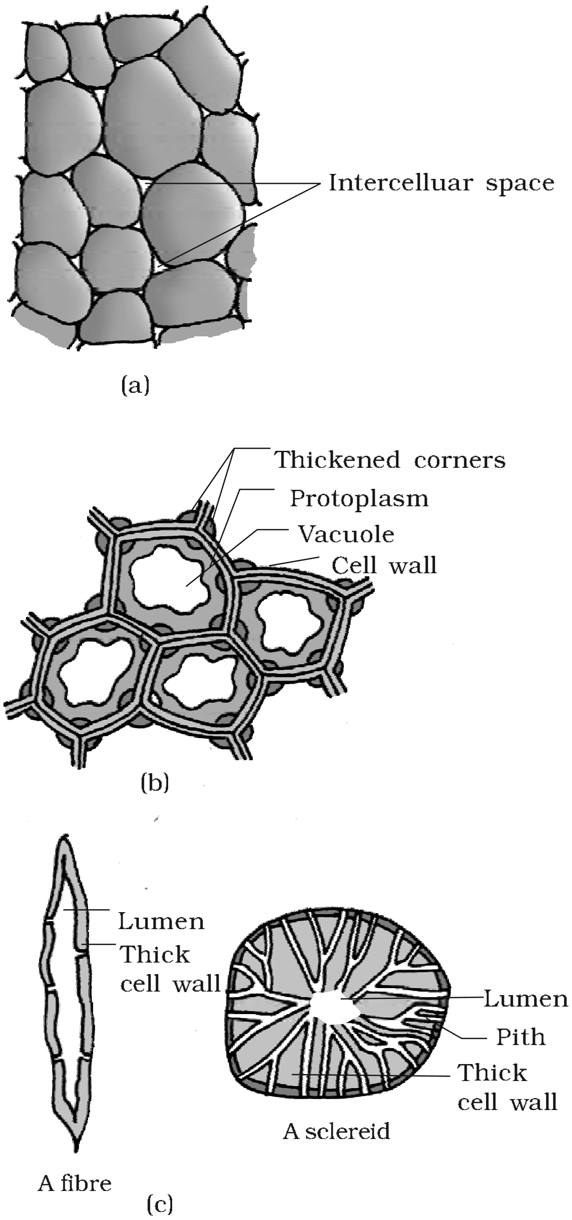


Figure 6.2 Simple tissues :
(a) Parenchyma
(b) Collenchyma
(c) Sclerenchyma

6.1.2 Permanent Tissues

The cells of the permanent tissues do not generally divide further. Permanent tissues having all cells similar in structure and function are called **simple tissues**. Permanent tissues having many different types of cells are called **complex tissues**.

6.1.2.1 Simple Tissues

A simple tissue is made of only one type of cells. The various simple tissues in plants are parenchyma, collenchyma and sclerenchyma (Figure 6.2). **Parenchyma** forms the major component within organs. The cells of the parenchyma are generally isodiametric. They may be spherical, oval, round, polygonal or elongated in shape. Their walls are thin and made up of cellulose. They may either be closely packed or have small intercellular spaces. The parenchyma performs various functions like photosynthesis, storage, secretion.

The **collenchyma** occurs in layers below the epidermis in dicotyledonous plants. It is found either as a homogeneous layer or in patches. It consists of cells which are much thickened at the corners due to a deposition of cellulose, hemicellulose and pectin. Collenchymatous cells may be oval, spherical or polygonal and often contain chloroplasts. These cells assimilate food when they contain chloroplasts. Intercellular spaces are absent. They provide mechanical support to the growing parts of the plant such as young stem and petiole of a leaf.

Sclerenchyma consists of long, narrow cells with thick and lignified cell walls having a few or numerous pits. They are usually dead and without protoplasts. On the basis of variation in form, structure, origin and development, sclerenchyma may be either fibres or sclereids. The **fibres** are thick-walled, elongated and pointed cells, generally occuring in groups, in various parts of the plant. The **sclereids** are spherical, oval or cylindrical, highly thickened dead cells with very narrow cavities (lumen). These are commonly found in the fruit walls of nuts; pulp of fruits like guava, pear and sapota; seed coats of legumes and leaves of tea. Sclerenchyma provides mechanical support to organs.

6.1.2.2 Complex Tissues

The complex tissues are made of more than one type of cells and these work together as a unit. Xylem and phloem constitute the complex tissues in plants (Figure 6.3).

Xylem functions as a conducting tissue for water and minerals from roots to the stem and leaves. It also provides mechanical strength to the plant parts. It is composed of four different kinds of elements, namely, tracheids, vessels, xylem fibres and xylem parenchyma. Gymnosperms lack vessels in their xylem. **Tracheids** are elongated or tube like cells with thick and lignified walls and tapering ends. These are dead and are without protoplasm. The inner layers of the cell walls have thickenings which vary in form. In flowering plants, tracheids and vessels are the main water transporting elements. **Vessel** is a long cylindrical tube-like structure made up of many cells called vessel members, each with lignified walls and a large central cavity. The vessel cells are also devoid of protoplasm. Vessel members are interconnected through perforations in their common walls. The presence of vessels is a characteristic feature of angiosperms. **Xylem fibres** have highly thickened walls and obliterated central lumens. These may either be septate or aseptate. **Xylem parenchyma** cells are living and thin-walled, and their cell walls are made up of cellulose. They store food materials in the form of starch or fat, and other substances like tannins. The radial conduction of water takes place by the ray parenchymatous cells.

Primary xylem is of two types – protoxylem and metaxylem. The first formed primary xylem elements are called **protoxylem** and the later formed primary xylem is called **metaxylem.** In stems, the protoxylem lies towards the centre (pith) and the metaxylem lies towards the periphery of the organ. This type of primary xylem is called **endarch**. In roots, the protoxylem lies towards periphery and metaxylem lies towards the centre. Such arrangement of primary xylem is called **exarch.**

Phloem transports food materials, usually from leaves to other parts of the plant. Phloem in angiosperms is composed of sieve tube elements, companion cells, phloem parenchyma

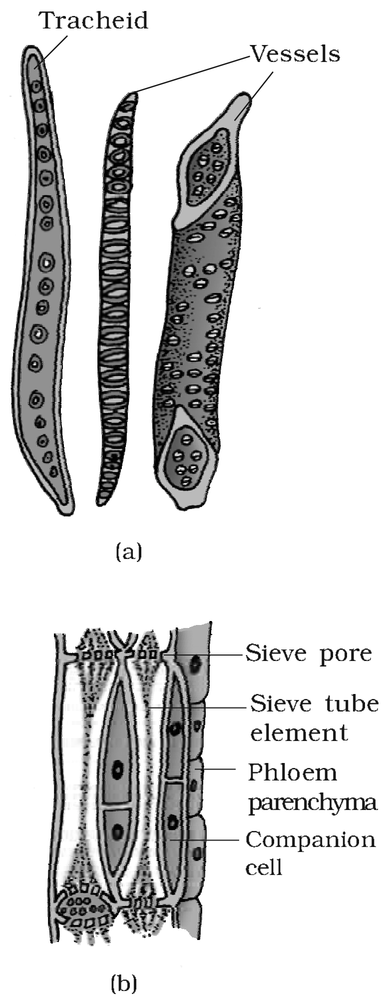


Figure 6.3 (a) Xylem
(b) Phloem tissues

and phloem fibres. Gymnosperms have albuminous cells and sieve cells. They lack sieve tubes and companion cells. **Sieve tube elements** are also long, tube-like structures, arranged longitudinally and are associated with the companion cells. Their end walls are perforated in a sieve-like manner to form the sieve plates. A mature sieve element possesses a peripheral cytoplasm and a large vacuole but lacks a nucleus. The functions of sieve tubes are controlled by the nucleus of companion cells. The **companion cells** are specialised parenchymatous cells, which are closely associated with sieve tube elements. The sieve tube elements and companion cells are connected by pit fields present between their common longitudinal walls. The companion cells help in maintaining the pressure gradient in the sieve tubes. **Phloem parenchyma** is made up of elongated, tapering cylindrical cells which have dense cytoplasm and nucleus. The cell wall is composed of cellulose and has pits through which plasmodesmatal connections exist between the cells. The phloem parenchyma stores food material and other substances like resins, latex and mucilage. Phloem parenchyma is absent in most of the monocotyledons. **Phloem fibres** (bast fibres) are made up of sclerenchymatous cells. These are generally absent in the primary phloem but are found in the secondary phloem. These are much elongated, unbranched and have pointed, needle like apices. The cell wall of phloem fibres is quite thick. At maturity, these fibres lose their protoplasm and become dead. Phloem fibres of jute, flax and hemp are used commercially. The first formed primary phloem consists of narrow sieve tubes and is referred to as **protophloem** and the later formed phloem has bigger sieve tubes and is referred to as **metaphloem**.

6.2 The Tissue System

We were discussing types of tissues based on the types of cells present. Let us now consider how tissues vary depending on their location in the plant body. Their structure and function would also be dependent on location. On the basis of their structure and location, there are three types of tissue systems. These are the epidermal tissue system, the ground or fundamental tissue system and the vascular or conducting tissue system.

6.2.1 Epidermal Tissue System

The epidermal tissue system forms the outer-most covering of the whole plant body and comprises epidermal cells, stomata and the epidermal appendages – the trichomes and hairs. The **epidermis** is the outermost layer of the primary plant body. It is made up of elongated, compactly arranged cells, which form a continuous layer. Epidermis is usually single-layered. Epidermal cells are parenchymatous with a small amount of cytoplasm lining the cell wall and a large vacuole. The outside of the epidermis is often covered with a waxy thick layer called the **cuticle** which prevents the loss of water. Cuticle is absent in roots. **Stomata** are structures present in the epidermis of leaves. Stomata regulate the process of transpiration and gaseous exchange. Each stoma is composed of two bean-shaped cells known as **guard cells.** In grasses, the guard cells are dumb-bell shaped. The outer walls of guard cells (away from the stomatal pore) are thin and the inner walls (towards the stomatal pore) are highly thickened. The guard cells possess chloroplasts and regulate the opening and closing of stomata. Sometimes, a few epidermal cells, in the vicinity of the guard cells become specialised in their shape and size and are known as **subsidiary cells**. The stomatal aperture, guard cells and the surrounding subsidiary cells are together called **stomatal apparatus** (Figure 6.4).

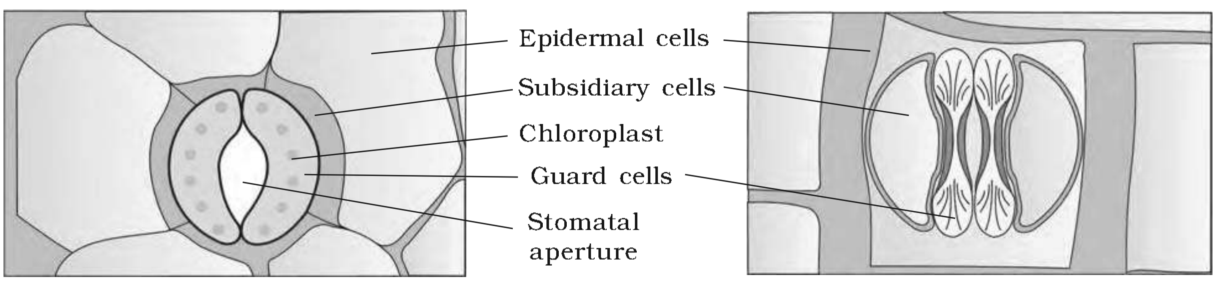


Figure 6.4 Diagrammatic representation: (a) stomata with bean-shaped guard cells (b) stomata with dumb-bell shaped guard cell

The cells of epidermis bear a number of hairs. The **root hairs** are unicellular elongations of the epidermal cells and help absorb water and minerals from the soil. On the stem the epidermal hairs are called **trichomes**. The trichomes in the shoot system are usually multicellular. They may be branched or unbranched and soft or stiff. They may even be secretory. The trichomes help in preventing water loss due to transpiration.

6.2.2 The Ground Tissue System

All tissues except epidermis and vascular bundles constitute the **ground tissue**. It consists of simple tissues such as parenchyma, collenchyma and sclerenchyma. Parenchymatous cells are usually present in cortex, pericycle, pith and medullary rays, in the primary stems and roots. In leaves, the ground tissue consists of thin-walled chloroplast containing cells and is called **mesophyll**.

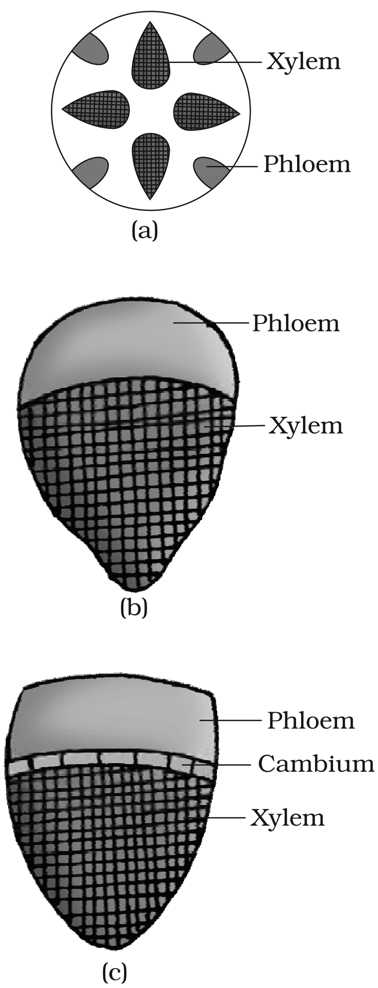


Figure 6.5 Various types of vascular bundles : (a) radial (b) conjoint closed (c) conjoint open

6.2.3 The Vascular Tissue System

The vascular system consists of complex tissues, the phloem and the xylem.The xylem and phloem together constitute vascular bundles (Figure 6.5). In dicotyledonous stems, **cambium** is present between phloem and xylem. Such vascular bundles because of the presence of cambium possess the ability to form secondary xylem and phloem tissues, and hence are called **open vascular bundles**. In the monocotyledons, the vascular bundles have no cambium present in them. Hence, since they do not form secondary tissues they are referred to as **closed**. When xylem and phloem within a vascular bundle are arranged in an alternate manner on different radii, the arrangement is called **radial** such as in roots. In **conjoint** type of vascular bundles, the xylem and phloem are situated at the same radius of vascular bundles. Such vascular bundles are common in stems and leaves. The conjoint vascular bundles usually have the phloem located only on the outer side of xylem.

6.3 Anatomy of Dicotyledonous and Monocotyledonous Plants

For a better understanding of tissue organisation of roots, stems and leaves, it is convenient to study the transverse sections of the mature zones of these organs.

6.3.1 Dicotyledonous Root

Look at Figure 6.6 (a), it shows the transverse section of the sunflower root. The internal tissue organisation is as follows:

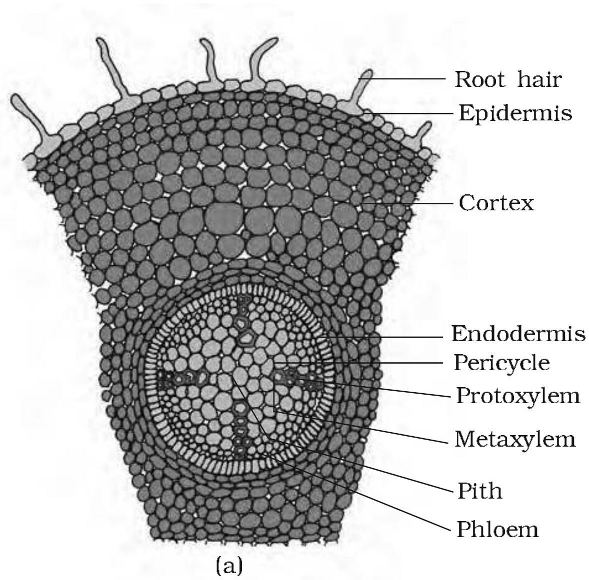
The outermost layer is **epidermis.** Many of the epidermal cells protrude in the form of unicellular root hairs. The **cortex** consists of several layers of thin-walled parenchyma cells with intercellular spaces. The innermost layer of the cortex is called **endodermis.** It comprises a single layer of barrel-shaped cells without any intercellular spaces. The tangential as well as radial walls of the endodermal cells have a deposition of water-impermeable, waxy material-suberin-in the form of **casparian strips**. Next to endodermis lies a few layers of thick-walled parenchyomatous cells referred to as **pericycle**. Initiation of lateral roots and vascular cambium during the secondary growth takes place in these cells. The pith is small or inconspicuous. The parenchymatous cells which lie between the xylem and the phloem are called **conjuctive tissue**. There are usually two to four xylem and phloem patches. Later, a cambium ring develops between the xylem and phloem. All tissues on the innerside of the endodermis such as pericycle, vascular bundles and pith constitute the **stele**.

6.3.2 Monocotyledonous Root

The anatomy of the monocot root is similar to the dicot root in many respects (Figure 6.6 b). It has epidermis, cortex, endodermis, pericycle, vascular bundles and pith. As compared to the dicot root which have fewer xylem bundles, there are usually more than six (polyarch) xylem bundles in the monocot root. Pith is large and well developed. Monocotyledonous roots do not undergo any secondary growth.

6.3.3 Dicotyledonous Stem

The transverse section of a typical young dicotyledonous stem shows that the **epidermis** is the outermost protective layer of the stem



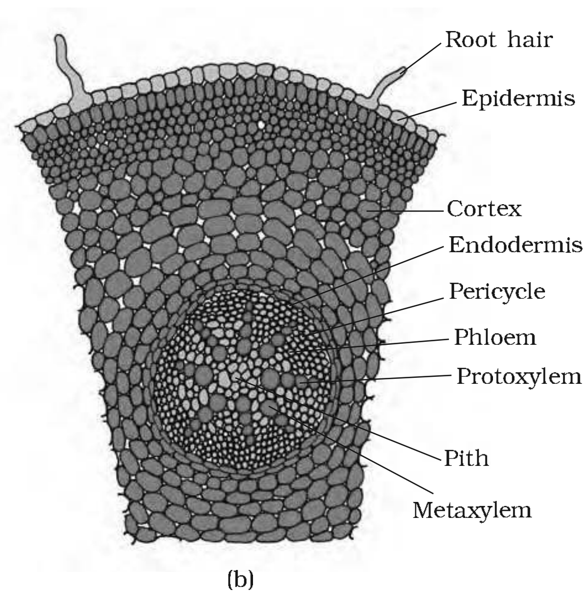


Figure 6.6 T.S (a) Dicot root (Primary) : (b) Monocot root

(Figure 6.7 a). Covered with a thin layer of cuticle, it may bear trichomes and a few stomata. The cells arranged in multiple layers between epidermis and pericycle constitute the cortex. It consists of three sub-zones. The outer **hypodermis**, consists of a few layers of collenchymatous cells just below the epidermis, which provide mechanical strength to the young stem. **Cortical layers** below hypodermis consist of rounded thin walled parenchymatous cells with conspicuous intercellular spaces. The innermost layer of the cortex is called the **endodermis.** The cells of the endodermis are rich in starch grains and the layer is also referred to as the **starch sheath. Pericycle** is

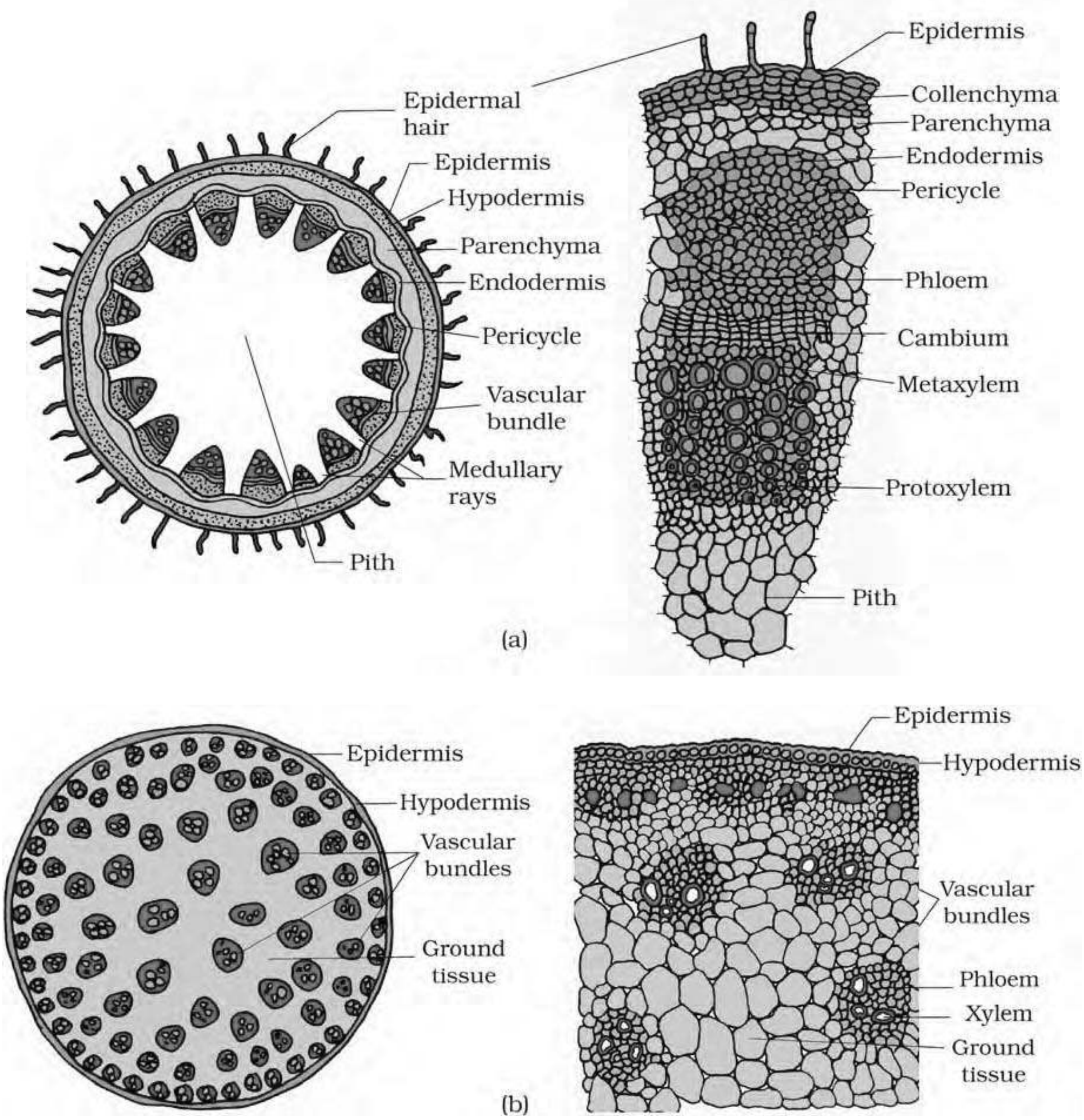


Figure 6.7 T.S. of stem : (a) Dicot (b) Monocot

present on the inner side of the endodermis and above the phloem in the form of semi-lunar patches of sclerenchyma. In between the vascular bundles there are a few layers of radially placed parenchymatous cells, which constitute medullary rays. A large number of **vascular bundles** are arranged in a ring ; the 'ring' arrangement of vascular bundles is a characteristic of dicot stem. Each vascular bundle is conjoint, open, and with endarch protoxylem. A large number of rounded, parenchymatous cells with large intercellular spaces which occupy the central portion of the stem constitute the **pith**.

6.3.4 Monocotyledonous Stem

The monocot stem has a sclerenchymatous hypodermis, a large number of scattered vascular bundles, each surrounded by a sclerenchymatous bundle sheath, and a large, conspicuous parenchymatous ground tissue (Figure 6.7b). Vascular bundles are conjoint and closed. Peripheral vascular bundles are generally smaller than the centrally located ones. The phloem parenchyma is absent, and water-containing cavities are present within the vascular bundles.

6.3.5 Dorsiventral (Dicotyledonous) Leaf

The vertical section of a dorsiventral leaf through the lamina shows three main parts, namely, epidermis, mesophyll and vascular system. The **epidermis** which covers both the upper surface (adaxial epidermis) and lower surface (abaxial epidermis) of the leaf has a conspicuous cuticle. The abaxial epidermis generally bears more stomata than the adaxial epidermis. The latter may even lack stomata. The tissue between the upper and the lower epidermis is called the **mesophyll**. Mesophyll, which possesses chloroplasts and carry out photosynthesis, is made up of parenchyma. It has two types of cells – the **palisade parenchyma** and the **spongy parenchyma**. The adaxially placed palisade parenchyma is made up of elongated cells, which are arranged vertically and parallel to each other. The oval or round and loosely arranged spongy parenchyma is situated below the palisade cells and extends to the lower epidermis. There are numerous large spaces and air cavities between these cells. **Vascular system** includes vascular bundles, which can be seen in the veins and the midrib. The size of the vascular bundles are dependent on the size of the veins. The veins vary in thickness in the reticulate venation of the dicot leaves. The vascular bundles are surrounded by a layer of thick walled **bundle sheath cells**. Look at Figure 6.8 (a) and find the position of xylem in the vascular bundle.

6.3.6 Isobilateral (Monocotyledonous) Leaf

The anatomy of isobilateral leaf is similar to that of the dorsiventral leaf in many ways. It shows the following characteristic differences. In an

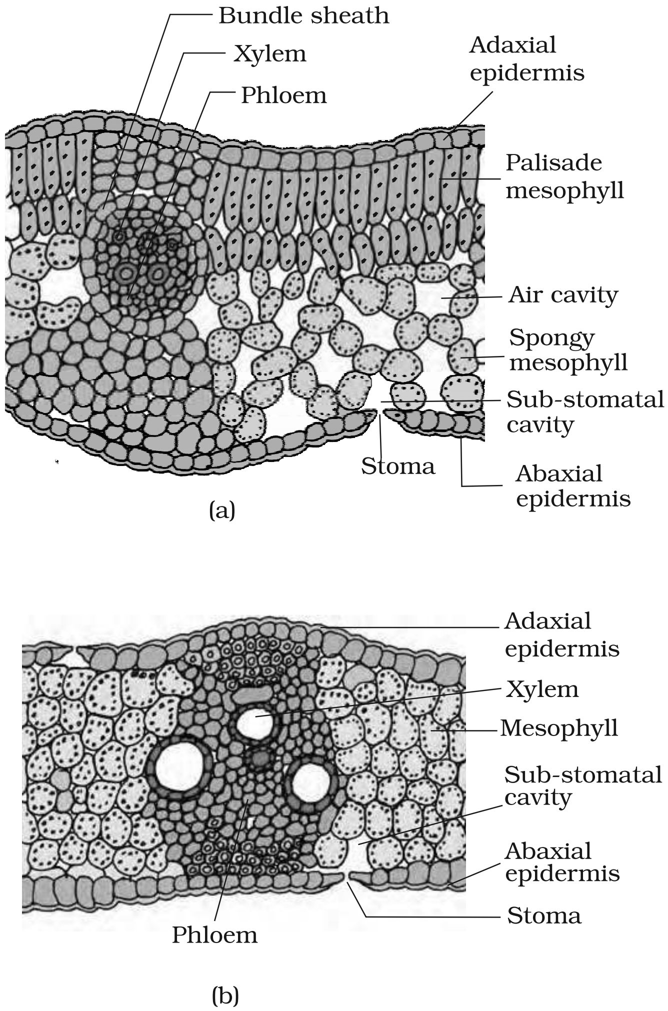


Figure 6.8 T.S. of leaf : (a) Dicot (b) Monocot

isobilateral leaf, the stomata are present on both the surfaces of the epidermis; and the mesophyll is not differentiated into palisade and spongy parenchyma (Figure 6.8 b).

In grasses, certain adaxial epidermal cells along the veins modify themselves into large, empty, colourless cells. These are called **bulliform cells.** When the bulliform cells in the leaves have absorbed water and are turgid, the leaf surface is exposed. When they are flaccid due to water stress, they make the leaves curl inwards to minimise water loss.

The parallel venation in monocot leaves is reflected in the near similar sizes of vascular bundles (except in main veins) as seen in vertical sections of the leaves.

6.4 SECONDARY GROWTH

The growth of the roots and stems in length with the help of apical meristem is called the primary growth. Apart from primary growth most dicotyledonous plants exhibit an increase in girth. This increase is called the **secondary growth**. The tissues involved in secondary growth are the two **lateral meristems: vascular cambium** and **cork cambium**.

6.4.1 Vascular Cambium

The meristematic layer that is responsible for cutting off vascular tissues – xylem and pholem – is called vascular cambium. In the young stem it is present in patches as a single layer between the xylem and phloem. Later it forms a complete ring.

6.4.1.1 Formation of cambial ring

In dicot stems, the cells of cambium present between primary xylem and primary phloem is the **intrafascicular cambium**.

The cells of medullary cells, adjoining these intrafascicular cambium become meristematic and form the **interfascicular cambium**. Thus, a continuous ring of cambium is formed.

6.4.1.2 Activity of the cambial ring

The cambial ring becomes active and begins to cut off new cells, both towards the inner and the outer sides. The cells cut off towards pith, mature into **secondary xylem** and the cells cut off towards periphery mature into **secondary phloem**. The cambium is generally more active on the inner side than on the outer. As a result, the amount of secondary xylem produced is more than secondary phloem and soon forms a compact mass. The primary and secondary phloems get gradually crushed due to the continued formation and accumulation of secondary xylem. The primary xylem however remains more or less intact, in or around the centre. At some places, the cambium forms a narrow band of parenchyma, which passes through the secondary xylem and the secondary phloem in the radial directions. These are the **secondary medullary rays** (Figure 6.9).

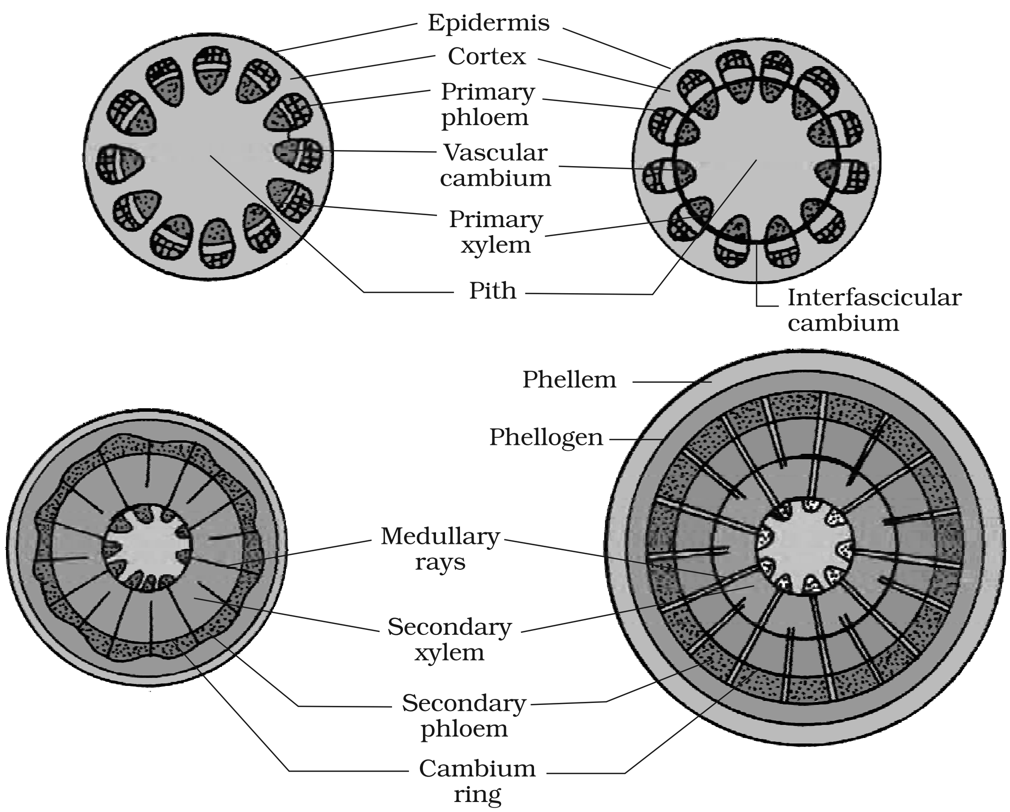


Figure 6.9 Secondary growth in a dicot stem (diagrammatic) – stages in transverse views

6.4.1.3 Spring wood and autumn wood

The activity of cambium is under the control of many physiological and environmental factors. In temperate regions, the climatic conditions are not uniform through the year. In the spring season, cambium is very active and produces a large number of xylary elements having vessels with wider cavities. The wood formed during this season is called **spring wood** or **early wood**. In winter, the cambium is less active and forms fewer xylary elements that have narrow vessels, and this wood is called **autumn wood** or **late wood**.

The spring wood is lighter in colour and has a lower density whereas the autumn wood is darker and has a higher density. The two kinds of woods that appear as alternate concentric rings, constitute an **annual ring.** Annual rings seen in a cut stem give an estimate of the age of the tree.

6.4.1.4 Heartwood and sapwood

In old trees, the greater part of secondary xylem is dark brown due to deposition of organic compounds like tannins, resins, oils, gums, aromatic substances and essential oils in the central or innermost layers of the stem. These substances make it hard, durable and resistant to the attacks of micro-organisms and insects. This region comprises dead elements with highly lignified walls and is called **heartwood.** The heartwood does not conduct water but it gives mechanical support to the stem. The peripheral region of the secondary xylem, is lighter in colour and is known as the **sapwood.** It is involved in the conduction of water and minerals from root to leaf.

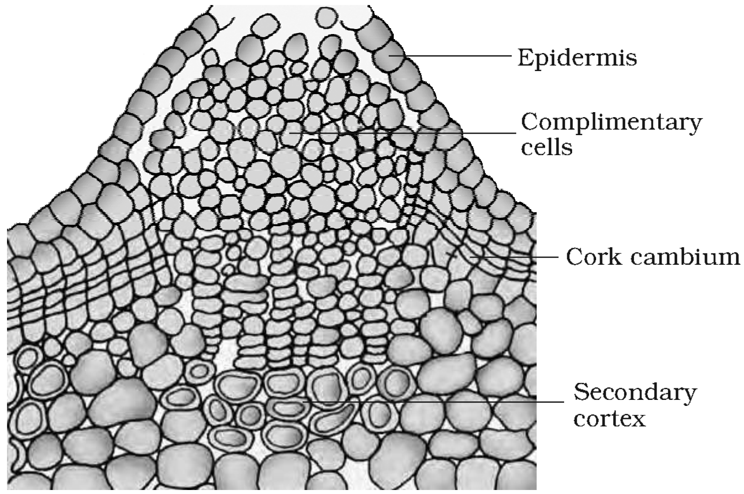
6.4.2 Cork Cambium

As the stem continues to increase in girth due to the activity of vascular cambium, the outer cortical and epidermis layers get broken and need to be replaced to provide new protective cell layers. Hence, sooner or later, another meristematic tissue called **cork cambium** or **phellogen** develops, usually in the cortex region. Phellogen is a couple of layers thick. It is made of narrow, thin-walled and nearly rectangular cells. Phellogen cuts off cells on both sides. The outer cells differentiate into **cork** or **phellem** while the inner cells differentiate into **secondary cortex** or **phelloderm.** The cork is impervious to water due to suberin deposition in the cell wall. The cells of secondary cortex are parenchymatous. Phellogen, phellem, and phelloderm are collectively known as **periderm**. Due to activity of the cork cambium, pressure builds up on the remaining layers peripheral to phellogen and ultimately these layers die and slough off. **Bark** is a non-technical term that refers to all tissues exterior to the vascular cambium, therefore including secondary phloem. Bark refers to a number of tissue types, viz., periderm and secondary phloem. Bark that is formed early in the season is called **early** or **soft** bark. Towards the end of the season **late** or **hard** bark is formed. *Name the various kinds of cell layers which constitute the bark.*

At certain regions, the phellogen cuts off closely arranged parenchymatous cells on the outer side instead of cork cells. These parenchymatous cells soon rupture the epidermis, forming a lens-shaped openings called lenticels. **Lenticels** permit the exchange of gases between the outer atmosphere and the internal tissue of the stem. These occur in most woody trees (Figure 6.10).

6.4.3 Secondary Growth in Roots

In the dicot root, the vascular cambium is completely secondary in origin. It originates from the tissue located just below the phloem bundles, a portion of pericycle tissue, above the protoxylem forming a complete and continuous wavy ring, which later becomes circular (Figure 6.11). Further events are similar to those already described above for a dicotyledon stem.



(a)

(b)

Figure 6.10 (a) Lenticel and (b) Bark

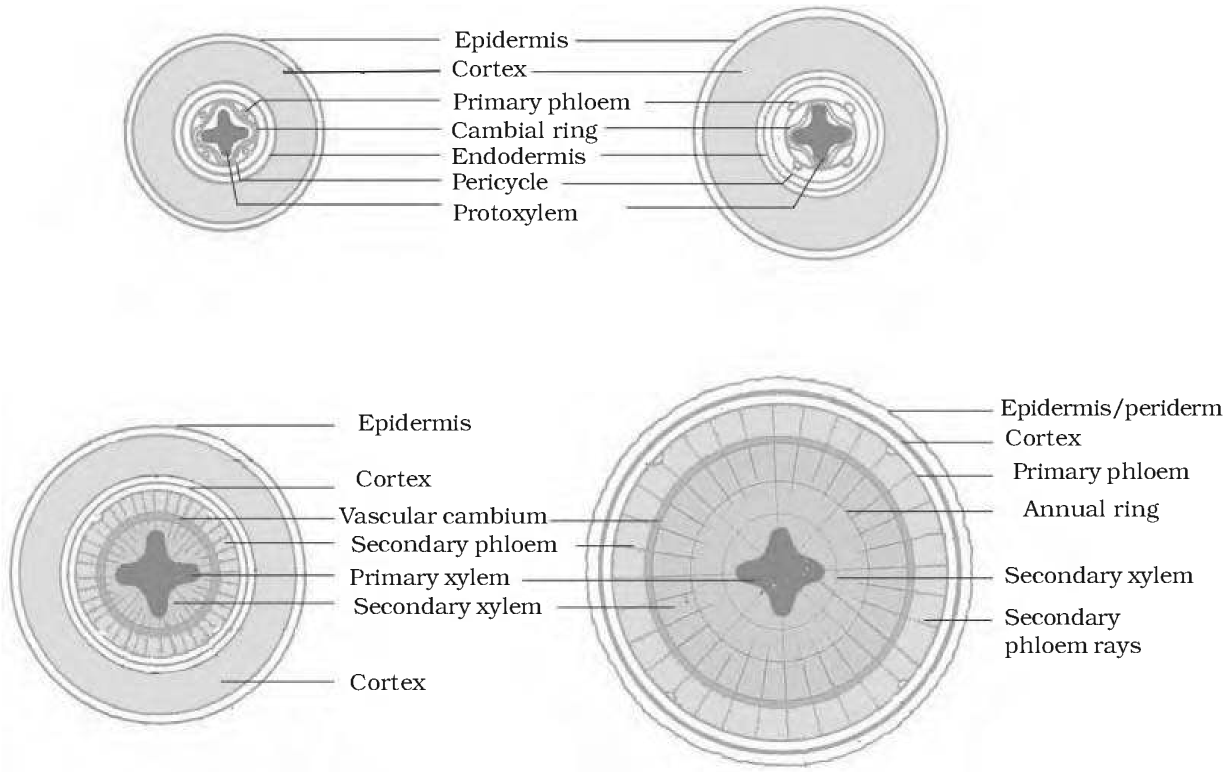


Figure 6.11 Different stages of the secondary growth in a typical dicot root

Secondary growth also occurs in stems and roots of gymnosperms. However, secondary growth does not occur in monocotyledons.

SUMMARY

Anatomically, a plant is made of different kinds of tissues. The plant tissues are broadly classified into meristematic (apical, lateral and intercalary) and permanent (simple and complex). Assimilation of food and its storage, transportation of water, minerals and photosynthates, and mechanical support are the main functions of tissues. There are three types of tissue systems – epidermal, ground and vascular. The epidermal tissue systems are made of epidermal cells, stomata and the epidermal appendages. The ground tissue system forms the main bulk of the plant. It is divided into three zones – cortex, pericycle and pith. The vascular tissue system is formed by the xylem and phloem. On the basis of presence of cambium, location of xylem and phloem, the vascular bundles are of different types. The vascular bundles form the conducting tissue and translocate water, minerals and food material.

Monocotyledonous and dicotyledonous plants show marked variation in their internal structures. They differ in type, number and location of vascular bundles. The secondary growth occurs in most of the dicotyledonous roots and stems and it increases the girth (diameter) of the organs by the activity of the vascular cambium and the cork cambium. The wood is actually a secondary xylem. There are different types of wood on the basis of their composition and time of production.

EXERCISES

1. State the location and function of different types of meristems.
2. Cork cambium forms tissues that form the cork. Do you agree with this statement? Explain.
3. Explain the process of secondary growth in the stems of woody angiosperms with the help of schematic diagrams. What is its significance?
4. Draw illustrations to bring out the anatomical difference between

   (a) Monocot root and Dicot root

   (b) Monocot stem and Dicot stem
5. Cut a transverse section of young stem of a plant from your school garden and observe it under the microscope. How would you ascertain whether it is a monocot stem or a dicot stem? Give reasons.
6. The transverse section of a plant material shows the following anatomical features - (a) the vascular bundles are conjoint, scattered and surrounded by a sclerenchymatous bundle sheaths. (b) phloem parenchyma is absent. What will you identify it as?
7. Why are xylem and phloem called complex tissues?
8. What is stomatal apparatus? Explain the structure of stomata with a labelled diagram.
9. Name the three basic tissue systems in the flowering plants. Give the tissue names under each system.
10. How is the study of plant anatomy useful to us?
11. What is periderm? How does periderm formation take place in the dicot stems?
12. Describe the internal structure of a dorsiventral leaf with the help of labelled diagrams.

CHAPTER 7

STRUCTURAL ORGANISATION IN ANIMALS

In the preceding chapters you came across a large variety of organisms, both unicellular and multicellular, of the animal kingdom. In unicellular organisms, all functions like digestion, respiration and reproduction are performed by a single cell. In the complex body of multicellular animals the same basic functions are carried out by different groups of cells in a well organised manner. The body of a simple organism like *Hydra* is made of different types of cells and the number of cells in each type can be in thousands. The human body is composed of billions of cells to perform various functions. How do these cells in the body work together? In multicellular animals, a group of similar cells alongwith intercellular substances perform a specific function. Such an organisation is called **tissue**.

You may be surprised to know that all complex animals consist of only four basic types of tissues. These tissues are organised in specific proportion and pattern to form an organ like stomach, lung, heart and kidney. When two or more organs perform a common function by their physical and/or chemical interaction, they together form organ system, e.g., digestive system, respiratory system, etc. Cells, tissues, organs and organ systems split up the work in a way that exhibits division of labour and contribute to the survival of the body as a whole.

7.1 ANIMAL TISSUES

The structure of the cells vary according to their function. Therefore, the tissues are different and are broadly classified into four types : (i) Epithelial, (ii) Connective, (iii) Muscular and (iv) Neural.

7.1.1 Epithelial Tissue

We commonly refer to an epithelial tissue as epithelium (pl.: epithelia). This tissue has a free surface, which faces either a body fluid or the outside environment and thus provides a covering or a lining for some part of the body. The cells are compactly packed with little intercellular matrix. There are two types of epithelial tissues namely **simple epithelium** and **compound epithelium**. Simple epithelium is composed of a single layer of cells and functions as a lining for body cavities, ducts, and tubes. The compound epithelium consists of two or more cell layers and has protective function as it does in our skin.

On the basis of structural modification of the cells, simple epithelium is further divided into three types. These are (i) Squamous, (ii) Cuboidal, (iii) Columnar (Figure 7.1).

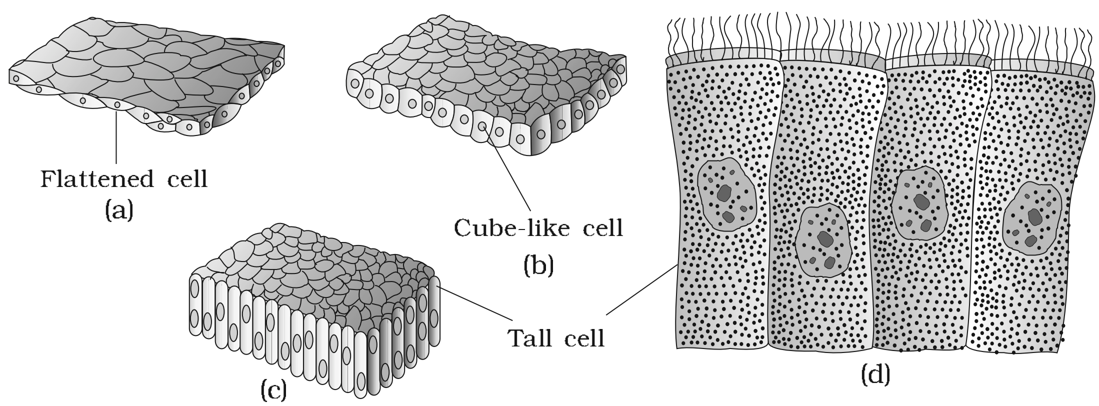


Figure 7.1 Simple epithelium: (a) Squamous (b) Cuboidal (c) Columnar (d) Columnar cells bearing cilia

The **squamous epithelium** is made of a single thin layer of flattened cells with irregular boundaries. They are found in the walls of blood vessels and air sacs of lungs and are involved in a functions like forming a diffusion boundary. The **cuboidal epithelium** is composed of a single layer of cube-like cells. This is commonly found in ducts of glands and tubular parts of nephrons in kidneys and its main functions are secretion and absorption. The epithelium of proximal convoluted tubule (PCT) of nephron in the kidney has microvilli. The **columnar epithelium** is composed of a single layer of tall and slender cells. Their nuclei are located at the base. Free surface may have microvilli. They are found in the lining of stomach and intestine and help in secretion and absorption. If the columnar or cuboidal cells bear cilia on their free surface they are called **ciliated epithelium** (Figure 7.1d). Their function is to move particles or mucus in a specific direction over the epithelium. They are mainly present in the inner surface of hollow organs like bronchioles and fallopian tubes.

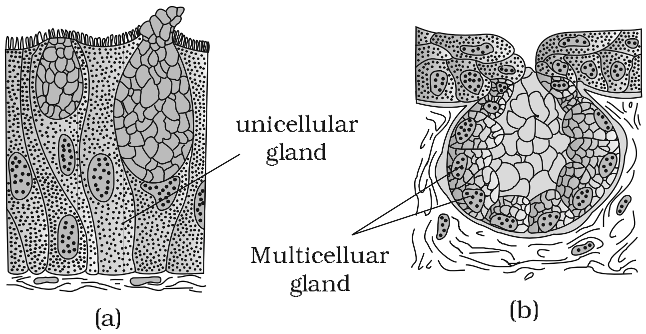


Figure 7.2 Glandular epithelium : (a) Unicellular (b) Multicellular

Some of the columnar or cuboidal cells get specialised for secretion and are called **glandular epithelium** (Figure 7.2). They are mainly of two types: unicellular, consisting of isolated glandular cells (goblet cells of the alimentary canal), and multicellular, consisting of cluster of cells (salivary gland). On the basis of the mode of pouring of their secretions, glands are divided into two categories namely **exocrine** and **endocrine** glands. Exocrine glands secrete mucus, saliva, earwax, oil, milk, digestive enzymes and other cell products. These products are released through ducts or tubes. In contrast, endocrine glands do not have ducts. Their products called hormones are secreted directly into the fluid bathing the gland.

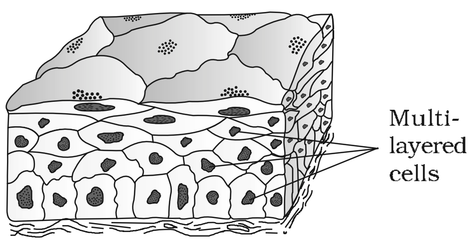


Figure 7.3 Compound epithelium

Compound epithelium is made of more than one layer (multi-layered) of cells and thus has a limited role in secretion and absorption (Figure 7.3). Their main function is to provide protection against chemical and mechanical stresses. They cover the dry surface of the skin, the moist surface of buccal cavity, pharynx, inner lining of ducts of salivary glands and of pancreatic ducts.

All cells in epithelium are held together with little intercellular material. In nearly all animal tissues, specialised junctions provide both structural and functional links between its individual cells. Three types of cell junctions are found in the epithelium and other tissues. These are called as tight, adhering and gap junctions. **Tight junctions** help to stop substances from leaking across a tissue. **Adhering junctions** perform cementing to keep neighbouring cells together. **Gap junctions** facilitate the cells to communicate with each other by connecting the cytoplasm of adjoining cells, for rapid transfer of ions, small molecules and sometimes big molecules.

7.1.2 Connective Tissue

Connective tissues are most abundant and widely distributed in the body of complex animals. They are named connective tissues because of their special function of linking and supporting other tissues/organs of the body. They range from soft connective tissues to specialised types, which

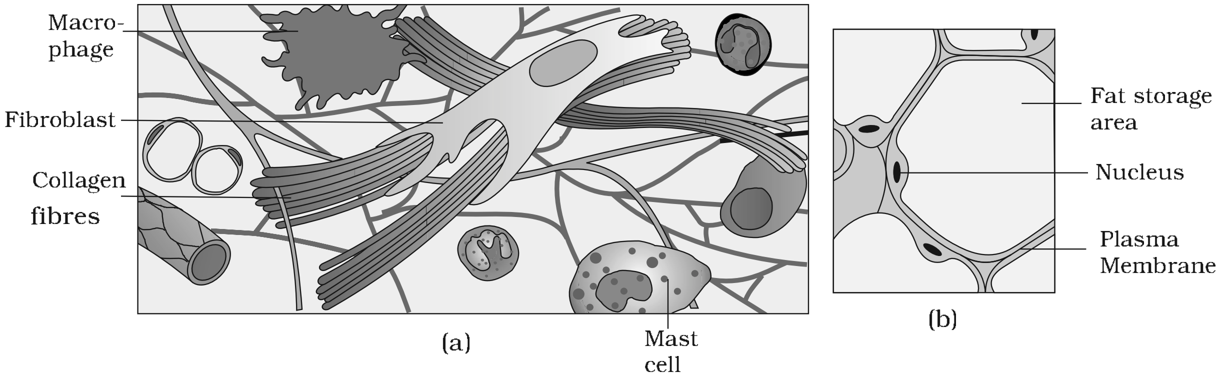


Figure 7.4 Loose connective tissue : (a) Areolar tissue (b) Adipose tissue

include cartilage, bone, adipose, and blood. In all connective tissues except blood, the cells secrete fibres of structural proteins called collagen or elastin. The fibres provide strength, elasticity and flexibility to the tissue. These cells also secrete modified polysaccharides, which accumulate between cells and fibres and act as matrix (ground substance). Connective tissues are classified into three types: (i) **Loose connective tissue,** (ii) **Dense connective tissue** and (iii) **Specialised connective tissue**.

Loose connective tissue has cells and fibres loosely arranged in a semi-fluid ground substance, for example, **areolar tissue** present beneath the skin (Figure 7.4). Often it serves as a support framework for epithelium. It contains fibroblasts (cells that produce and secrete fibres), macrophages and mast cells. **Adipose tissue** is another type of loose connective tissue located mainly beneath the skin. The cells of this tissue are specialised to store fats. The excess of nutrients which are not used immediately are converted into fats and are stored in this tissue.

Fibres and fibroblasts are compactly packed in the **dense connective tissues**. Orientation of fibres show a regular or irregular pattern and are called **dense regular** and **dense irregular tissues**. In the dense **regular connective tissues**, the collagen fibres are present in rows between many parallel bundles of fibres. Tendons, which attach skeletal muscles to bones and ligaments which attach one bone to another are examples of this tissue. Dense irregular connective tissue has fibroblasts and many fibres (mostly collagen) that are oriented differently (Figure 7.5). This tissue is present in the skin. Cartilage,

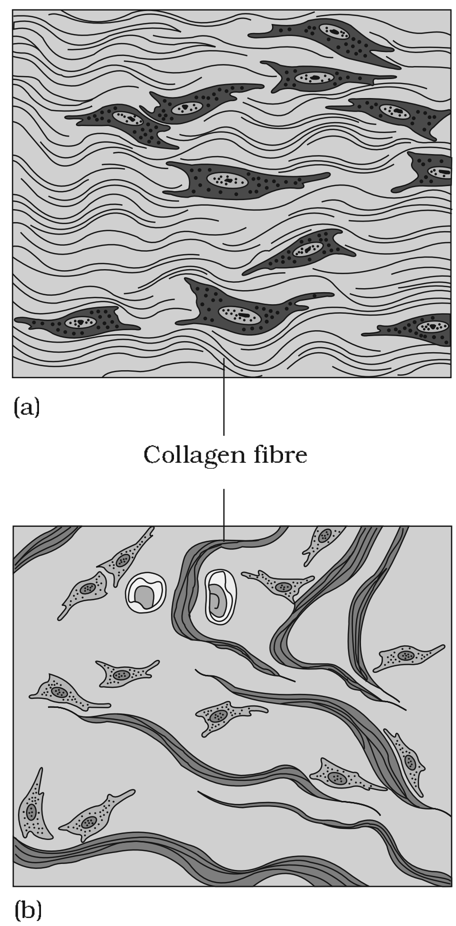


Figure 7.5 Dense connective tissue:
(a) Dense regular
(b) Dense irregular

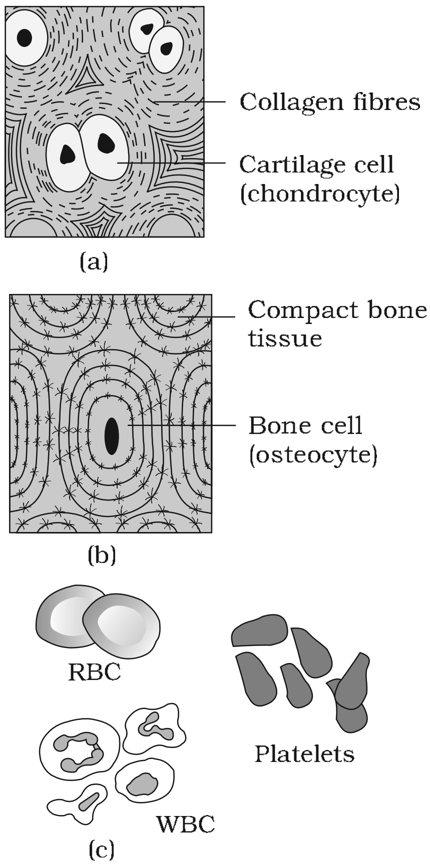


Figure 7.6 Specialised connective tissues : (a) Cartilage (b) Bone (c) Blood

bones and blood are various types of **specialised connective tissues**.

The intercellular material of **cartilage** is solid and pliable and resists compression. Cells of this tissue (chondrocytes) are enclosed in small cavities within the matrix secreted by them (Figure 7.6a). Most of the cartilages in vertebrate embryos are replaced by bones in adults. Cartilage is present in the tip of nose, outer ear joints, between adjacent bones of the vertebral column, limbs and hands in adults.

Bones have a hard and non-pliable ground substance rich in calcium salts and collagen fibres which give bone its strength (Figure 7.6b). It is the main tissue that provides structural frame to the body. Bones support and protect softer tissues and organs. The bone cells (osteocytes) are present in the spaces called lacunae. Limb bones, such as the long bones of the legs, serve weight-bearing functions. They also interact with skeletal muscles attached to them to bring about movements. The bone marrow in some bones is the site of production of blood cells.

Blood is a fluid connective tissue containing plasma, red blood cells (RBC), white blood cells (WBC) and platelets (Figure 7.6c). It is the main circulating fluid that helps in the transport of various substances. You will learn more about blood in Chapters 17 and 18.

7.1.3 Muscle Tissue

Each muscle is made of many long, cylindrical fibres arranged in parallel arrays. These fibres are composed of numerous fine fibrils, called myofibrils. Muscle fibres contract (shorten) in response to stimulation, then relax (lengthen) and return to their uncontracted state in a coordinated fashion. Their action moves the body to adjust to the changes in the environment and to maintain the positions of the various parts of the body. In general, muscles play an active role in all the movements of the body. Muscles are of three types, skeletal, smooth, and cardiac.

Skeletal muscle tissue is closely attached to skeletal bones. In a typical muscle such as the biceps, striated (striped) skeletal muscle fibres are bundled together in a parallel fashion (Figure 7.7a). A sheath of tough connective tissue encloses several bundles of muscle fibres (You will learn more about this in Chapter 20).

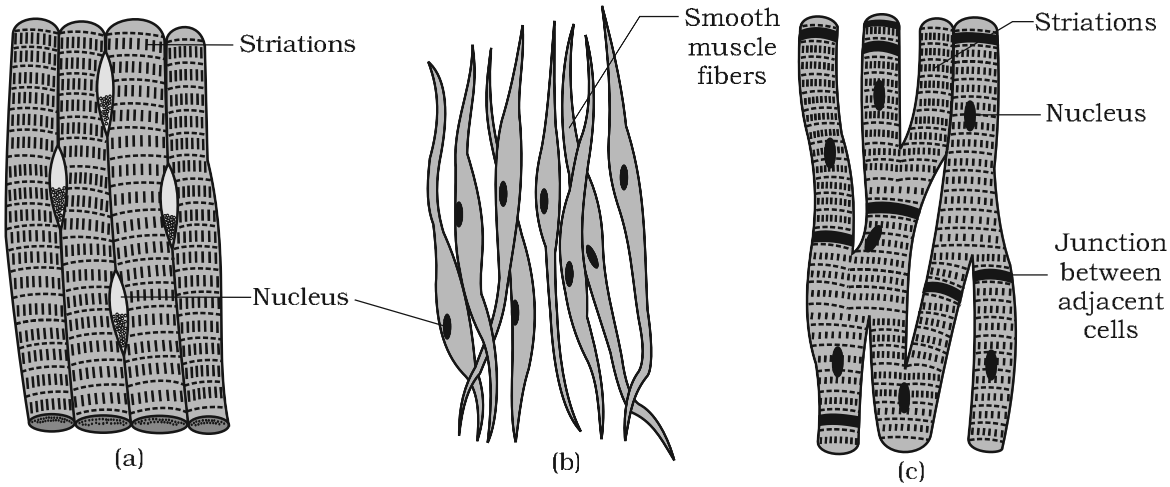


Figure 7.7 Muscle tissue : (a) Skeletal (striated) muscle tissue (b) Smooth muscle tissue (c) Cardiac muscle tissue

The **smooth muscle** fibres taper at both ends (fusiform) and do not show striations (Figure 7.7b). Cell junctions hold them together and they are bundled together in a connective tissue sheath. The wall of internal organs such as the blood vessels, stomach and intestine contains this type of muscle tissue. Smooth muscles are 'involuntary' as their functioning cannot be directly controlled. We usually are not able to make it contract merely by thinking about it as we can do with skeletal muscles.

Cardiac muscle tissue is a contractile tissue present only in the heart. Cell junctions fuse the plasma membranes of cardiac muscle cells and make them stick together (Figure 7.7c). Communication junctions (intercalated discs) at some fusion points allow the cells to contract as a unit, i.e., when one cell receives a signal to contract, its neighbours are also stimulated to contract.

7.1.4 Neural Tissue

Neural tissue exerts the greatest control over the body's responsiveness to changing conditions. Neurons, the unit of neural system are excitable cells (Figure 7.8). The neuroglial cell which constitute the rest of the neural system protect and support neurons. Neuroglia make up more than one-half the volume of neural tissue in our body.

When a neuron is suitably stimulated, an electrical disturbance is generated which swiftly travels along its plasma

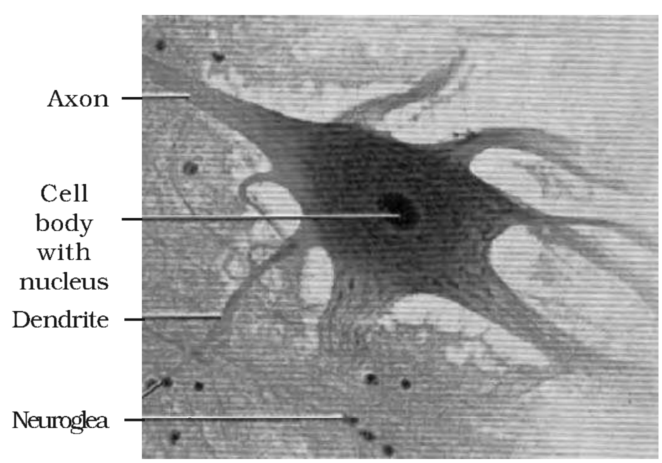


Figure 7.8 Neural tissue (Neuron with neuroglea)

membrane. Arrival of the disturbance at the neuron's endings, or output zone, triggers events that may cause stimulation or inhibition of adjacent neurons and other cells (You will study the details in Chapter 21).

7.2 Organ and Organ System

The basic tissues mentioned above organise to form organs which in turn associate to form organ systems in the multicellular organisms. Such an organisation is essential for more efficient and better coordinated activities of millions of cells constituting an organism. Each organ in our body is made of one or more type of tissues. For example, our heart consists of all the four types of tissues, i.e., epithelial, connective, muscular and neural. We also notice, after some careful study that the complexity in organ and organ systems displays certain discernable trend. This discernable trend is called evolutionary trend (You will study the details in class XII). You are being introduced to morphology and anatomy of three organisms at different evolutionary levels to show their organisation and functioning. Morphology refers to study of form or externally visible features. In the case of plants or microbes, the term morphology precisely means only this. In case of animals this refers to the external appearance of the organs or parts of the body. The word anatomy conventionally is used for the study of morphology of internal organs in the animals. You will learn the morphology and anatomy of earthworm, cockroach and frog representing invertebrates and vertebrates.

7.3 Earthworm

Earthworm is a reddish brown terrestrial invertebrate that inhabits the upper layer of the moist soil. During day time, they live in burrows made by boring and swallowing the soil. In the gardens, they can be traced by their faecal deposits known as worm castings. The common Indian earthworms are *Pheretima* and *Lumbricus.*

7.3.1 Morphology

Earthworms have long cylindrical body. The body is divided into more than hundred short segments which are similar (metameres about 100-120 in number). The dorsal surface of the body is marked by a dark median mid dorsal line (dorsal blood vessel) along the longitudinal axis of the body. The ventral surface is distinguished by the presence of genital openings (pores). Anterior end consists of the mouth and the prostomium, a lobe which serves as a covering for the mouth and as a wedge to force open cracks in the soil into which the earthworm may crawl. The prostomium is sensory in function. The first body segment is called the peristomium (buccal segment) which contains the mouth. In a mature worm, segments

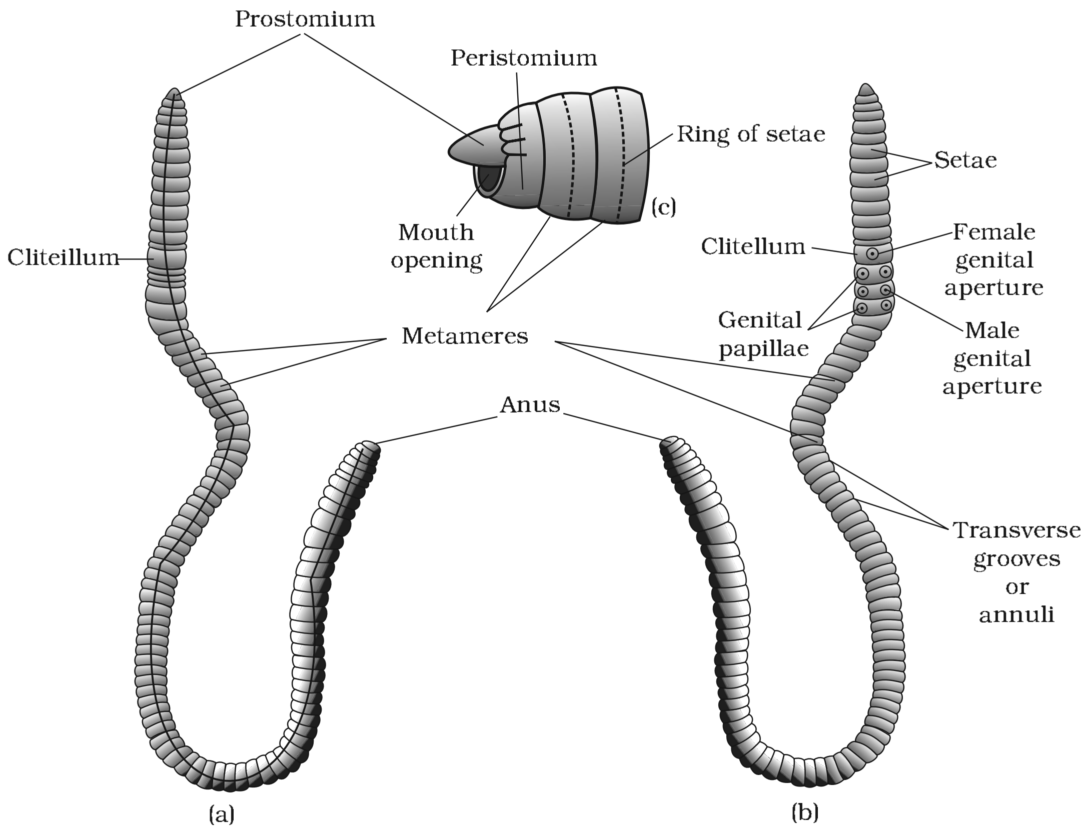


Figure 7.9 Body of earthworm : (a) dorsal view (b) ventral view (c) lateral view showing mouth opening

14-16 are covered by a prominent dark band of glandular tissue called **clitellum**. Thus the body is divisible into three prominent regions – preclitellar, clitellar and postclitellar segments (Figure 7.9).

Four pairs of spermathecal apertures are situated on the ventro-lateral sides of the intersegmental grooves, i.e., 5^{th} -9^{th} segments. A single female genital pore is present in the mid-ventral line of 14^{th} segment. A pair of male genital pores are present on the ventro-lateral sides of the 18^{th} segment. Numerous minute pores called nephridiopores open on the surface of the body. In each body segment, except the first, last and clitellum, there are rows of S-shaped **setae**, embedded in the epidermal pits in the middle of each segment. Setae can be extended or retracted. Their principal role is in locomotion.

7.3.2 Anatomy

The body wall of the earthworm is covered externally by a thin non-cellular cuticle below which is the epidermis, two muscle layers (circular and longitudinal) and an innermost coelomic epithelium. The epidermis is made

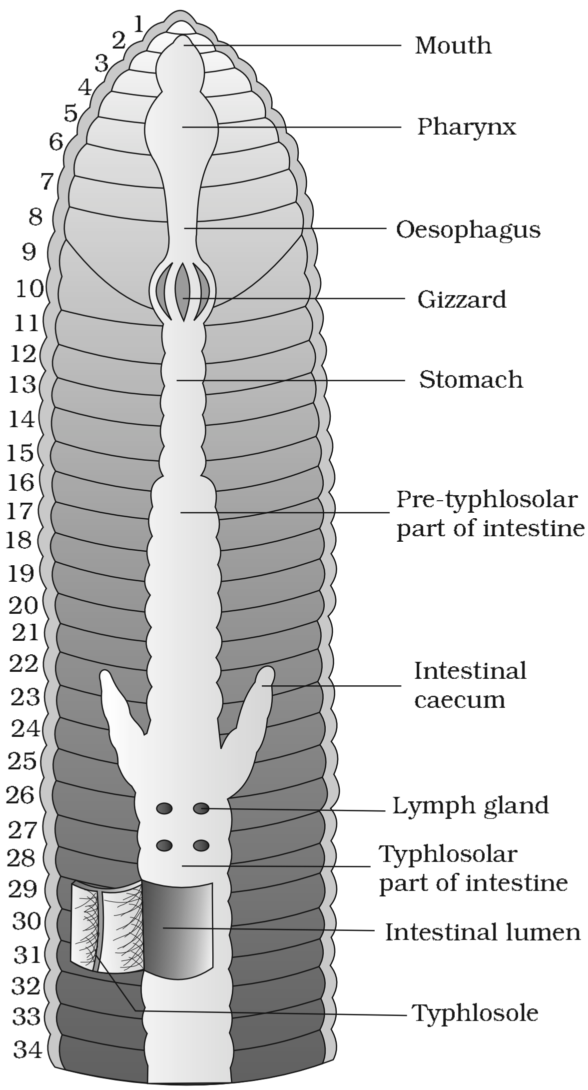


Figure 7.10 Alimentary canal of earthworm

up of a single layer of columnar epithelial cells which contain secretory gland cells.

The alimentary canal is a straight tube and runs between first to last segment of the body. (Figure 7.10). A terminal mouth opens into the buccal cavity (1-3 segments) which leads into muscular pharynx. A small narrow tube, oesophagus (5-7 segments), continues into a muscular gizzard (8-9 segments). It helps in grinding the soil particles and decaying leaves, etc. The stomach extends from 9-14 segments. The food of the earthworm is decaying leaves and organic matter mixed with soil. Calciferous glands, present in the stomach, neutralise the humic acid present in humus. Intestine starts from the 15^{th} segment onwards and continues till the last segment. A pair of short and conical intestinal caecae project from the intestine on the 26^{th} segment. The characteristic feature of the intestine between 26-35 segments is the presence of internal median fold of dorsal wall called **typhlosole**. This increases the effective area of absorption in the intestine. The alimentary canal opens to the exterior by a small rounded aperture called anus. The ingested organic rich soil passes through the digestive tract where digestive enzymes breakdown complex food into smaller absorbable units. These simpler molecules are absorbed through intestinal membranes and are utilised.

Pheretima exhibits a closed type of blood vascular system, consisting of blood vessels, capillaries and heart. (Figure 7.11). Due to closed circulatory system, blood is confined to the heart and blood vessels. Contractions keep blood circulating in one direction. Smaller blood vessels supply the gut, nerve cord, and the body wall. Blood glands are present on the 4^{th}, 5^{th} and 6^{th} segments. They produce blood cells and haemoglobin which is dissolved in blood plasma. Blood cells are phagocytic in nature. Earthworms lack specialised breathing devices. Respiratory exchange occurs through moist body surface into their blood stream.

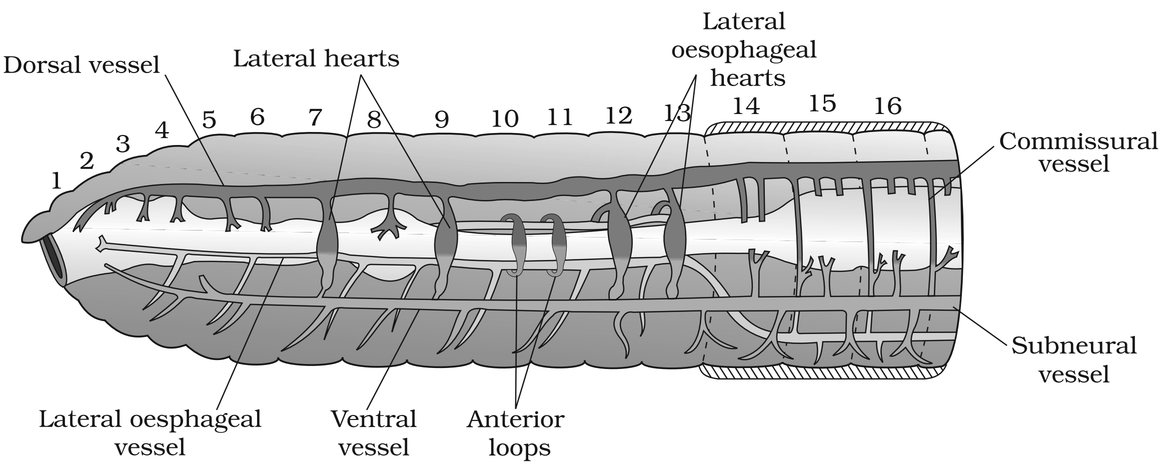


Figure 7.11 Closed circulatory system

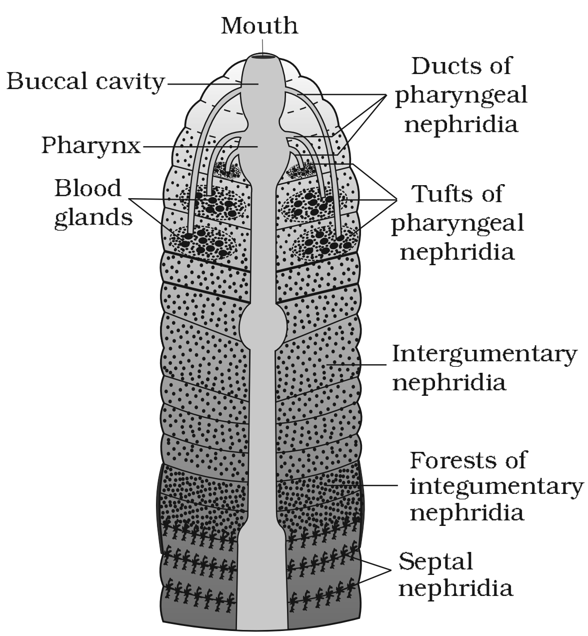


Figure 7.12 Nephridial system in earthworm

The excretory organs occur as segmentally arranged coiled tubules called nephridia (sing.: *nephridium*). They are of three types: (i) septal nephridia, present on both the sides of intersegmental septa of segment 15 to the last that open into intestine, (ii) integumentary nephridia, attached to lining of the body wall of segment 3 to the last that open on the body surface and (iii) pharyngeal nephridia, present as three paired tufts in the 4^{th}, 5^{th} and 6^{th} segments (Figure 7.12). These different types of nephridia are basically similar in structure. Nephridia regulate the volume and composition of the body fluids. A nephridium starts out as a funnel that collects excess fluid from coelomic chamber. The funnel connects with a tubular part of the nephridium which delivers the wastes through a pore to the surface in the body wall into the digestive tube.

Nervous system is basically represented by ganglia arranged segmentwise on the ventral paired nerve cord. The nerve cord in the anterior region (3^{rd} and 4^{th} segments) bifurcates, laterally encircling the pharynx and joins the cerebral ganglia dorsally to form a nerve ring. The cerebral ganglia alongwith other nerves in the ring integrate sensory input as well as command muscular responses of the body.

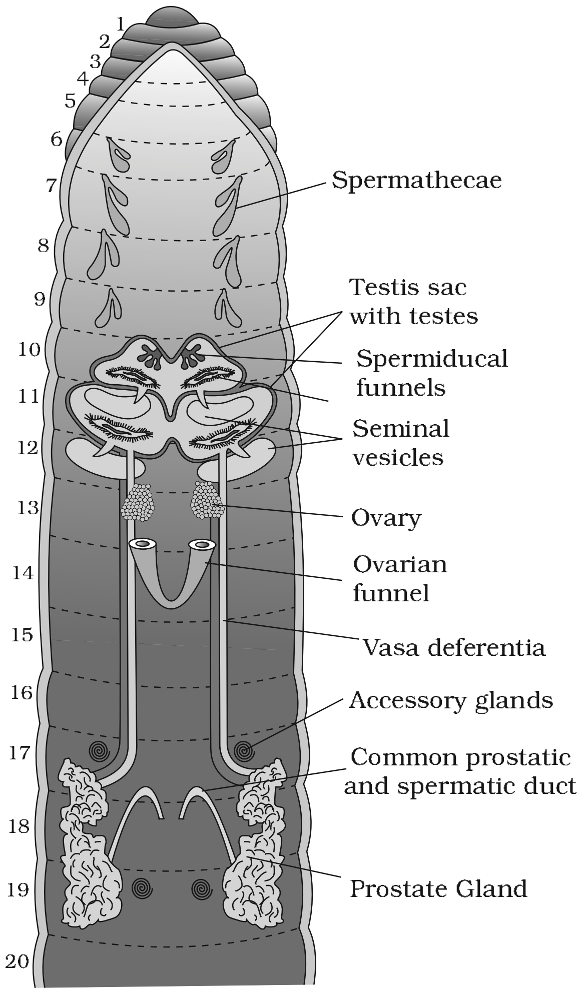


Figure 7.13 Reproductive system of earthworm

Sensory system does not have eyes but does possess light and touch sensitive organs (receptor cells) to distinguish the light intensities and to feel the vibrations in the ground. Worms have specialised chemoreceptors (taste receptors) which react to chemical stimuli. These sense organs are located on the anterior part of the worm.

Earthworm is hermaphrodite (bisexual), i.e., testes and ovaries are present in the same individual (Figure 7.13). There are two pairs of testes present in the 10^{th} and 11^{th} segments. Their vasa deferentia run up to the 18^{th} segment where they join the prostatic duct. Two pairs of accessory glands are present one pair each in the 17^{th} and 19^{th} segments. The common prostrate and spermatic duct (vary differential) opens to the exterior by a pair of male genital pores on the ventro-lateral side of the 18^{th} segment. Four pairs of spermathecae are located in 6^{th}-9^{th} segments (one pair in each segment). They receive and store spermatozoa during copulation. One pair of ovaries is attached at the inter-segmental septum of the 12^{th} and 13^{th} segments. Ovarian funnels are present beneath the ovaries which continue into oviduct, join together and open on the ventral side as a single median female genital pore on the 14^{th} segment.

A mutual exchange of sperm occurs between two worms during mating. One worm has to find another worm and they mate juxtaposing opposite gonadal openings exchanging packets of sperms called spermatophores. Mature sperm and egg cells and nutritive fluid are deposited in cocoons produced by the gland cells of clitellum. Fertilisation and development occur within the cocoons which are deposited in soil. The ova (eggs) are fertilised by the sperm cells within the cocoon which then slips off the worm and is deposited in or on the soil. The cocoon holds the worm embryos. After about 3 weeks, each cocoon produces two to twenty baby worms with an average of four. Earthworms development is direct, i.e., there is no larva formed.

Earthworms are known as 'friends of farmers' because they make burrows in the soil and make it porous which helps in respiration and penetration of the developing plant roots. The process of increasing fertility of soil by the earthworms is called vermicomposting. They are also used as bait in game fishing.

7.4 COCKROACH

Cockroaches are brown or black bodied animals that are included in class Insecta of Phylum Arthropoda. Bright yellow, red and green coloured cockroaches have also been reported in tropical regions. Their size ranges from inches to 3 inches (0.6-7.6 cm) and have long antenna, legs and flat extension of the upper body wall that conceals head. They are nocturnal omnivores that live in damp places throughout the world. They have become residents of human homes and thus are serious pests and vectors of several diseases.

7.4.1 Morphology

The adults of the common species of cockroach, *Periplaneta americana* are about 34-53 mm long with wings *that extend beyond the tip of the abdomen in males.* The body of the cockroach is segmented and divisible into three distinct regions – head, thorax and abdomen (Figure 7.14). The entire body is covered by a hard chitinous exoskeleton (brown in colour). In each segment, exoskeleton has hardened plates called sclerites (tergites dorsally and sternites ventrally) that are joined to each other by a thin and flexible articular membrane (arthrodial membrane).

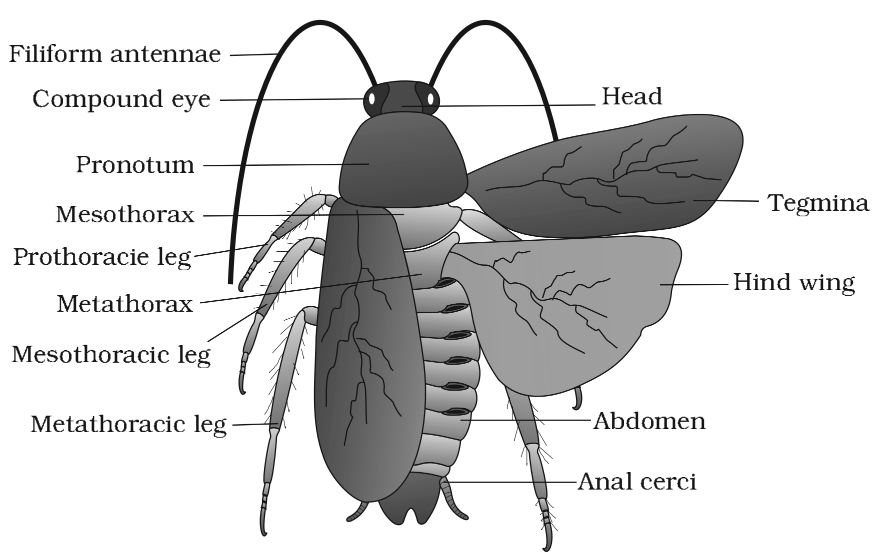


Figure 7.14 External features of cockroach

Head is triangular in shape and lies anteriorly at right angles to the longitudinal body axis. It is formed by the fusion of six segments and shows great mobility in all directions due to flexible neck (Figure 7.15). The head capsule bears a pair of compound eyes. A pair of thread like antennae arise from membranous sockets lying in front of eyes. Antennae have sensory receptors that help in monitoring the environment. Anterior end of the head bears appendages forming biting and chewing type of mouth parts. The mouthparts consisting of a labrum (upper lip), a pair of mandibles, a pair of maxillae and a labium (lower lip). A median flexible lobe, acting as tongue (hypopharynx), lies within the cavity enclosed by the mouthparts (Figure 7.15b). Thorax consists of three parts – prothorax, mesothorax and metathorax. The head is connected with thorax by a short extension of the prothorax known as the neck. Each thoracic segment bears a pair of walking legs. The first pair of wings arises from mesothorax and the second pair from metathorax. Forewings (mesothoracic) called tegmina are opaque dark and leathery and cover the hind wings when at rest. The hind wings are transparent, membranous and are used in flight.

The abdomen in both males and females consists of 10 segments. In females, the 7^{th} sternum is boat shaped and together with the 8^{th} and 9^{th} sterna forms a brood or genital pouch whose anterior part contains female gonopore, spermathecal pores and collateral glands. In males, genital pouch or chamber lies at the hind end of abdomen bounded dorsally by 9^{th} and 10^{th} terga and ventrally by the 9^{th} sternum. It contains dorsal anus, ventral male genital pore and gonapophysis. Males bear a pair of short, thread-like anal styles which are absent in females. In both sexes, the 10^{th} segment bears a pair of jointed filamentous structures called anal cerci.

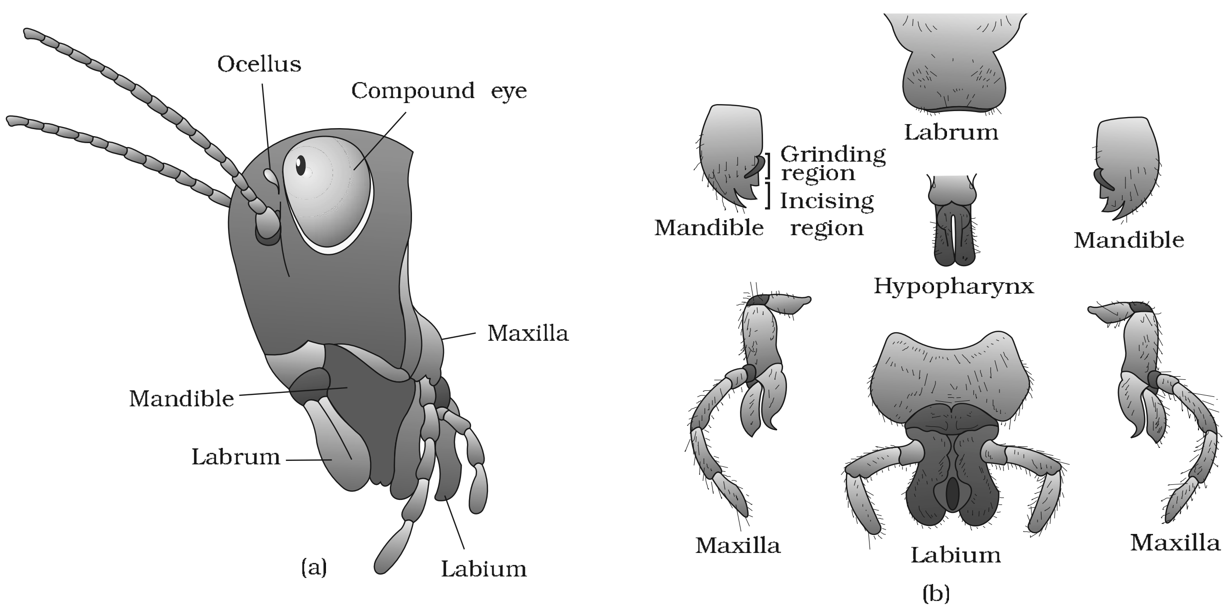


Figure 7.15 Head region of cockroach : (a) parts of head region (b) mouth parts

7.4.2 Anatomy

The alimentary canal present in the body cavity is divided into three regions: foregut, midgut and hindgut (Figure 7.16). The mouth opens into a short tubular pharynx, leading to a narrow tubular passage called oesophagus. This in turn opens into a sac like structure called crop used for storing of food. The crop is followed by gizzard or proventriculus. It has an outer layer of thick circular muscles and thick inner culicle forming six highly chitinous plate called teeth. Gizzard helps in grinding the food particles. The entire foregut is lined by cuticle. A ring of 6-8 blind tubules called hepatic or gastric caecae is present at the junction of foregut and midgut, which secrete digestive juice. At the junction of midgut and hindgut is present another ring of 100-150 yellow coloured thin filamentous **Malphigian tubules**. They help in removal of excretory products from haemolymph. The hindgut is broader than midgut and is differentiated into ileum, colon and rectum. The rectum opens out through anus.

Blood vascular system of cockroach is an open type (Figure 7.17). Blood vessels are poorly developed and open into space (haemocoel). Visceral organs located in the haemocoel are bathed in blood (haemolymph). The haemolymph is composed of colourless plasma and haemocytes. Heart of cockroach consists of elongated muscular tube lying along mid dorsal line of thorax and abdomen. It is differentiated into funnel shaped chambers with ostia on either side. Blood from sinuses enter heart through ostia and is pumped anteriorly to sinuses again.

The respiratory system consists of a network of trachea, that open through 10 pairs of small holes called spiracles present on the lateral side of the body. Thin branching tubes (tracheal tubes subdivided into tracheoles) carry oxygen from the air to all the parts. The

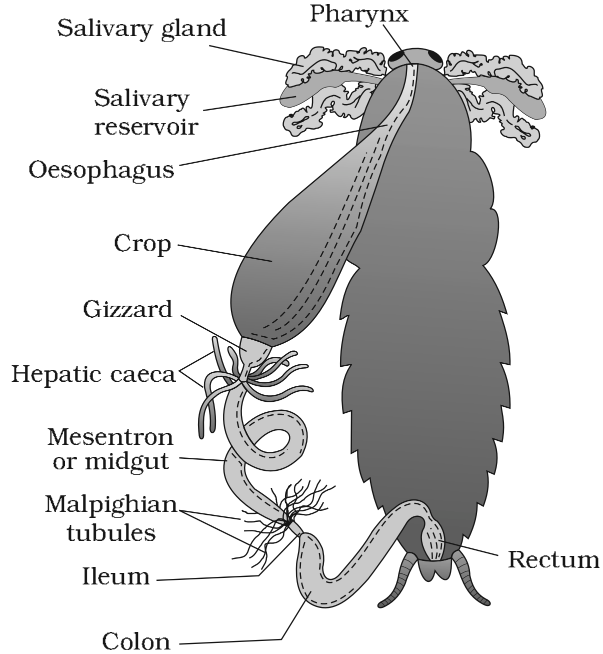


Figure 7.16 Alimentary canal of cockroach

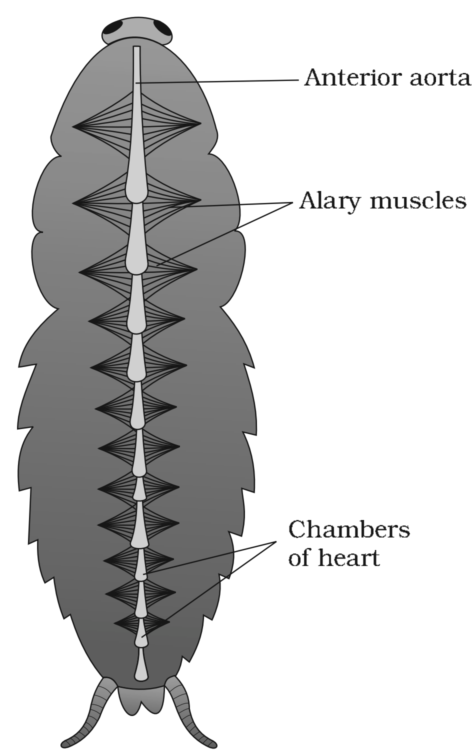


Figure 7.17 Open circulatory system of cockroach

opening of the spiracles is regulated by the sphincters. Exchange of gases take place at the tracheoles by diffusion.

Excretion is performed by Malpighian tubules. Each tubule is lined by glandular and ciliated cells. They absorb nitrogenous waste products and convert them into uric acid which is excreted out through the hindgut. Therefore, this insect is called **uricotelic**. In addition, the fat body, nephrocytes and urecose glands also help in excretion.

The nervous system of cockroach consists of a series of fused, segmentally arranged ganglia joined by paired longitudinal connectives on the ventral side. Three ganglia lie in the thorax, and six in the abdomen. The nervous system of cockroach is spread throughout the body. The head holds a bit of a nervous system while the rest is situated along the ventral (belly-side) part of its body. So, now you understand that if the head of a cockroach is cut off, it will still live for as long as one week. In the head region, the brain is represented by supra-oesophageal ganglion which supplies nerves to antennae and compound eyes. In cockroach, the sense organs are antennae, eyes, maxillary palps, labial palps, anal cerci, etc. The compound eyes are situated at the dorsal surface of the head. Each eye consists of about 2000 hexagonal ommatidia (sing.: *ommatidium*). With the help of several ommatidia, a cockroach can receive several images of an object. This kind of vision is known as mosaic vision with more sensitivity but less resolution, being common during night (hence called nocturnal vision).

Cockroaches are dioecious and both sexes have well developed reproductive organs (Figure 7.18). Male reproductive system consists of a pair of testes lying one on each lateral side in the 4^{th} -6^{th} abdominal segments. From each testis arises a thin vas deferens, which opens into ejaculatory duct through seminal vesicle. The ejaculatory duct opens into male gonopore situated ventral to anus. A characteristic mushroom-shaped gland is present in the 6^{th}-7^{th} abdominal segments which functions as an accessory reproductive gland. The external genitalia are represented by male gonapophysis or phallomere (chitinous asymmetrical structures, surrounding the male gonopore). The sperms are stored in the seminal vesicles and are glued together in the form of bundles called spermatophores which are discharged during copulation. The female reproductive sysytem consists of two large ovaries, lying laterally in the 2^{nd} – 6^{th} abdominal segments. Each ovary is formed of a group of eight ovarian tubules or ovarioles, containing a chain of developing ova. Oviducts of each ovary unite into a single median oviduct (also called vagina) which opens into the genital chamber. A pair of spermatheca is present in the 6^{th} segment which opens into the genital chamber.

Sperms are transferred through spermatophores. Their fertilised eggs are encased in capsules called oothecae. Ootheca is a dark reddish to blackish brown capsule, about 3/8" (8 mm) long. They are dropped or

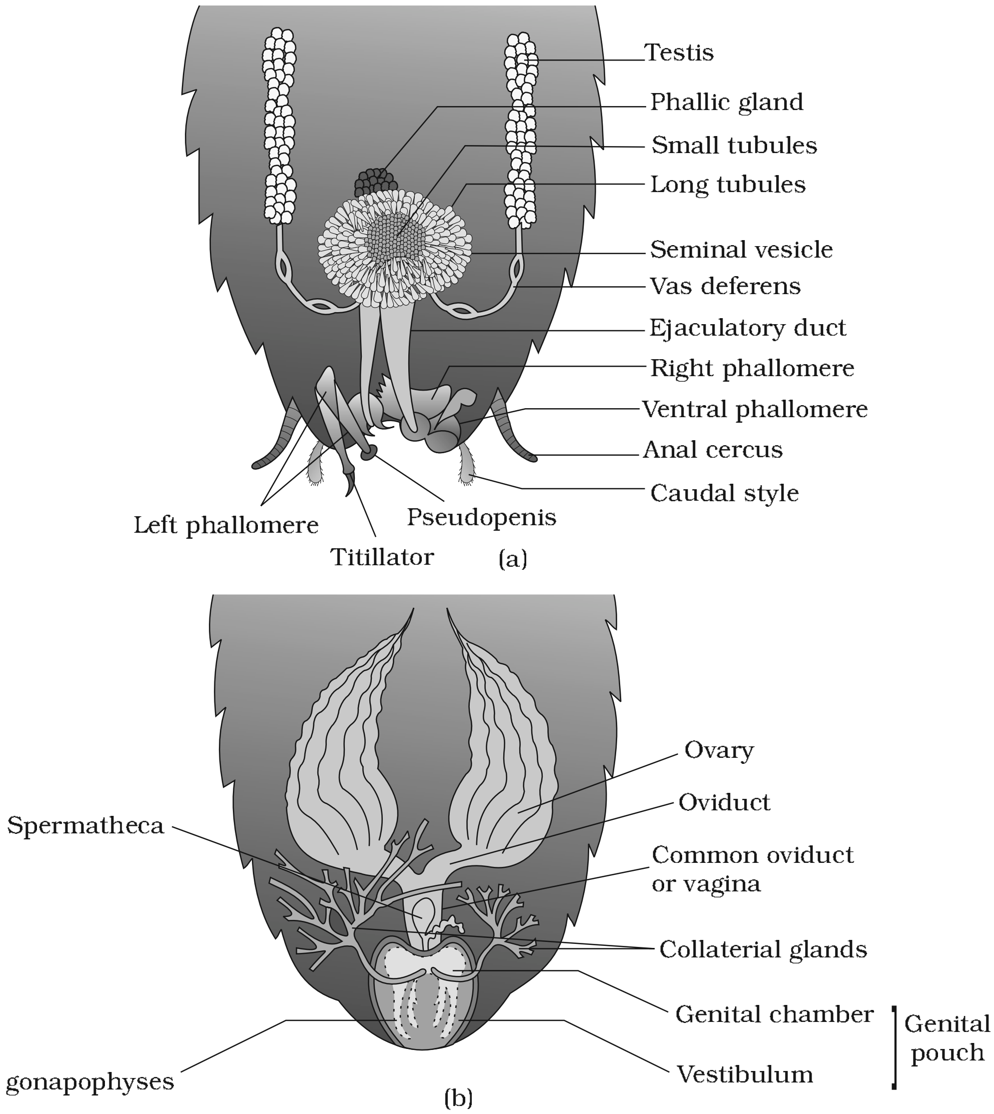


Figure 7.18 Reproductive system of cockroach : (a) male (b) female

glued to a suitable surface, usually in a crack or crevice of high relative humidity near a food source. On an average, females produce 9-10 oothecae, each containing 14-16 eggs. The development of *P. americana* is paurometabolous, meaning there is development through nymphal stage. The nymphs look very much like adults. The nymph grows by moulting about 13 times to reach the adult form. The next to last nymphal stage has wing pads but only adult cockroaches have wings.

Many species of cockroaches are wild and are of no economic importance. A few species thrive in and around human habitat. They are pests because they destroy food and contaminate it with their smelly excreta. They can transmit a variety of bacterial diseases by contaminating food material.

7.5 Frogs

Frogs can live both on land and in freshwater and belong to class Amphibia of phylum Chordata. The most common species of frog found in India is *Rana tigrina.*

They do not have constant body temperature i.e., their body temperature varies with the temperature of the environment. Such animals are called cold blooded or poikilotherms. You might have also noticed changes in the colour of the frogs while they are in grasses and on dry land. They have the ability to change the colour to hide them from their enemies (camouflage). This protective coloration is called mimicry. You may also know that the frogs are not seen during peak summer and winter. During this period they take shelter in deep burrows to protect them from extreme heat and cold. This is called as summer sleep (aestivation) and winter sleep (hibernation).

7.5.1 Morphology

Have you ever touched the skin of frog? The skin is smooth and slippery due to the presence of mucus. The skin is always maintained in a moist condition. The colour of dorsal side of body is generally olive green with dark irregular spots. On the ventral side the skin is uniformly pale yellow. The frog never drinks water but absorb it through the skin.

Body of a frog is divisible into head and trunk (Figure 7.19). A neck and tail are absent. Above the mouth, a pair of nostrils is present. Eyes are bulged and covered by a nictitating membrane that protects them while in water. On either side of eyes a membranous tympanum (ear) receives sound signals. The forelimbs and hind limbs help in swimming, walking, leaping and burrowing. The hind limbs end in five digits and they are larger and muscular than fore limbs that end in four digits. Feet have webbed digits that help in swimming. Frogs exhibit sexual dimorphism. Male frogs can be distinguished by the presence of sound producing vocal sacs and also a copulatory pad on the first digit of the fore limbs which are absent in female frogs.

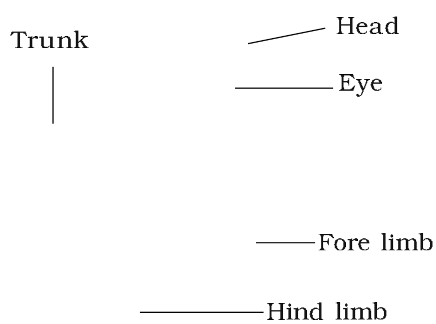


Figure 7.19 External features of frog

7.5.2 Anatomy

The body cavity of frogs accommodate different organ systems such as digestive, circulatory, respiratory, nervous, excretory and reproductive systems with well developed structures and functions (Figure 7.20).

The digestive system consists of alimentary canal and digestive glands. The alimentary canal is short because frogs are carnivores and hence the length of intestine is reduced. The mouth opens into the buccal cavity

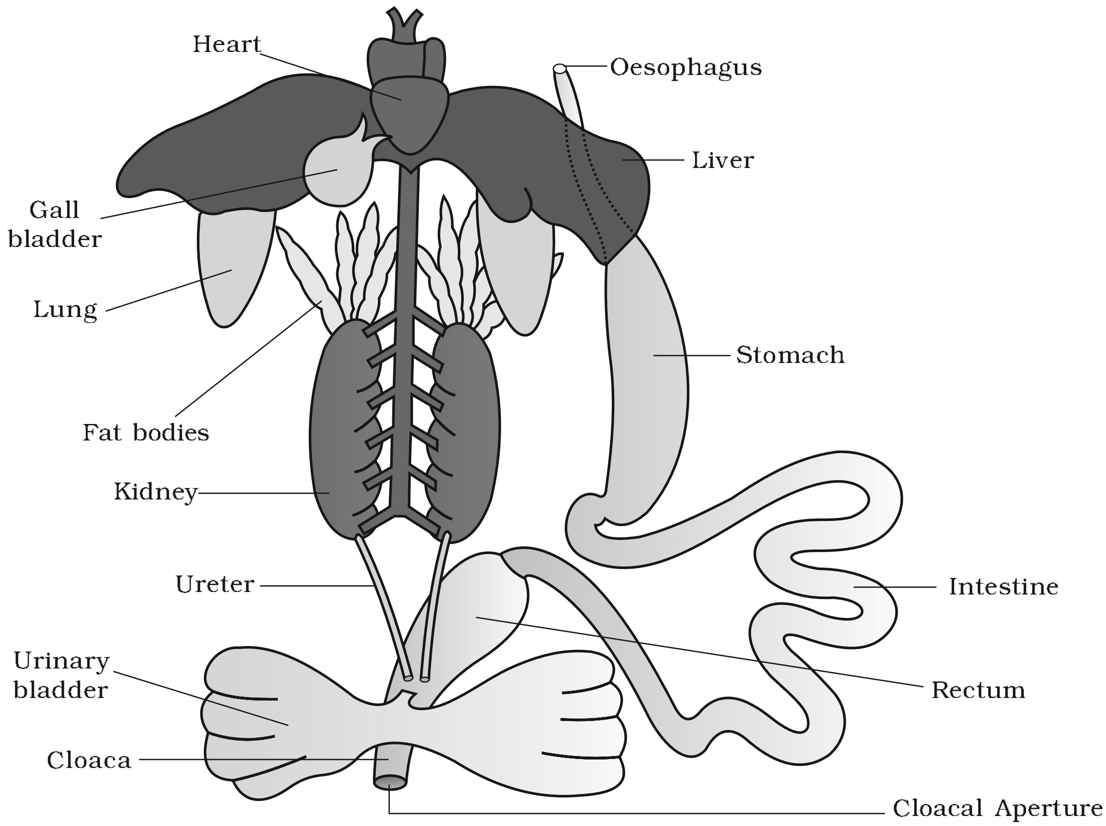


Figure 7.20 Diagrammatic representation of internal organs of frog showing complete digestive system

that leads to the oesophagus through pharynx. Oesophagus is a short tube that opens into the stomach which in turn continues as the intestine, rectum and finally opens outside by the cloaca. Liver secretes bile that is stored in the gall bladder. Pancreas, a digestive gland produces pancreatic juice containing digestive enzymes. Food is captured by the bilobed tongue. Digestion of food takes place by the action of HCl and gastric juices secreted from the walls of the stomach. Partially digested food called chyme is passed from stomach to the first part of the intestine, the duodenum. The duodenum receives bile from gall bladder and pancreatic juices from the pancreas through a common bile duct. Bile emulsifies fat and pancreatic juices digest carbohydrates and proteins. Final digestion takes place in the intestine. Digested food is absorbed by the numerous finger-like folds in the inner wall of intestine called villi and microvilli. The undigested solid waste moves into the rectum and passes out through cloaca.

Frogs respire on land and in the water by two different methods. In water, skin acts as aquatic respiratory organ (cutaneous respiration). Dissolved oxygen in the water is exchanged through the skin by diffusion.

On land, the buccal cavity, skin and lungs act as the respiratory organs. The respiration by lungs is called pulmonary respiration. The lungs are a pair of elongated, pink coloured sac-like structures present in the upper part of the trunk region (thorax). Air enters through the nostrils into the buccal cavity and then to lungs. During aestivation and hibernation gaseous exchange takes place through skin.

The vascular system of frog is well-developed closed type. Frogs have a lymphatic system also. The blood vascular system involves heart, blood vessels and blood. The lymphatic system consists of lymph, lymph channels and lymph nodes. Heart is a muscular structure situated in the upper part of the body cavity. It has three chambers, two atria and one ventricle and is covered by a membrane called pericardium. A triangular structure called sinus venosus joins the right atrium. It receives blood through the major veins called vena cava. The ventricle opens into a sac-like conus arteriosus on the ventral side of the heart. The blood from the heart is carried to all parts of the body by the arteries (arterial system). The veins collect blood from different parts of body to the heart and form the venous system. Special venous connection between liver and intestine as well as the kidney and lower parts of the body are present in frogs. The former is called hepatic portal system and the latter is called renal portal system. The blood is composed of plasma and cells. The blood cells are RBC (red blood cells) or erythrocytes, WBC (white blood cells) or leucocytes and platelets. RBC's are nucleated and contain red coloured pigment namely haemoglobin. The lymph is different from blood. It lacks few proteins and RBCs. The blood carries nutrients, gases and water to the respective sites during the circulation. The circulation of blood is achieved by the pumping action of the muscular heart.

The elimination of nitrogenous wastes is carried out by a well developed excretory system. The excretory system consists of a pair of kidneys, ureters, cloaca and urinary bladder. These are compact, dark red and bean like structures situated a little posteriorly in the body cavity on both sides of vertebral column. Each kidney is composed of several structural and functional units called uriniferous tubules or nephrons. Two ureters emerge from the kidneys in the male frogs. The ureters act as urinogenital duct which opens into the cloaca. In females the ureters and oviduct open seperately in the cloaca. The thin-walled urinary bladder is present ventral to the rectum which also opens in the cloaca. The frog excretes urea and thus is a **ureotelic** animal. Excretory wastes are carried by blood into the kidney where it is separated and excreted.

The system for control and coordination is highly evolved in the frog. It includes both neural system and endocrine glands. The chemical coordination of various organs of the body is achieved by hormones which are secreted by the endocrine glands. The prominent endocrine glands found in frog are pituitary, thyroid, parathyroid, thymus, pineal body, pancreatic islets, adrenals and gonads. The nervous system is organised into a central nervous system (brain and spinal cord), a peripheral nervous system (cranial and spinal nerves) and an autonomic nervous system (sympathetic and parasympathetic). There are ten pairs of cranial nerves arising from the brain. Brain is enclosed in a bony structure called brain box (cranium). The brain is divided into fore-brain, mid-brain and hind-brain. Forebrain includes olfactory lobes, paired cerebral hemispheres and unpaired diencephalon. The midbrain is characterised by a pair of optic lobes. Hind-brain consists of cerebellum and medulla oblongata. The medulla oblongata passes out through the foramen magnum and continues into spinal cord, which is enclosed in the vertebral column.

Frog has different types of sense organs, namely organs of touch (sensory papillae), taste (taste buds), smell (nasal epithelium), vision (eyes) and hearing (tympanum with internal ears). Out of these, eyes and internal ears are well-organised structures and the rest are cellular aggregations around nerve endings. Eyes in a frog are a pair of spherical structures situated in the orbit in skull. These are simple eyes (possessing only one unit). External ear is absent in frogs and only tympanum can be seen externally. The ear is an organ of hearing as well as balancing (equilibrium).

Frogs have well organised male and female reproductive systems. Male reproductive organs consist of a pair of yellowish ovoid testes (Figure 7.21), which are found adhered to the upper part of kidneys by a double fold of peritoneum called mesorchium. Vasa efferentia are 10-12 in number that arise from testes. They enter the kidneys on their side and open into Bidder's canal. Finally it communicates with the urinogenital duct that comes out of the kidneys and opens into the cloaca. The cloaca is a small, median chamber that is used to pass faecal matter, urine and sperms to the exterior.

The female reproductive organs include a pair of ovaries (Figure 7.22). The ovaries are situated near kidneys and there is no functional connection with kidneys. A pair of oviduct arising

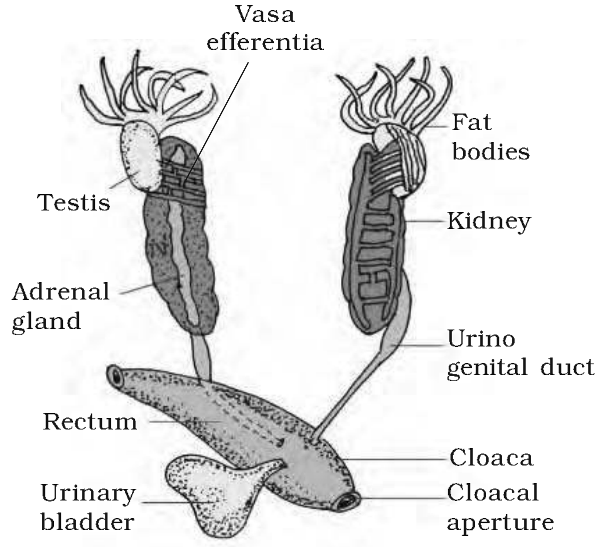


Figure 7.21 Male reproductive system

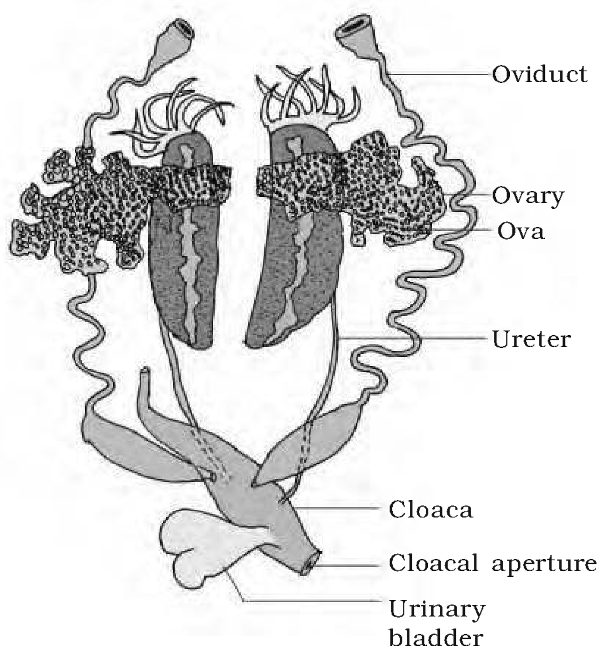


Figure 7.22 Female reproductive system

from the ovaries opens into the cloaca separately. A mature female can lay 2500 to 3000 ova at a time. Fertilisation is external and takes place in water. Development involves a larval stage called tadpole. Tadpole undergoes metamorphosis to form the adult.

Frogs are beneficial for mankind because they eat insects and protect the crop. Frogs maintain ecological balance because these serve as an important link of food chain and food web in the ecosystem. In some countries the muscular legs of frog are used as food by man.

SUMMARY

Cells, tissues, organs and organ systems split up the work in a way that ensures the survival of the body as a whole and exhibit division of labour. A tissue is defined as group of cells along with intercellular substances performing one or more functions in the body. Epithelia are sheet like tissues lining the body's surface and its cavities, ducts and tubes. Epithelia have one free surface facing a body fluid or the outside environment. Their cells are structurally and functionally connected at junctions.

Diverse types of connective tissues bind together, support, strengthen, protect, and insulate other tissue in the body. Soft connective tissues consist of protein fibres as well as a variety of cells arranged in a ground substance. Cartilage, bone, blood, and adipose tissue are specialised connective tissues. Cartilage and bone are both structural materials. Blood is a fluid tissue with transport functions. Adipose tissue is a reservoir of stored energy. Muscle tissue, which can contract (shorten) in response to stimulation, helps in movement of the body and specific body parts. Skeletal muscle is the muscle tissue attached to bones. Smooth muscle is a component of internal organs. Cardiac muscle makes up the contractile walls of the heart. Connective tissue covers all three types of tissues. Nervous tissue exerts greatest control over the response of body. Neurons are the basic units of nervous tissue.

Earthworm, Cockroach and Frog show characteristic features in body organisation. In P*heretima posthuma* (earthworm), the body is covered by cuticle. All segments of its body are alike except the 14^{th}, 15^{th} and 16^{th} segment, which are thick and dark and glandular, forming clitellum. A ring of S-shaped chitinous setae is found in each segment. These setae help in locomotion. On the ventral side spermathecal openings are present in between the grooves of 5 and 6, 6 and 7, 7 and 8 and 8 and 9 segments. Female genital pores are present on 14^{th} segment and male genital pores on 18^{th} segment. The alimentary canal is a narrow tube made of mouth, buccal cavity, pharynx, gizzard, stomach, intestine and anus. The blood vascular system is of closed type with heart and valves. Nervous system is represented by ventral nerve cord. Earthworm is hermaphorodite. Two pairs of

testes occur in the 10^{th} and 11^{th} segment, respectively. A pair of ovaries are present on 12 and 13^{th} intersegmental septum. It is a protandrous animal with cross-fertilisation. Fertilisation and development take place in cocoon secreted by the glands of clitellum.

The body of Cockroach *(Periplaneta americana)* is covered by chitinous exoskeleton. It is divided into head, thorax and abdomen. Segments bear jointed appendages. There are three segments of thorax, each bearing a pair of walking legs. Two pairs of wings are present, one pair each on 2^{nd} and 3^{rd} segment. There are ten segments in abdomen. Alimentary canal is well developed with a mouth surrounded by mouth parts, a pharynx, oesophagus, crop, gizzard, midgut, hindgut and anus. Hepatic caecae are present at the junction of foregut and midgut. Malpighian tubules are present at the junction of midgut and hindgut and help in excretion. A pair of salivary gland is present near crop. The blood vascular system is of open type. Respiration takes place by network of tracheae. Trachea opens outside with spiracles. Nervous system is represented by segmentally arranged ganglia and ventral nerve cord. A pair of testes is present in 4^{th} and 5^{th} segments and ovaries in 4^{th}, 5^{th} and 6^{th} segments. Fertilisation is internal. Female produces 10-40 ootheca bearing developing embryos. After rupturing of single ootheca sixteen young ones, called nymphs come out.

The Indian bullfrog, *Rana tigrina,* is the common frog found in India. Body is covered by skin. Mucous glands are present in the skin which is highly vascularised and helps in respiration in water and on land. Body is divisible into head and trunk. A muscular tongue is present, which is bilobed at the tip and is used in capturing the prey. The alimentary canal consists of oesophagous, stomach, intestine and rectum, which open into the cloaca. The main digestive glands are liver and pancreas. It can respire in water through skin and through lungs on land. Circulatory system is closed with single circulation. RBCs are nucleated. Nervous system is organised into central, peripheral and autonomic. The organs of urinogenital system are kidneys and urinogenital ducts, which open into the cloaca. The male reproductive organ is a pair of testes. The female reproductive organ is a pair of ovaries. A female lays 2500-3000 ova at a time. The fertilisation and development are external. The eggs hatch into tadpoles, which metamorphose into frogs.

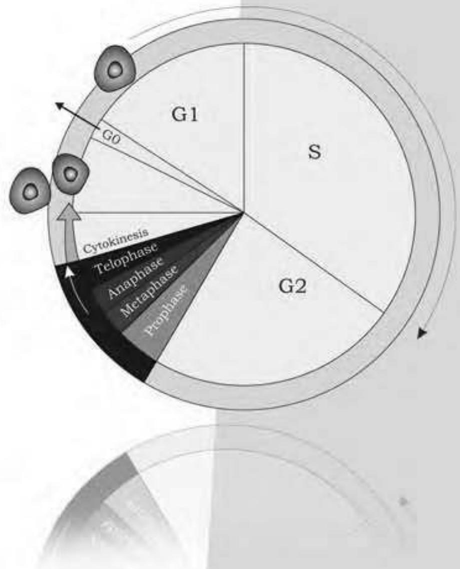
EXERCISES

1. Answer in one word or one line.
   (i) Give the common name of *Periplanata americana.*
   (ii) How many spermathecae are found in earthworm?
   (iii) What is the position of ovaries in cockroach?
   (iv) How many segments are present in the abdomen of cockroach?
   (v) Where do you find Malpighian tubules?

2. Answer the following:
   (i) What is the function of nephridia?
   (ii) How many types of nephridia are found in earthworm based on their location?
3. Draw a labelled diagram of the reproductive organs of an earthworm.
4. Draw a labelled diagram of alimentary canal of a cockroach.
5. Distingusish between the followings
   (a) Prostomium and peristomium
   (b) Septal nephridium and pharyngeal nephridium
6. What are the cellular components of blood?
7. What are the following and where do you find them in animal body.
   (a) Chondriocytes
   (b) Axons
   (c) Ciliated epithelium
8. Describe various types of epithelial tissues with the help of labelled diagrams.
9. Distinguish between
   (a) Simple epithelium and compound epithelium
   (b) Cardiac muscle and striated muscle
   (c) Dense regular and dense irregular connective tissues
   (d) Adipose and blood tissue
   (e) Simple gland and compound gland
10. Mark the odd one in each series:
   (a) Areolar tissue; blood; neuron; tendon
   (b) RBC; WBC; platelets; cartilage
   (c) Exocrine; endocrime; salivary gland; ligament
   (d) Maxilla; mandible; labrum; antenae
   (e) Protonema; mesothorax; metathorax; coxa
11. Match the terms in column I with those in column II:

Column I	**Column II**
(a) Compound epithelium	(i) Alimentry canal
(b) Compound eye	(ii) Cockroach
(c) Septal nephridia	(iii) Skin
(d) Open circulatory system	(iv) Mosaic vision
(e) Typhlosole	(v) Earthworm
(f) Osteocytes	(vi) Phallomere
(g) Genitalia	(vii) Bone

12. Mention breifly about the circulatory system of earthworm
13. Draw a neat diagram of digestive system of frog.
14. Mention the function of the following
   (a) Ureters in frog
   (b) Malpighian tubules
   (c) Body wall in earthworm



UNIT 3

CELL: STRUCTURE AND FUNCTIONS

Biology is the study of living organisms. The detailed description of their form and appearance only brought out their diversity. It is the cell theory that emphasised the unity underlying this diversity of forms, i.e., the cellular organisation of all life forms. A description of cell structure and cell growth by division is given in the chapters comprising this unit. Cell theory also created a sense of mystery around living phenomena, i.e., physiological and behavioural processes. This mystery was the requirement of integrity of cellular organisation for living phenomena to be demonstrated or observed. In studying and understanding the physiological and behavioural processes, one can take a physico-chemical approach and use cell-free systems to investigate. This approach enables us to describe the various processes in molecular terms. The approach is established by analysis of living tissues for elements and compounds. It will tell us what types of organic compounds are present in living organisms. In the next stage, one can ask the question: What are these compounds doing inside a cell? And, in what way they carry out gross physiological processes like digestion, excretion, memory, defense, recognition, etc. In other words we answer the question, what is the molecular basis of all physiological processes? It can also explain the abnormal processes that occur during any diseased condition. This physico-chemical approach to study and understand living organisms is called 'Reductionist Biology'. The concepts and techniques of physics and chemistry are applied to understand biology. In Chapter 9 of this unit, a brief discription of biomolecules is provided.

G.N. Ramachandran
(1922 – 2001)

G.N. RAMACHANDRAN, an outstanding figure in the field of protein structure, was the founder of the 'Madras school' of conformational analysis of biopolymers. His discovery of the triple helical structure of collagen published in *Nature* in 1954 and his analysis of the allowed conformations of proteins through the use of the 'Ramachandran plot' rank among the most outstanding contributions in structural biology. He was born on October 8, 1922, in a small town, not far from Cochin on the southwestern coast of India. His father was a professor of mathematics at a local college and thus had considerable influence in shaping Ramachandran's interest in mathematics. After completing his school years, Ramachandran graduated in 1942 as the top-ranking student in the B.Sc. (Honors) Physics course of the University of Madras. He received a Ph.D. from Cambridge University in 1949. While at Cambridge, Ramachandran met Linus Pauling and was deeply influenced by his publications on models of the α-helix and β-sheet structures that directed his attention to solving the structure of collagen. He passed away at the age of 78, on April 7, 2001.

Chapter 8

Cell: The Unit of Life

When you look around, you see both living and non-living things. You must have wondered and asked yourself – 'what is it that makes an organism living, or what is it that an inanimate thing does not have which a living thing has' ? The answer to this is the presence of the basic unit of life – the cell in all living organisms.

All organisms are composed of cells. Some are composed of a single cell and are called unicellular organisms while others, like us, composed of many cells, are called multicellular organisms.

8.1 What is a Cell?

Unicellular organisms are capable of (i) independent existence and (ii) performing the essential functions of life. Anything less than a complete structure of a cell does not ensure independent living. Hence, cell is the fundamental structural and functional unit of all living organisms.

Anton Von Leeuwenhoek first saw and described a live cell. Robert Brown later discovered the nucleus. The invention of the microscope and its improvement leading to the electron microscope revealed all the structural details of the cell.

8.2 Cell Theory

In 1838, Malthias Schleiden, a German botanist, examined a large number of plants and observed that all plants are composed of different kinds of cells which form the tissues of the plant. At about the same time, Theodore

Schwann (1839), a British Zoologist, studied different types of animal cells and reported that cells had a thin outer layer which is today known as the 'plasma membrane'. He also concluded, based on his studies on plant tissues, that the presence of cell wall is a unique character of the plant cells. On the basis of this, Schwann proposed the hypothesis that the bodies of animals and plants are composed of cells and products of cells.

Schleiden and Schwann together formulated the cell theory. This theory however, did not explain as to how new cells were formed. Rudolf Virchow (1855) first explained that cells divided and new cells are formed from pre-existing cells (*Omnis cellula-e cellula*). He modified the hypothesis of Schleiden and Schwann to give the cell theory a final shape. Cell theory as understood today is:

(i) all living organisms are composed of cells and products of cells.

(ii) all cells arise from pre-existing cells.

8.3 AN OVERVIEW OF CELL

You have earlier observed cells in an onion peel and/or human cheek cells under the microscope. Let us recollect their structure. The onion cell which is a typical plant cell, has a distinct cell wall as its outer boundary and just within it is the cell membrane. The cells of the human cheek have an outer membrane as the delimiting structure of the cell. Inside each cell is a dense membrane bound structure called nucleus. This nucleus contains the chromosomes which in turn contain the genetic material, DNA. Cells that have membrane bound nuclei are called eukaryotic whereas cells that lack a membrane bound nucleus are prokaryotic. In both prokaryotic and eukaryotic cells, a semi-fluid matrix called cytoplasm occupies the volume of the cell. The cytoplasm is the main arena of cellular activities in both the plant and animal cells. Various chemical reactions occur in it to keep the cell in the 'living state'.

Besides the nucleus, the eukaryotic cells have other membrane bound distinct structures called **organelles** like the endoplasmic reticulum (ER), the golgi complex, lysosomes, mitochondria, microbodies and vacuoles. The prokaryotic cells lack such membrane bound organelles.

Ribosomes are non-membrane bound organelles found in all cells – both eukaryotic as well as prokaryotic. Within the cell, ribosomes are found not only in the cytoplasm but also within the two organelles – chloroplasts (in plants) and mitochondria and on rough ER.

Animal cells contain another non-membrane bound organelle called centriole which helps in cell division.

Cells differ greatly in size, shape and activities (Figure 8.1). For example, Mycoplasmas, the smallest cells, are only 0.3 μm in length while bacteria

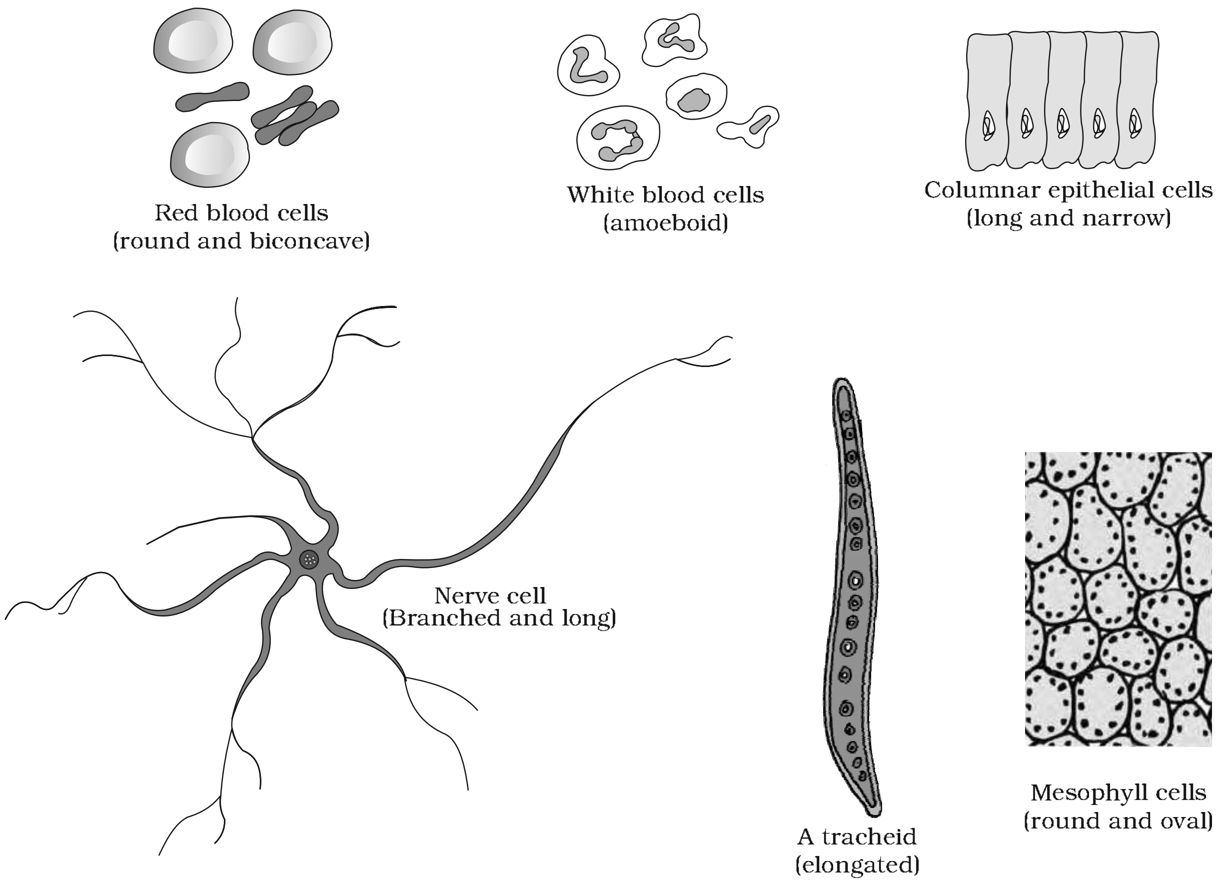


Figure 8.1 Diagram showing different shapes of the cells

could be 3 to 5 µm. The largest isolated single cell is the egg of an ostrich. Among multicellular organisms, human red blood cells are about 7.0 µm in diameter. Nerve cells are some of the longest cells. Cells also vary greatly in their shape. They may be disc-like, polygonal, columnar, cuboid, thread like, or even irregular. The shape of the cell may vary with the function they perform.

8.4 PROKARYOTIC CELLS

The prokaryotic cells are represented by bacteria, blue-green algae, mycoplasma and PPLO (Pleuro Pneumonia Like Organisms). They are generally smaller and multiply more rapidly than the eukaryotic cells (Figure 8.2). They may vary greatly in shape and size. The four basic shapes of bacteria are bacillus (rod like), coccus (spherical), vibrio (comma shaped) and spirillum (spiral).

The organisation of the prokaryotic cell is fundamentally similar even though prokaryotes exhibit a wide variety of shapes and functions. All

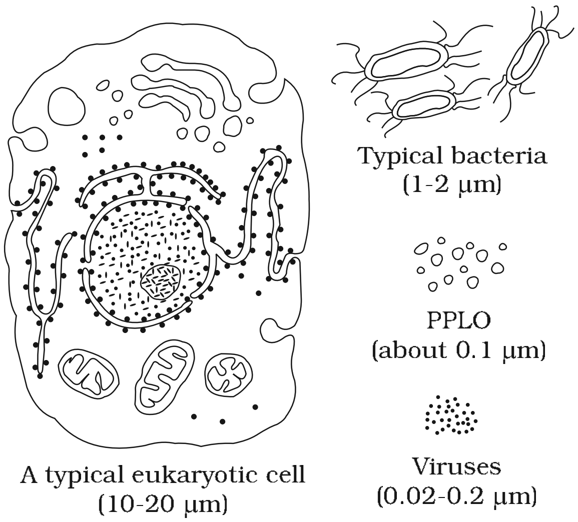


Figure 8.2 Diagram showing comparison of eukaryotic cell with other organisms

prokaryotes have a cell wall surrounding the cell membrane. The fluid matrix filling the cell is the cytoplasm. There is no well-defined nucleus. The genetic material is basically naked, not enveloped by a nuclear membrane. In addition to the genomic DNA (the single chromosome/circular DNA), many bacteria have small circular DNA outside the genomic DNA. These smaller DNA are called plasmids. The plasmid DNA confers certain unique phenotypic characters to such bacteria. One such character is resistance to antibiotics. In higher classes you will learn that this plasmid DNA is used to monitor bacterial transformation with foreign DNA. Nuclear membrane is found in eukaryotes. No organelles, like the ones in eukaryotes, are found in prokaryotic cells except for ribosomes. Prokaryotes have something unique in the form of inclusions. A specialised differentiated form of cell membrane called mesosome is the characteristic of prokaryotes. They are essentially infoldings of cell membrane.

8.4.1 Cell Envelope and its Modifications

Most prokaryotic cells, particularly the bacterial cells, have a chemically complex cell envelope. The cell envelope consists of a tightly bound three layered structure i.e., the outermost glycocalyx followed by the cell wall and then the plasma membrane. Although each layer of the envelope performs distinct function, they act together as a single protective unit. Bacteria can be classified into two groups on the basis of the differences in the cell envelopes and the manner in which they respond to the staining procedure developed by Gram viz., those that take up the gram stain are **Gram positive** and the others that do not are called **Gram negative** bacteria.

Glycocalyx differs in composition and thickness among different bacteria. It could be a loose sheath called the **slime layer** in some, while in others it may be thick and tough, called the **capsule**. The **cell wall** determines the shape of the cell and provides a strong structural support to prevent the bacterium from bursting or collapsing.

The plasma membrane is semi-permeable in nature and interacts with the outside world. This membrane is similar structurally to that of the eukaryotes.

A special membranous structure is the **mesosome** which is formed by the extensions of plasma membrane into the cell. These extensions are in the **form of vesicles, tubules and lamellae**. They help in cell wall formation, DNA replication and distribution to daughter cells. They also help in respiration, secretion processes, to increase the surface area of the plasma membrane and enzymatic content. In some prokaryotes like cyanobacteria, there are other membranous extensions into the cytoplasm called chromatophores which contain pigments.

Bacterial cells may be motile or non-motile. If motile, they have thin filamentous extensions from their cell wall called flagella. Bacteria show a range in the number and arrangement of flagella. Bacterial flagellum is composed of three parts – **filament, hook** and **basal body**. The filament is the longest portion and extends from the cell surface to the outside.

Besides flagella, Pili and Fimbriae are also surface structures of the bacteria but do not play a role in motility. The **pili** are elongated tubular structures made of a special protein. The **fimbriae** are small bristle like fibres sprouting out of the cell. In some bacteria, they are known to help attach the bacteria to rocks in streams and also to the host tissues.

8.4.2 Ribosomes and Inclusion Bodies

In prokaryotes ribosomes are associated with the plasma membrane of the cell. They are about 15 nm by 20 nm in size and are made of two subunits - 50S and 30S units which when present together form 70S prokaryotic ribosomes. Ribosomes are the site of protein synthesis. Several ribosomes may attach to a single mRNA and form a chain called **polyribosomes** or **polysome**. The ribosomes of a polysome translate the mRNA into proteins.

Inclusion bodies: Reserve material in prokaryotic cells are stored in the cytoplasm in the form of inclusion bodies. These are not bounded by any membrane system and lie free in the cytoplasm, e.g., phosphate granules, cyanophycean granules and glycogen granules. Gas vacuoles are found in blue green and purple and green photosynthetic bacteria.

8.5 EUKARYOTIC CELLS

The eukaryotes include all the protists, plants, animals and fungi. In eukaryotic cells there is an extensive compartmentalisation of cytoplasm through the presence of membrane bound organelles. Eukaryotic cells possess an organised nucleus with a nuclear envelope. In addition, eukaryotic cells have a variety of complex locomotory and cytoskeletal structures. Their genetic material is organised into chromosomes.

All eukaryotic cells are not identical. Plant and animal cells are different as the former possess cell walls, plastids and a large central vacuole which are absent in animal cells. On the other hand, animal cells have centrioles which are absent in almost all plant cells (Figure 8.3).

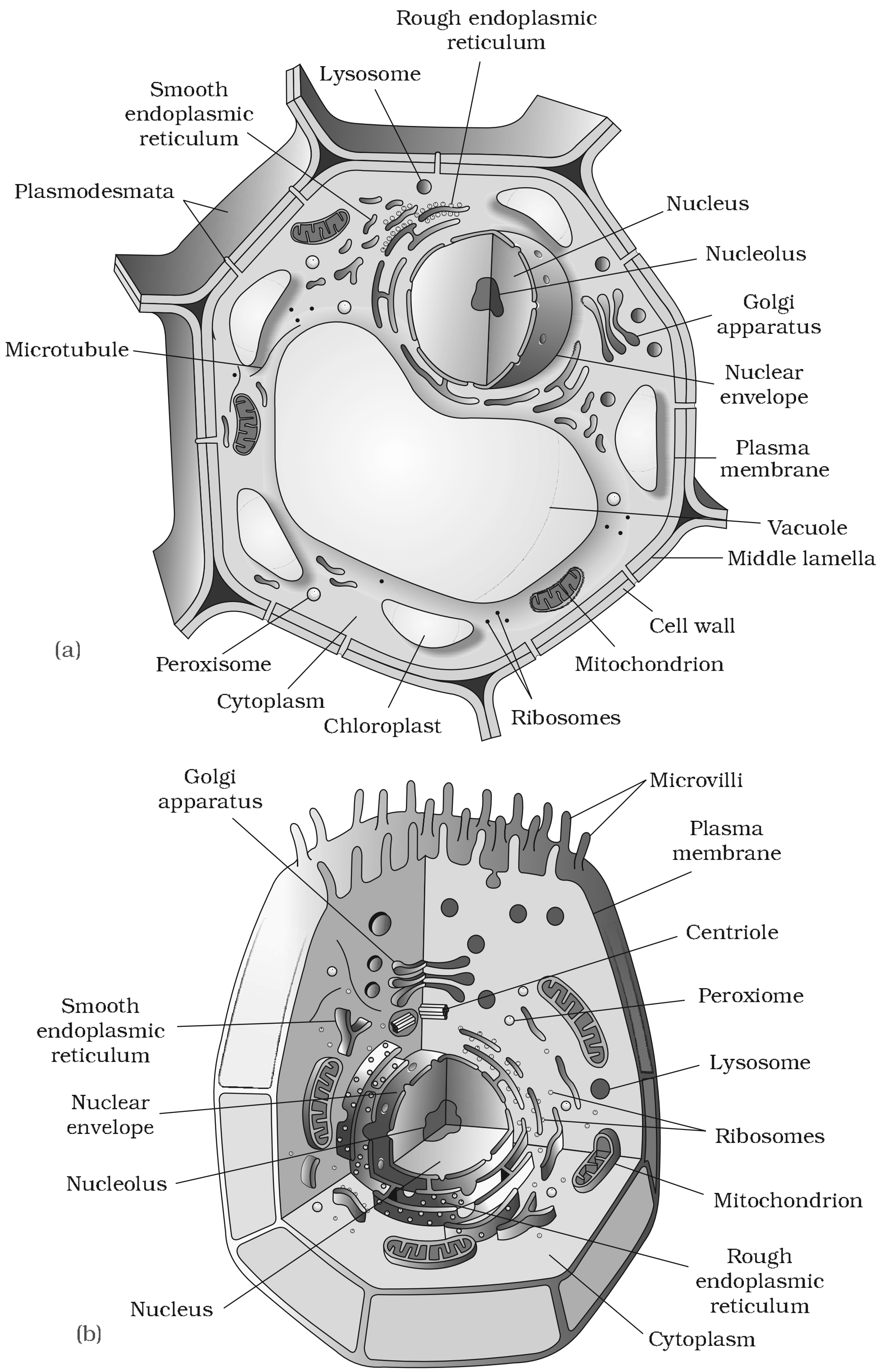


Figure 8.3 Diagram showing : (a) Plant cell (b) Animal cell

Let us now look at individual cell organelles to understand their structure and functions.

8.5.1 Cell Membrane

The detailed structure of the membrane was studied only after the advent of the electron microscope in the 1950s. Meanwhile, chemical studies on the cell membrane, especially in human red blood cells (RBCs), enabled the scientists to deduce the possible structure of plasma membrane.

These studies showed that the cell membrane is composed of lipids that are arranged in a bilayer. Also, the lipids are arranged within the membrane with the polar head towards the outer sides and the hydrophobic tails towards the inner part.This ensures that the nonpolar tail of saturated hydrocarbons is protected from the aqueous environment (Figure 8.4). The lipid component of the membrane mainly consists of phosphoglycerides.

Later, biochemical investigation clearly revealed that the cell membranes also possess protein and carbohydrate. The ratio of protein and lipid varies considerably in different cell types. In human beings, the membrane of the erythrocyte has approximately 52 per cent protein and 40 per cent lipids.

Depending on the ease of extraction, membrane proteins can be classified as integral or peripheral. Peripheral proteins lie on the surface of membrane while the integral proteins are partially or totally buried in the membrane.

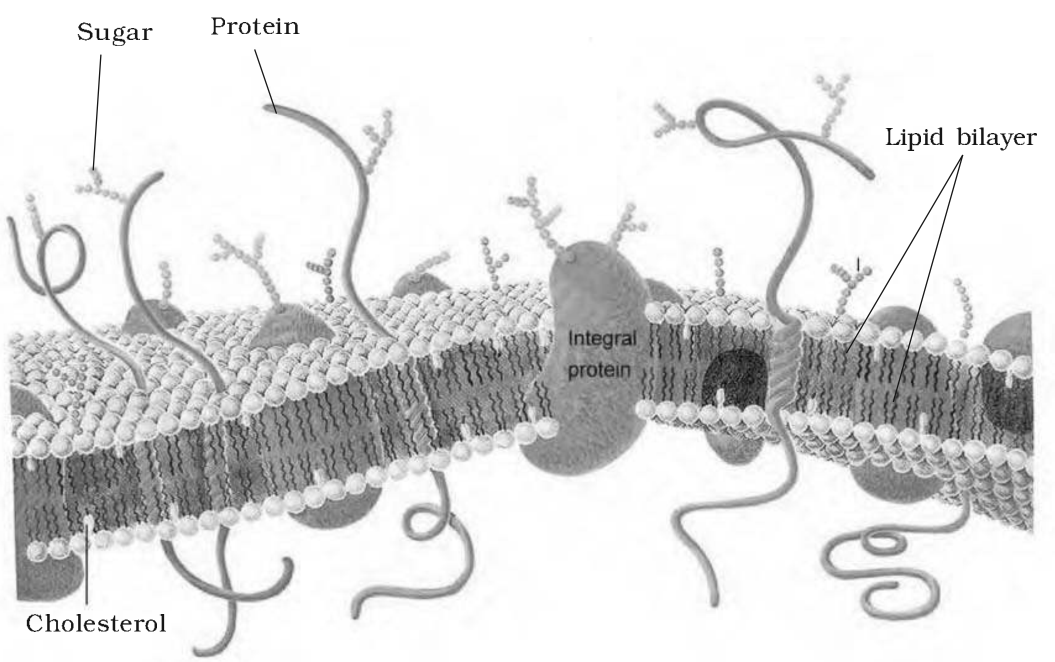


Figure 8.4 Fluid mosaic model of plasma membrane

An improved model of the structure of cell membrane was proposed by Singer and Nicolson (1972) widely accepted as **fluid mosaic model** (Figure 8.4). According to this, the quasi-fluid nature of lipid enables lateral movement of proteins within the overall bilayer. This ability to move within the membrane is measured as its fluidity.

The fluid nature of the membrane is also important from the point of view of functions like cell growth, formation of intercellular junctions, secretion, endocytosis, cell division etc.

One of the most important functions of the plasma membrane is the transport of the molecules across it. The membrane is selectively permeable to some molecules present on either side of it. Many molecules can move briefly across the membrane without any requirement of energy and this is called the **passive transport**. Neutral solutes may move across the membrane by the process of simple diffusion along the concentration gradient, i.e., from higher concentration to the lower. Water may also move across this membrane from higher to lower concentration. Movement of water by diffusion is called **osmosis**. As the polar molecules cannot pass through the nonpolar lipid bilayer, they require a carrier protein of the membrane to facilitate their transport across the membrane. A few ions or molecules are transported across the membrane against their concentration gradient, i.e., from lower to the higher concentration. Such a transport is an energy dependent process, in which ATP is utilised and is called **active transport**, e.g., Na^+/K^+ Pump.

8.5.2 Cell Wall

As you may recall, a non-living rigid structure called the cell wall forms an outer covering for the plasma membrane of fungi and plants. Cell wall not only gives shape to the cell and protects the cell from mechanical damage and infection, it also helps in cell-to-cell interaction and provides barrier to undesirable macromolecules. Algae have cell wall, made of cellulose, galactans, mannans and minerals like calcium carbonate, while in other plants it consists of cellulose, hemicellulose, pectins and proteins. The cell wall of a young plant cell, the **primary wall** is capable of growth, which gradually diminishes as the cell matures and the secondary wall is formed on the inner (towards membrane) side of the cell.

The middle lamella is a layer mainly of calcium pectate which holds or glues the different neighbouring cells together. The cell wall and middle lamellae may be traversed by plasmodesmata which connect the cytoplasm of neighbouring cells.

8.5.3 Endomembrane System

While each of the membranous organelles is distinct in terms of its structure and function, many of these are considered together as an endomembrane system because their functions are coordinated. The endomembrane system include endoplasmic reticulum (ER), golgi complex, lysosomes and vacuoles. Since the functions of the mitochondria, chloroplast and peroxisomes are not coordinated with the above components, these are not considered as part of the endomembrane system.

8.5.3.1 The Endoplasmic Reticulum (ER)

Electron microscopic studies of eukaryotic cells reveal the presence of a network or reticulum of tiny tubular structures scattered in the cytoplasm that is called the endoplasmic reticulum (ER) (Figure 8.5). Hence, ER divides the intracellular space into two distinct compartments, i.e., luminal (inside ER) and extra luminal (cytoplasm) compartments.

The ER often shows ribosomes attached to their outer surface. The endoplasmic reticulun bearing ribosomes on their surface is called rough endoplasmic reticulum (RER). In the absence of ribosomes they appear smooth and are called smooth endoplasmic reticulum (SER).

RER is frequently observed in the cells actively involved in protein synthesis and secretion. They are extensive and continuous with the outer membrane of the nucleus.

The smooth endoplasmic reticulum is the major site for synthesis of lipid. In animal cells lipid-like steroidal hormones are synthesised in SER.

8.5.3.2 Golgi apparatus

Camillo Golgi (1898) first observed densely stained reticular structures near the nucleus. These were later named Golgi bodies after him. They consist of many flat, disc-shaped sacs or cisternae of 0.5µm to 1.0µm diameter (Figure 8.6). These are stacked parallel to each other. Varied number of cisternae are present in a Golgi complex. The Golgi cisternae are concentrically arranged near the nucleus with distinct convex *cis* or the forming face and concave *trans* or the maturing face.

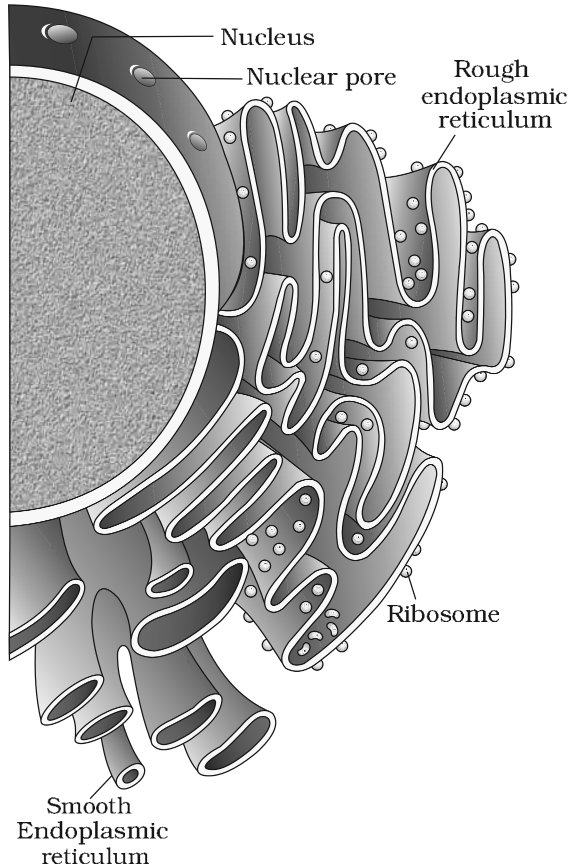


Figure 8.5 Endoplasmic reticulum

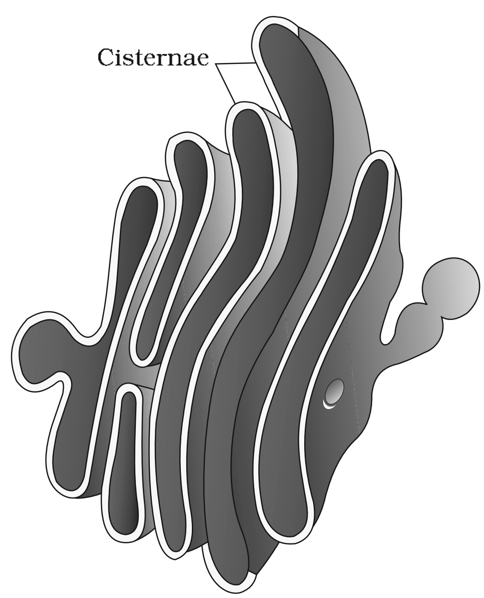


Figure 8.6 Golgi apparatus

The *cis* and the *trans* faces of the organelle are entirely different, but interconnected.

The golgi apparatus principally performs the function of packaging materials, to be delivered either to the intra-cellular targets or secreted outside the cell. Materials to be packaged in the form of vesicles from the ER fuse with the *cis* face of the golgi apparatus and move towards the maturing face. This explains, why the golgi apparatus remains in close association with the endoplasmic reticulum. A number of proteins synthesised by ribosomes on the endoplasmic reticulum are modified in the cisternae of the golgi apparatus before they are released from its *trans* face. Golgi apparatus is the important site of formation of glycoproteins and glycolipids.

8.5.3.3 Lysosomes

These are membrane bound vesicular structures formed by the process of packaging in the golgi apparatus. The isolated lysosomal vesicles have been found to be very rich in almost all types of hydrolytic enzymes (hydrolases – lipases, proteases, carbohydrases) optimally active at the acidic pH. These enzymes are capable of digesting carbohydrates, proteins, lipids and nucleic acids.

8.5.3.4 Vacuoles

The vacuole is the membrane-bound space found in the cytoplasm. It contains water, sap, excretory product and other materials not useful for the cell. The vacuole is bound by a single membrane called tonoplast. In plant cells the vacuoles can occupy up to 90 per cent of the volume of the cell.

In plants, the tonoplast facilitates the transport of a number of ions and other materials against concentration gradients into the vacuole, hence their concentration is significantly higher in the vacuole than in the cytoplasm.

In *Amoeba* the **contractile vacuole** is important for excretion. In many cells, as in protists, **food vacuoles** are formed by engulfing the food particles.

8.5.4 Mitochondria

Mitochondria (sing.: mitochondrion), unless specifically stained, are not easily visible under the microscope. The number of mitochondria per cell is variable depending on the physiological activity of the cells. In terms of shape and size also, considerable degree of variability is observed. Typically it is sausage-shaped or cylindrical having a diameter of 0.2-1.0μm (average 0.5μm) and length 1.0-4.1μm. Each mitochondrion is a double membrane-bound structure with the outer membrane and the inner

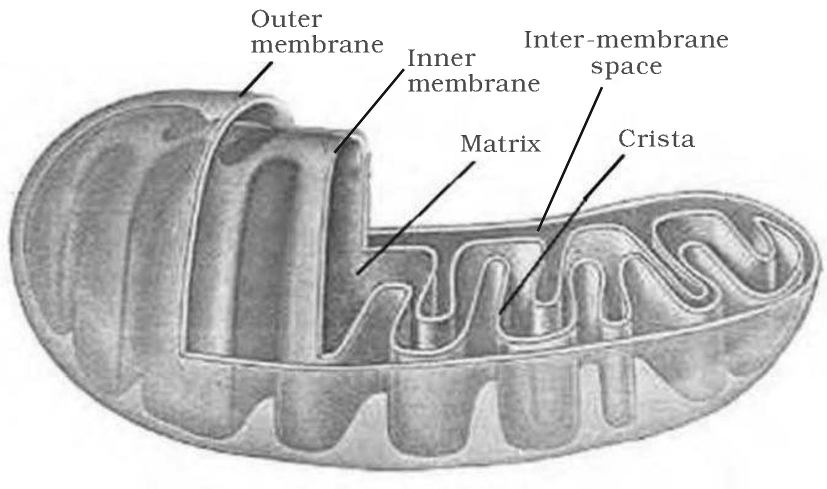


Figure 8.7 Structure of mitochondrion (Longitudinal section)

membrane dividing its lumen distinctly into two aqueous compartments, i.e., the outer compartment and the inner compartment. The inner compartment is called the **matrix**. The outer membrane forms the continuous limiting boundary of the organelle. The inner membrane forms a number of infoldings called the cristae (sing.: crista) towards the matrix (Figure 8.7). The cristae increase the surface area. The two membranes have their own specific enzymes associated with the mitochondrial function. Mitochondria are the sites of aerobic respiration. They produce cellular energy in the form of ATP, hence they are called 'power houses' of the cell. The matrix also possesses single circular DNA molecule, a few RNA molecules, ribosomes (70S) and the components required for the synthesis of proteins. The mitochondria divide by fission.

8.5.5 Plastids

Plastids are found in all plant cells and in euglenoides. These are easily observed under the microscope as they are large. They bear some specific pigments, thus imparting specific colours to the plants. Based on the type of pigments plastids can be classified into **chloroplasts, chromoplasts** and **leucoplasts.**

The chloroplasts contain **chlorophyll** and carotenoid pigments which are responsible for trapping light energy essential for photosynthesis. In the chromoplasts fat soluble **carotenoid** pigments like carotene, xanthophylls and others are present. This gives the part of the plant a yellow, orange or red colour. The leucoplasts are the colourless plastids of varied shapes and sizes with stored nutrients: **Amyloplasts** store carbohydrates (starch), e.g., potato; **elaioplasts** store oils and fats whereas the **aleuroplasts** store proteins.

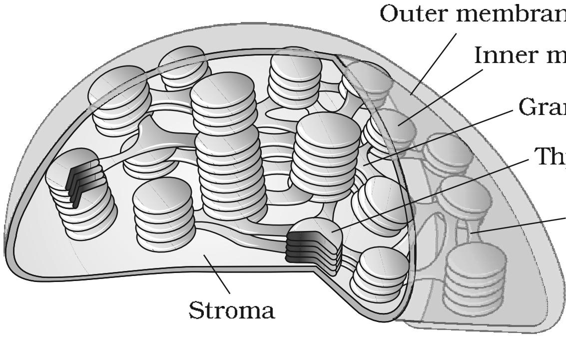


Figure 8.8 Sectional view of chloroplast

Majority of the chloroplasts of the green plants are found in the mesophyll cells of the leaves. These are lens-shaped, oval, spherical, discoid or even ribbon-like organelles having variable length (5-10mm) and width (2-4mm). Their number varies from 1 per cell of the *Chlamydomonas*, a green alga to 20-40 per cell in the mesophyll.

Like mitochondria, the chloroplasts are also double membrane bound. Of the two, the inner chloroplast membrane is relatively less permeable. The space limited by the inner membrane of the chloroplast is called the stroma. A number of organised flattened membranous sacs called the **thylakoids**, are present in the stroma (Figure 8.8). Thylakoids are arranged in stacks like the piles of coins called grana (singular: granum) or the intergranal thylakoids. In addition, there are flat membranous tubules called the stroma lamellae connecting the thylakoids of the different grana. The membrane of the thylakoids enclose a space called a lumen. The stroma of the chloroplast contains enzymes required for the synthesis of carbohydrates and proteins. It also contains small, double-stranded circular DNA molecules and ribosomes. Chlorophyll pigments are present in the thylakoids. The ribosomes of the chloroplasts are smaller (70S) than the cytoplasmic ribosomes (80S).

8.5.6 Ribosomes

Ribosomes are the granular structures first observed under the electron microscope as dense particles by George Palade (1953). They are composed of ribonucleic acid (RNA) and proteins and are not surrounded by any membrane.

The eukaryotic ribosomes are 80S while the prokaryotic ribosomes are 70S. Here 'S' stands for the sedimentation coefficient; it indirectly is a measure of density and size. Both 70S and 80S ribosomes are composed of two subunits.

8.5.7 Cytoskeleton

An elaborate network of filamentous proteinaceous structures present in the cytoplasm is collectively referred to as the **cytoskeleton**. The cytoskeleton in a cell are involved in many functions such as mechanical support, motility, maintenance of the shape of the cell.

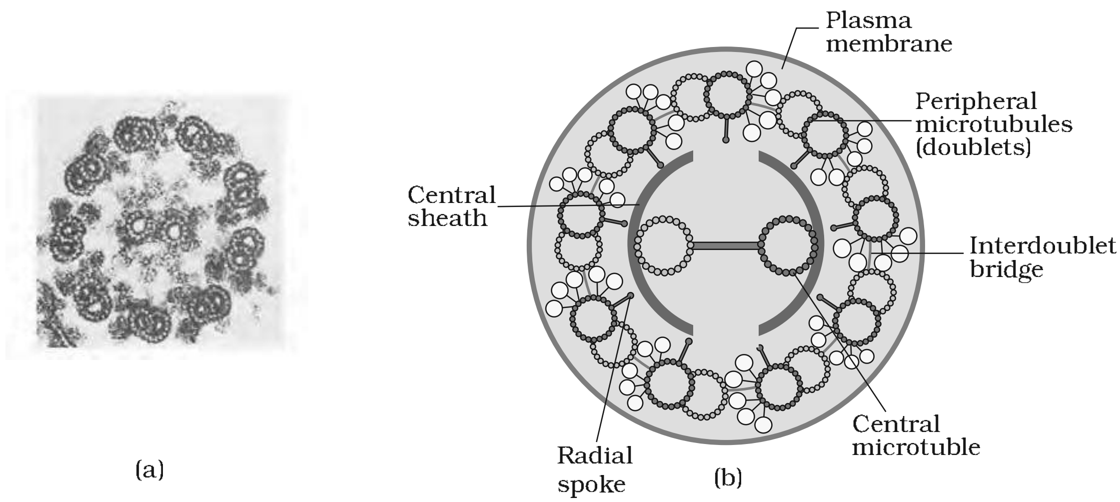


Figure 8.9 Section of cilia/flagella showing different parts : (a) Electron micrograph (b) Diagrammatic representation of internal structure

8.5.8 Cilia and Flagella

Cilia (sing.: cilium) and flagella (sing.: flagellum) are hair-like outgrowths of the cell membrane. Cilia are small structures which work like oars, causing the movement of either the cell or the surrounding fluid. Flagella are comparatively longer and responsible for cell movement. The prokaryotic bacteria also possess flagella but these are structurally different from that of the eukaryotic flagella.

The electron microscopic study of a cilium or the flagellum show that they are covered with plasma membrane. Their core called the **axoneme,** possesses a number of microtubules running parallel to the long axis. The axoneme usually has nine pairs of doublets of radially arranged peripheral microtubules, and a pair of centrally located microtubules. Such an arrangement of axonemal microtubules is referred to as the 9+2 array (Figure 8.9). The central tubules are connected by bridges and is also enclosed by a central sheath, which is connected to one of the tubules of each peripheral doublets by a radial spoke. Thus, there are nine radial spokes. The peripheral doublets are also interconnected by linkers. Both the cilium and flagellum emerge from centriole-like structure called the basal bodies.

8.5.9 Centrosome and Centrioles

Centrosome is an organelle usually containing two cylindrical structures called centrioles. They are surrounded by amorphous pericentriolar materials. Both the centrioles in a centrosome lie perpendicular to each other in which each has an organisation like the cartwheel. They are made up of nine evenly spaced peripheral fibrils of tubulin. Each of the peripheral fibril is a triplet.The adjacent triplets are also linked. The central part of the centriole is also proteinaceous and called the **hub**, which is connected with tubules of the peripheral triplets by radial **spokes** made of protein. The centrioles form the basal body of cilia or flagella, and spindle fibres that give rise to spindle apparatus during cell division in animal cells.

8.5.10 Nucleus

Nucleus as a cell organelle was first described by Robert Brown as early as 1831. Later the material of the nucleus stained by the basic dyes was given the name **chromatin** by Flemming.

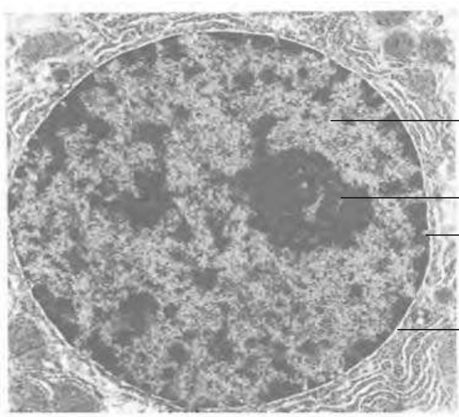


Figure 8.10 Structure of nucleus

The interphase nucleus (nucleus of a cell when it is not dividing) has highly extended and elaborate nucleoprotein fibres called chromatin, nuclear matrix and one or more spherical bodies called **nucleoli** (sing.: nucleolus) (Figure 8.10). Electron microscopy has revealed that the nuclear envelope, which consists of two parallel membranes with a space between (10 to 50 nm) called the **perinuclear space**, forms a barrier between the materials present inside the nucleus and that of the cytoplasm. The outer membrane usually remains continuous with the endoplasmic reticulum and also bears ribosomes on it. At a number of places the nuclear envelope is interrupted by minute pores, which are formed by the fusion of its two membranes. These nuclear pores are the passages through which movement of RNA and protein molecules takes place in both directions between the nucleus and the cytoplasm. Normally, there is only one nucleus per cell, variations in the number of nuclei are also frequently observed. *Can you recollect names of organisms that have more than one nucleus per cell?* Some mature cells even lack nucleus, e.g., erythrocytes of many mammals and sieve tube cells of vascular plants. *Would you consider these cells as 'living'?*

The nuclear matrix or the **nucleoplasm** contains nucleolus and chromatin. The nucleoli are spherical structures present in the nucleoplasm. The content of nucleolus is continuous with the rest of the nucleoplasm as it is not a membrane bound structure. It is a site for active ribosomal RNA synthesis. Larger and more numerous nucleoli are present in cells actively carrying out protein synthesis.

You may recall that the interphase nucleus has a loose and indistinct network of nucleoprotein fibres called chromatin. But during different stages of cell division, cells show structured **chromosomes** in place of the nucleus. Chromatin contains DNA and some basic proteins called **histones**, some non-histone proteins and also RNA. A single human cell has approximately two metre long thread of DNA distributed among its forty six (twenty three pairs) chromosomes. You will study the details of DNA packaging in the form of a chromosome in class XII.

Every chromosome essentially has a primary constriction or the **centromere** on the sides of which disc shaped structures called **kinetochores** are present (Figure 8.11). Based on the position of the centromere, the chromosomes can be classified into four types (Figure 8.12). The **metacentric** chromosome has middle centromere forming two equal arms of the chromosome. The **sub-metacentric** chromosome has centromere nearer to one end of the chromosome resulting into one shorter arm and one longer arm. In case of **acrocentric** chromosome the centromere is situated close to its end forming one extremely short and one very long arm, whereas the **telocentric** chromosome has a terminal centromere.

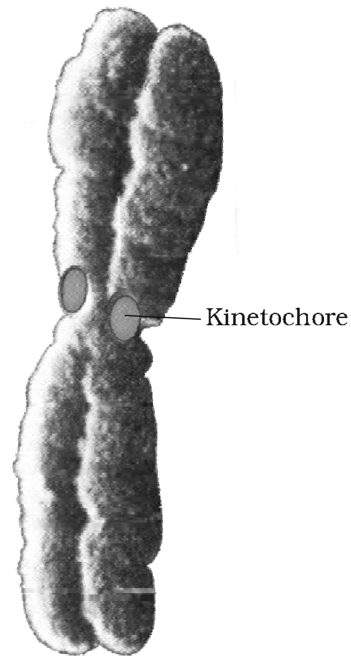


Figure 8.11 Chromosome with kinetochore

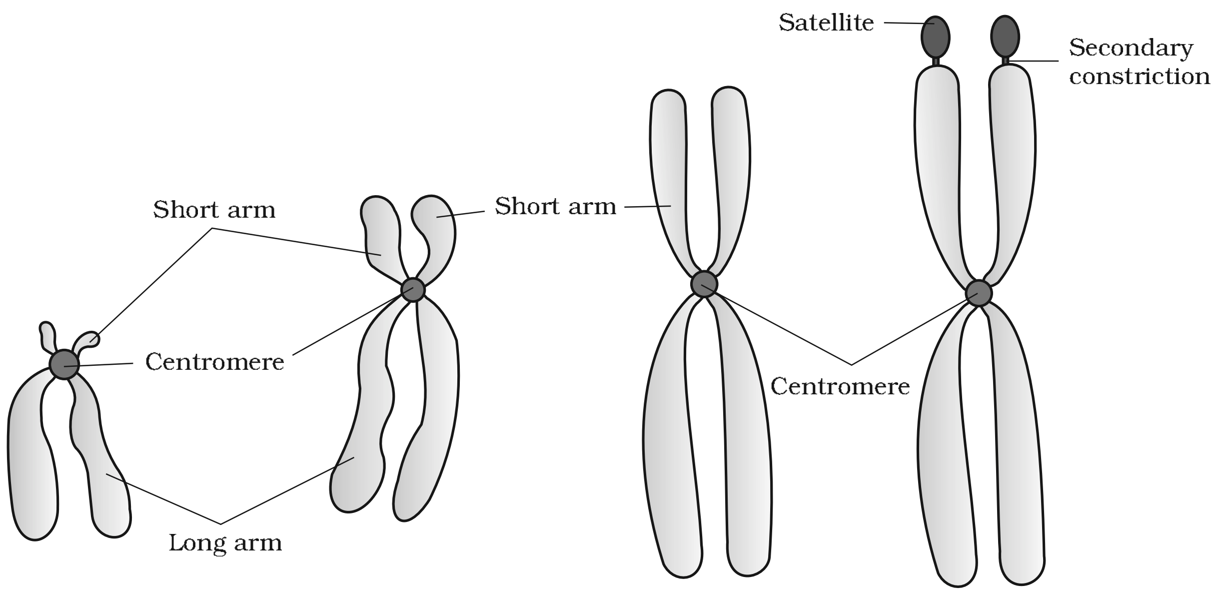


Figure 8.12 Types of chromosomes based on the position of centromere

Sometimes a few chromosomes have non-staining secondary constrictions at a constant location. This gives the appearance of a small fragment called the **satellite**.

8.5.11 Microbodies

Many membrane bound minute vesicles called microbodies that contain various enzymes, are present in both plant and animal cells.

Summary

All organisms are made of cells or aggregates of cells. Cells vary in their shape, size and activities/functions. Based on the presence or absence of a membrane bound nucleus and other organelles, cells and hence organisms can be named as eukaryotic or prokaryotic.

A typical eukaryotic cell consists of a cell membrane, nucleus and cytoplasm. Plant cells have a cell wall outside the cell membrane. The plasma membrane is selectively permeable and facilitates transport of several molecules. The endomembrane system includes ER, golgi complex, lysosomes and vacuoles. All the cell organelles perform different but specific functions. Centrosome and centriole form the basal body of cilia and flagella that facilitate locomotion. In animal cells, centrioles also form spindle apparatus during cell division. Nucleus contains nucleoli and chromatin network. It not only controls the activities of organelles but also plays a major role in heredity.

Endoplasmic reticulum contains tubules or cisternae. They are of two types: rough and smooth. ER helps in the transport of substances, synthesis of proteins, lipoproteins and glycogen. The golgi body is a membranous organelle composed of flattened sacs. The secretions of cells are packed in them and transported from the cell. Lysosomes are single membrane structures containing enzymes for digestion of all types of macromolecules. Ribosomes are involved in protein synthesis. These occur freely in the cytoplasm or are associated with ER. Mitochondria help in oxidative phosphorylation and generation of adenosine triphosphate. They are bound by double membrane; the outer membrane is smooth and inner one folds into several cristae. Plastids are pigment containing organelles found in plant cells only. In plant cells, chloroplasts are responsible for trapping light energy essential for photosynthesis. The grana, in the plastid, is the site of light reactions and the stroma of dark reactions. The green coloured plastids are chloroplasts, which contain chlorophyll, whereas the other coloured plastids are chromoplasts, which may contain pigments like carotene and xanthophyll. The nucleus is enclosed by nuclear envelop, a double membrane structure with nuclear pores. The inner membrane encloses the nucleoplasm and the chromatin material. Thus, cell is the structural and functional unit of life.

EXERCISES

1. Which of the following is not correct?
   (a) Robert Brown discovered the cell.
   (b) Schleiden and Schwann formulated the cell theory.
   (c) Virchow explained that cells are formed from pre-existing cells.
   (d) A unicellular organism carries out its life activities within a single cell.
2. New cells generate from
   (a) bacterial fermentation (b) regeneration of old cells
   (c) pre-existing cells (d) abiotic materials
3. Match the following

(a) Cristae	(i) Flat membranous sacs in stroma
(b) Cisternae	(ii) Infoldings in mitochondria
(c) Thylakoids	(iii) Disc-shaped sacs in Golgi apparatus

4. Which of the following is correct:
   (a) Cells of all living organisms have a nucleus.
   (b) Both animal and plant cells have a well defined cell wall.
   (c) In prokaryotes, there are no membrane bound organelles.
   (d) Cells are formed *de novo* from abiotic materials.
5. What is a mesosome in a prokaryotic cell? Mention the functions that it performs.
6. How do neutral solutes move across the plasma membrane? Can the polar molecules also move across it in the same way? If not, then how are these transported across the membrane?
7. Name two cell-organelles that are double membrane bound. What are the characteristics of these two organelles? State their functions and draw labelled diagrams of both.
8. What are the characteristics of prokaryotic cells.
9. Multicellular organisms have division of labour. Explain.
10. Cell is the basic unit of life. Discuss in brief.
11. What are nuclear pores? State their function.
12. Both lysosomes and vacuoles are endomembrane structures, yet they differ in terms of their functions. Comment.
13. Describe the structure of the following with the help of labelled diagrams.
    (i) Nucleus (ii) Centrosome
14. What is a centromere? How does the position of centromere form the basis of classification of chromosomes. Support your answer with a diagram showing the position of centromere on different types of chromosomes.

CHAPTER 9

BIOMOLECULES

There is a wide diversity in living organisms in our biosphere. Now a question that arises in our minds is: Are all living organisms made of the same chemicals, i.e., elements and compounds? You have learnt in chemistry how elemental analysis is performed. If we perform such an analysis on a plant tissue, animal tissue or a microbial paste, we obtain a list of elements like carbon, hydrogen, oxygen and several others and their respective content per unit mass of a living tissue. If the same analysis is performed on a piece of earth's crust as an example of non-living matter, we obtain a similar list. What are the differences between the two lists? In absolute terms, no such differences could be made out. All the elements present in a sample of earth's crust are also present in a sample of living tissue. However, a closer examination reveals that the relative abundance of carbon and hydrogen with respect to other elements is higher in any living organism than in earth's crust (Table 9.1).

9.1 HOW TO ANALYSE CHEMICAL COMPOSITION?

We can continue asking in the same way, what type of organic compounds are found in living organisms? How does one go about finding the answer? To get an answer, one has to perform a chemical analysis. We can take any living tissue (a vegetable or a piece of liver, etc.) and grind it in trichloroacetic acid (Cl_3CCOOH) using a mortar and a pestle. We obtain a thick slurry. If we were to strain this through a cheesecloth or cotton we would obtain two fractions. One is called the filtrate or more technically, the acid-soluble pool, and the second, the retentate or the acid-insoluble fraction. Scientists have found thousands of organic compounds in the acid-soluble pool.

In higher classes you will learn about how to analyse a living tissue sample and identify a particular organic compound. It will suffice to say here that one extracts the compounds, then subjects the extract to various separation techniques till one has separated a compound from all other compounds. In other words, one isolates and purifies a compound. Analytical techniques, when applied to the compound give us an idea of the molecular formula and the probable structure of the compound. All the carbon compounds that we get from living tissues can be called 'biomolecules'. However, living organisms have also got inorganic elements and compounds in them. How do we know this? A slightly different but destructive experiment has to be done. One weighs a small amount of a living tissue (say a leaf or liver and this is called wet weight) and dry it. All the water, evaporates. The remaining material gives dry weight. Now if the tissue is fully burnt, all the carbon compounds are oxidised to gaseous form (CO_2, water vapour) and are removed. What is remaining is called 'ash'. This ash contains inorganic elements (like calcium, magnesium etc). Inorganic compounds like sulphate, phosphate, etc., are also seen in the acid-soluble fraction. Therefore elemental analysis gives elemental composition of living tissues in the form of hydrogen, oxygen, chlorine, carbon etc. while analysis for compounds gives an idea of the kind of organic (Figure 9.1) and inorganic constituents (Table 9.2) present in living tissues. From a chemistry point of view, one can identify functional groups like aldehydes, ketones, aromatic compounds, etc. But from a biological point of view, we shall classify them into amino acids, nucleotide bases, fatty acids etc.

TABLE 9.1 A Comparison of Elements Present in Non-living and Living Matter*

Element	% Weight of Earth's crust	% Weight of Human body
Hydrogen (H)	0.14	0.5
Carbon (C)	0.03	18.5
Oxygen (O)	46.6	65.0
Nitrogen (N)	very little	3.3
Sulphur (S)	0.03	0.3
Sodium (Na)	2.8	0.2
Calcium (Ca)	3.6	1.5
Magnesium (Mg)	2.1	0.1
Silicon (Si)	27.7	negligible

* Adapted from CNR Rao, *Understanding Chemistry*, Universities Press, Hyderabad.

TABLE 9.2 A List of Representative Inorganic Constituents of Living Tissues

Component	Formula
Sodium	Na^+
Potassium	K^+
Calcium	Ca^{++}
Magnesium	Mg^{++}
Water	H_2O
Compounds	$NaCl$, $CaCO_3$, PO_4^{3-}, SO_4^{2-}

Amino acids are organic compounds containing an amino group and an acidic group as substituents on the same carbon i.e., the α-carbon. Hence, they are called α-amino acids. They are substituted methanes. There are four substituent groups occupying the four valency positions. These are hydrogen, carboxyl group, amino group and a variable group designated as R group. Based on the nature of R group there are many amino acids. However, those which occur in proteins are only of twenty one types. The R group in these proteinaceous amino acids could be a hydrogen (the amino acid is called glycine), a methyl group (alanine), hydroxy methyl (serine), etc. Three of the twenty one are shown in Figure 9.1.

The chemical and physical properties of amino acids are essentially of the amino, carboxyl and the R functional groups. Based on number of amino and carboxyl groups, there are acidic (e.g., glutamic acid), basic (lysine) and neutral (valine) amino acids. Similarly, there are aromatic amino acids (tyrosine, phenylalanine, tryptophan). A particular property of amino acids is the ionizable nature of $-NH_2$ and $-COOH$ groups. Hence in solutions of different pHs, the structure of amino acids changes.

$$\underset{(A)}{H_3\overset{+}{N}-\overset{\overset{R}{|}}{CH}-COOH} \rightleftharpoons \underset{(B)}{H_3\overset{+}{N}-\overset{\overset{R}{|}}{CH}-COO^-} \rightleftharpoons \underset{(C)}{H_2N-\overset{\overset{R}{|}}{CH}-COO^-}$$

B is called zwitterionic form.

Lipids are generally water insoluble. They could be simple fatty acids. A fatty acid has a carboxyl group attached to an R group. The R group could be a methyl ($-CH_3$), or ethyl ($-C_2H_5$) or higher number of $-CH_2$ groups (1 carbon to 19 carbons). For example, palmitic acid has 16 carbons including carboxyl carbon. Arachidonic acid has 20 carbon atoms including the carboxyl carbon. Fatty acids could be saturated (without double bond) or unsaturated (with one or more C=C double bonds). Another simple lipid is glycerol which is trihydroxy propane. Many lipids have both glycerol and fatty acids. Here the fatty acids are found esterified with glycerol. They can be then monoglycerides, diglycerides and triglycerides. These are also called fats and oils based on melting point. Oils have lower melting point (e.g., gingely oil) and hence remain as oil in winters. Can you identify a fat from the market? Some lipids have phosphorous and a phosphorylated organic compound in them. These are phospholipids. They are found in cell membrane. Lecithin is one example. Some tissues especially the neural tissues have lipids with more complex structures.

Living organisms have a number of carbon compounds in which heterocyclic rings can be found. Some of these are nitrogen bases – adenine, guanine, cytosine, uracil, and thymine. When found attached to a sugar, they are called nucleosides. If a phosphate group is also found esterified to the sugar they are called nucleotides. Adenosine, guanosine, thymidine, uridine and cytidine are nucleosides. Adenylic acid, thymidylic acid, guanylic acid, uridylic acid and cytidylic acid are nucleotides. Nucleic acids like DNA and RNA consist of nucleotides only. DNA and RNA function as genetic material.

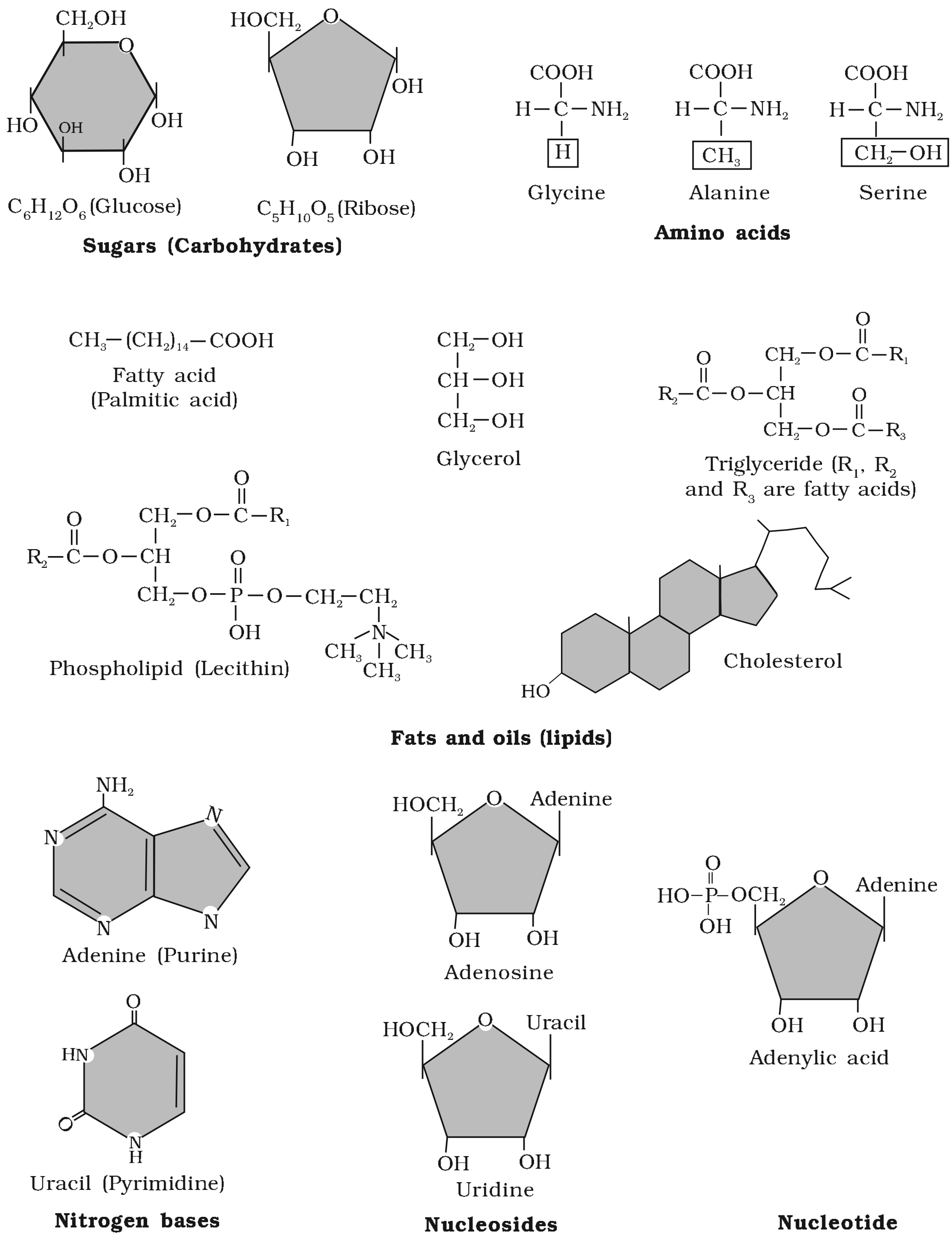


Figure 9.1 Diagrammatic representation of small molecular weight organic compounds in living tissues

9.2 Primary and Secondary Metabolites

The most exciting aspect of chemistry deals with isolating thousands of compounds, small and big, from living organisms, determining their structure and if possible synthesising them.

If one were to make a list of biomolecules, such a list would have thousands of organic compounds including amino acids, sugars, etc. For reasons that are given in section 9.10, we can call these biomolecules as 'metabolites'. In animal tissues, one notices the presence of all such categories of compounds shown in Figure 9.1. These are called primary metabolites. However, when one analyses plant, fungal and microbial cells, one would see thousands of compounds other than these called primary metabolites, e.g. alkaloides, flavonoides, rubber, essential oils, antibiotics, coloured pigments, scents, gums, spices. These are called **secondary metabolites** (Table 9.3). While primary metabolites have identifiable functions and play known roles in normal physiologial processes, we do not at the moment, understand the role or functions of all the 'secondary metabolites' in host organisms. However, many of them are useful to 'human welfare' (e.g., rubber, drugs, spices, scents and pigments). Some secondary metabolites have ecological importance. In the later chapters and years you will learn more about this.

Table 9.3 Some Secondary Metabolites

Pigments	Carotenoids, Anthocyanins, etc.
Alkaloids	Morphine, Codeine, etc.
Terpenoides	Monoterpenes, Diterpenes etc.
Essential oils	Lemon grass oil, etc.
Toxins	Abrin, Ricin
Lectins	Concanavalin A
Drugs	Vinblastin, curcumin, etc.
Polymeric substances	Rubber, gums, cellulose

9.3 Biomacromolecules

There is one feature common to all those compounds found in the acid soluble pool. They have molecular weights ranging from 18 to around 800 daltons (Da) approximately.

The acid insoluble fraction, has only four types of organic compounds i.e., proteins, nucleic acids, polysaccharides and lipids. These classes of compounds with the exception of lipids, have molecular weights in the range of ten thousand daltons and above. For this very reason, biomolecules, i.e., chemical compounds found in living organisms are of two types. One, those which have molecular weights less than one thousand dalton and are usually referred to as micromolecules or simply biomolecules while those which are found in the acid insoluble fraction are called macromolecules or **biomacromolecules**.

The molecules in the insoluble fraction with the exception of lipids are polymeric substances. Then why do lipids, whose molecular weights do not exceed 800 Da, come under acid insoluble fraction, i.e., macromolecular fraction? Lipids are indeed small molecular weight compounds and are present not only as such but also arranged into structures like cell membrane and other membranes. When we grind a tissue, we are disrupting the cell structure. Cell membrane and other membranes are broken into pieces, and form vesicles which are not water soluble. Therefore, these membrane fragments in the form of vesicles get separated along with the acid insoluble pool and hence in the macromolecular fraction. Lipids are not strictly macromolecules.

The acid soluble pool represents roughly the cytoplasmic composition. The macromolecules from cytoplasm and organelles become the acid insoluble fraction. Together they represent the entire chemical composition of living tissues or organisms.

In summary if we represent the chemical composition of living tissue from abundance point of view and arrange them class-wise, we observe that water is the most abundant chemical in living organisms (Table 9.4).

TABLE 9.4 Average Composition of Cells

Component	% of the total cellular mass
Water	70-90
Proteins	10-15
Carbohydrates	3
Lipids	2
Nucleic acids	5-7
Ions	1

9.4 PROTEINS

Proteins are polypeptides. They are linear chains of amino acids linked by peptide bonds as shown in Figure 9.2.

Each protein is a polymer of amino acids. As there are 21 types of amino acids (e.g., alanine, cysteine, proline, tryptophan, lysine, etc.), a protein is a heteropolymer and not a homopolymer. A homopolymer has only one type of monomer repeating 'n' number of times. This information about the amino acid content is important as later in your nutrition lessons, you will learn that certain amino acids are essential for our health and they have to be supplied through our diet. Hence, dietary proteins are the source of essential amino acids. Therefore, amino acids can be essential or non-essential. The latter are those which our body can make, while we get essential amino acids through our diet/food. Proteins carry out many functions in living organisms, some transport nutrients across cell membrane, some fight infectious organisms, some are hormones, some are enzymes,

TABLE 9.5 Some Proteins and their Functions

Protein	Functions
Collagen	Intercellular ground substance
Trypsin	Enzyme
Insulin	Hormone
Antibody	Fights infectious agents
Receptor	Sensory reception (smell, taste, hormone, etc.)
GLUT-4	Enables glucose transport into cells

etc. (Table 9.5). Collagen is the most abundant protein in animal world and Ribulose bisphosphate Carboxylase-Oxygenase (RUBISCO) is the most abundant protein in the whole of the biosphere.

9.5 Polysaccharides

The acid insoluble pellet also has polysaccharides (carbohydrates) as another class of macromolecules. Polysaccharides are long chains of sugars. They are threads (literally a cotton thread) containing different monosaccharides as building blocks. For example cellulose is a polymeric polysaccharide consisting of only one type of monosaccharide i.e., glucose. Cellulose is a homopolymer. Starch is a variant of this but present as a store house of energy in plant tissues. Animals have another variant called glycogen. Inulin is a polymer of fructose. In a polysaccharide chain (say glycogen), the right end is called the reducing end and the left end is called the non-reducing end. It has branches as shown in the form of a cartoon (Figure 9.2). Starch forms helical secondary structures. In fact, starch can hold I_2 molecules in the helical portion. The starch-I_2 is blue in colour. Cellulose does not contain complex helices and hence cannot hold I_2.

Plant cell walls are made of cellulose. Paper made from plant pulp is

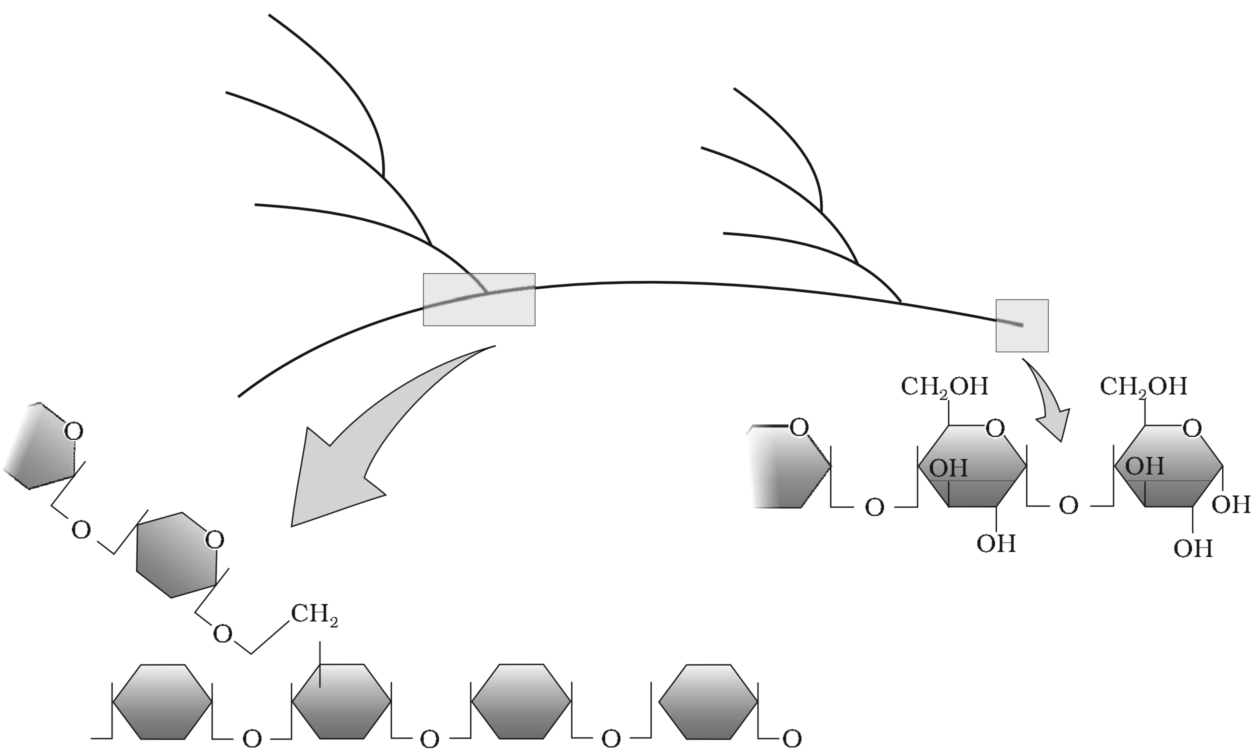


Figure 9.2 Diagrammatic representation of a portion of glycogen

cellulose. Cotton fibre is cellulose. There are more complex polysaccharides in nature. They have as building blocks, amino-sugars and chemically modified sugars (e.g., glucosamine, N-acetyl galactosamine, etc.). Exoskeletons of arthropods, for example, have a complex polysaccharide called chitin. These complex polysaccharides are heteropolymers.

9.6 NUCLEIC ACIDS

The other type of macromolecule that one would find in the acid insoluble fraction of any living tissue is the nucleic acid. These are polynucleotides. Together with polysaccharides and polypeptides these comprise the true macromolecular fraction of any living tissue or cell. For nucleic acids, the building block is a nucleotide. A nucleotide has three chemically distinct components. One is a heterocyclic compound, the second is a monosaccharide and the third a phosphoric acid or phosphate.

As you notice in Figure 9.1, the heterocyclic compounds in nucleic acids are the nitrogenous bases named adenine, guanine, uracil, cytosine, and thymine. Adenine and Guanine are substituted purines while the rest are substituted pyrimidines. The skeletal heterocyclic ring is called as purine and pyrimidine respectively. The sugar found in polynucleotides is either ribose (a monosaccharide pentose) or 2' deoxyribose. A nucleic acid containing deoxyribose is called deoxyribonucleic acid (DNA) while that which contains ribose is called ribonucleic acid (RNA).

9.7 STRUCTURE OF PROTEINS

Proteins, as mentioned earlier, are heteropolymers containing strings of amino acids. Structure of molecules means different things in different contexts. In inorganic chemistry, the structure invariably refers to the molecular formulae (e.g., $NaCl$, $MgCl_2$, etc.). Organic chemists always write a two dimensional view of the molecules while representing the structure of the molecules (e.g., benzene, naphthalene, etc.). Physicists conjure up the three dimensional views of molecular structures while biologists describe the protein structure at four levels. The sequence of amino acids i.e., the positional information in a protein – which is the first amino acid, which is second, and so on – is called the **primary structure** (Figure 9.3) of a protein. A protein is imagined as a line, the left end represented by the first amino acid and the right end represented by the last amino acid. The first aminoacid is also called as N-terminal amino acid. The last amino acid is called the C-terminal amino acid. A protein thread does not exist throughout as an extended rigid rod. The thread is folded in the form of a helix (similar to a revolving staircase). Of course, only some portions of

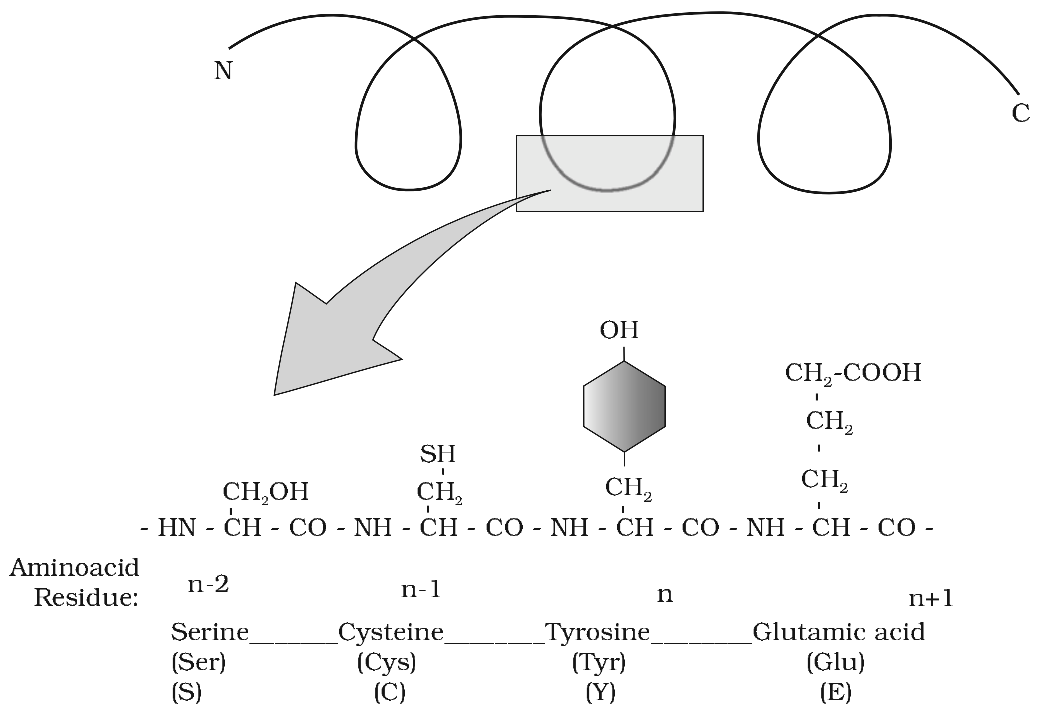


Figure 9.3 Primary structure of a portion of a hypothetical protein. N and C refer to the two termini of every protein. Single letter codes and three letter abbreviations for amino acids are also indicated.

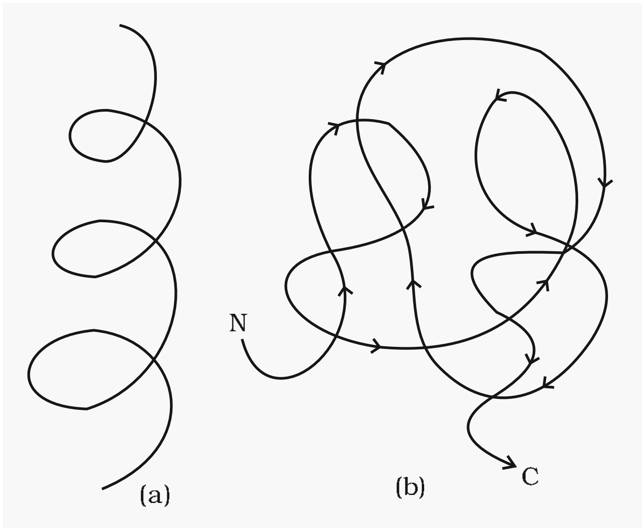


Figure 9.4 Cartoon showing : (a) A secondary structure and (b) A tertiary structure of proteins

the protein thread are arranged in the form of a helix. In proteins, only right handed helices are observed. Other regions of the protein thread are folded into other forms in what is called the **secondary structure**. In addition, the long protein chain is also folded upon itself like a hollow wollen ball, giving rise to the **tertiary structure** (Figure 9.4 a, b). This gives us a 3-dimensional view of a protein. Tertiary structure is absolutely necessary for the many biological activities of proteins.

Some proteins are an assembly of more than one polypeptide or subunits. The manner in which these individual folded polypeptides or subunits are arranged with respect to each other (e.g. linear string of spheres, spheres arranged one upon each other in the form of a cube or plate etc.) is the architecture of a protein otherwise called the **quaternary structure** of a protein. Adult human haemoglobin consists of 4 subunits. Two of these are identical to each other. Hence, two subunits of α type and two subunits of β type together constitute the human haemoglobin (Hb).

9.8 Nature of Bond Linking Monomers in a Polymer

In a polypeptide or a protein, amino acids are linked by a **peptide bond** which is formed when the carboxyl (-COOH) group of one amino acid reacts with the amino ($-NH_2$) group of the next amino acid with the elimination of a water moiety (the process is called dehydration). In a polysaccharide the individual monosaccharides are linked by a **glycosidic bond**. This bond is also formed by dehydration. This bond is formed between two carbon atoms of two adjacent monosaccharides. In a nucleic acid a phosphate moiety links the 3'-carbon of one sugar of one nucleotide to the 5'-carbon of the sugar of the succeeding nucleotide. The bond between the phosphate and hydroxyl group of sugar is an ester bond. As there is one such ester bond on either side, it is called phosphodiester bond (Figure 9.5).

Nucleic acids exhibit a wide variety of secondary structures. For example, one of the secondary structures exhibited by DNA is the famous Watson-Crick model. This model says that DNA exists as a double helix. The two strands of polynucleotides are antiparallel i.e., run in the opposite direction. The backbone is formed by the sugar-phosphate-sugar chain. The nitrogen bases are projected more or less perpendicular to this backbone but face inside. A and G of one strand compulsorily base pairs

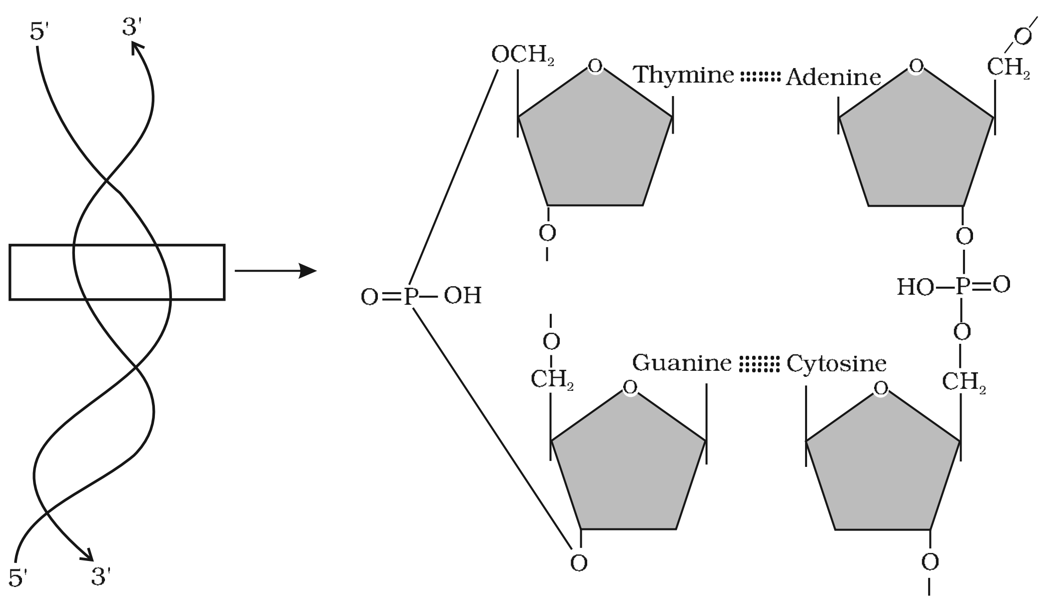


Figure 9.5 Diagram indicating secondary structure of DNA

with T and C, respectively, on the other strand. There are two hydrogen bonds between A and T. There are three hydrogen bonds between G and C. Each strand appears like a helical staircase. Each step of ascent is represented by a pair of bases. At each step of ascent, the strand turns 36°. One full turn of the helical strand would involve ten steps or ten base pairs. Attempt drawing a line diagram. The pitch would be 34Å. The rise per base pair would be 3.4Å. This form of DNA with the above mentioned salient features is called B-DNA. In higher classes, you will be told that there are more than a dozen forms of DNA named after English alphabets with unique structural features.

9.9 Dynamic State of Body Constituents – Concept of Metabolism

What we have learnt till now is that living organisms, be it a simple bacterial cell, a protozoan, a plant or an animal, contain thousands of organic compounds. These compounds or biomolecules are present in certain concentrations (expressed as mols/cell or mols/litre etc.). One of the greatest discoveries ever made was the observation that all these biomolecules have a **turn over**. This means that they are constantly being changed into some other biomolecules and also made from some other biomolecules. This breaking and making is through chemical reactions constantly occuring in living organisms. Together all these chemical reactions are called **metabolism**. Each of the metabolic reactions results in the transformation of biomolecules. A few examples for such metabolic transformations are: removal of CO_2 from amino acids making an amino acid into an amine, removal of amino group in a nucleotide base; hydrolysis of a glycosidic bond in a disaccharide, etc. We can list tens and thousands of such examples. Majority of these metabolic reactions do not occur in isolation but are always linked to some other reactions. In other words, metabolites are converted into each other in a series of linked reactions called metabolic pathways. These metabolic pathways are similar to the automobile traffic in a city. These pathways are either linear or circular. These pathways criss-cross each other, i.e., there are traffic junctions. Flow of metabolites through metabolic pathway has a definite rate and direction like automobile traffic. This metabolite flow is called the dynamic state of body constituents. What is most important is that this interlinked metabolic traffic is very smooth and without a single reported mishap for healthy conditions. Another feature of these metabolic reactions is that every chemical reaction is a **catalysed reaction**. There is no uncatalysed metabolic conversion in living systems. Even CO_2 dissolving in water, a physical process, is a catalysed reaction in living systems. The catalysts which hasten the rate of a given metabolic conversation are also proteins. These proteins with catalytic power are named **enzymes**.

9.10 METABOLIC BASIS FOR LIVING

Metabolic pathways can lead to a more complex structure from a simpler structure (for example, acetic acid becomes cholesterol) or lead to a simpler structure from a complex structure (for example, glucose becomes lactic acid in our skeletal muscle). The former cases are called biosynthetic pathways or **anabolic** pathways. The latter constitute degradation and hence are called **catabolic** pathways. Anabolic pathways, as expected, consume energy. Assembly of a protein from amino acids requires energy input. On the other hand, catabolic pathways lead to the release of energy. For example, when glucose is degraded to lactic acid in our skeletal muscle, energy is liberated. This metabolic pathway from glucose to lactic acid which occurs in 10 metabolic steps is called glycolysis. Living organisms have learnt to trap this energy liberated during degradation and store it in the form of chemical bonds. As and when needed, this bond energy is utilised for biosynthetic, osmotic and mechanical work that we perform. The most important form of energy currency in living systems is the bond energy in a chemical called **adenosine triphosphate (ATP)**.

How do living organisms derive their energy? What strategies have they evolved? How do they store this energy and in what form? How do they convert this energy into work? You will study and understand all this under a sub-discipline called 'Bioenergetics' later in your higher classes.

9.11 THE LIVING STATE

At this level, you must understand that the tens and thousands of chemical compounds in a living organism, otherwise called metabolites, or biomolecules, are present at concentrations characteristic of each of them. For example, the blood concentration of glucose in a normal healthy individual is 4.5-5.0 mM, while that of hormones would be nanograms/mL. The most important fact of biological systems is that all living organisms exist in a steady-state characterised by concentrations of each of these biomolecules. These biomolecules are in a metabolic flux. Any chemical or physical process moves spontaneously to equilibrium. The steady state is a non-equilibirium state. One should remember from physics that systems at equilibrium cannot perform work. As living organisms work continuously, they cannot afford to reach equilibrium. **Hence the living state is a non-equilibrium steady-state to be able to perform work**; living process is a constant effort to prevent falling into equilibrium. This is achieved by energy input. Metabolism provides a mechanism for the production of energy. Hence the living state and metabolism are synonymous. Without metabolism there cannot be a living state.

9.12 ENZYMES

Almost all enzymes are proteins. There are some nucleic acids that behave like enzymes. These are called ribozymes. One can depict an enzyme by a line diagram. An enzyme like any protein has a primary structure, i.e., amino acid sequence of the protein. An enzyme like any protein has the secondary and the tertiary structure. When you look at a tertiary structure (Figure 9.4 b) you will notice that the backbone of the protein chain folds upon itself, the chain criss-crosses itself and hence, many crevices or pockets are made. One such pocket is the 'active site'. An active site of an enzyme is a crevice or pocket into which the substrate fits. Thus enzymes, through their active site, catalyse reactions at a high rate. Enzyme catalysts differ from inorganic catalysts in many ways, but one major difference needs mention. Inorganic catalysts work efficiently at high temperatures and high pressures, while enzymes get damaged at high temperatures (say above 40°C). However, enzymes isolated from organisms who normally live under extremely high temperatures (e.g., hot vents and sulphur springs), are stable and retain their catalytic power even at high temperatures (upto 80°-90°C). Thermal stability is thus an important quality of such enzymes isolated from thermophilic organisms.

9.12.1 Chemical Reactions

How do we understand these enzymes? Let us first understand a chemical reaction. Chemical compounds undergo two types of changes. A physical change simply refers to a change in shape without breaking of bonds. This is a physical process. Another physical process is a change in state of matter: when ice melts into water, or when water becomes a vapour. These are physical processes. However, when bonds are broken and new bonds are formed during transformation, this will be called a chemical reaction. For example:

$$Ba(OH)_2 + H_2SO_4 \rightarrow BaSO_4 + 2H_2O$$

is an inorganic chemical reaction. Similarly, hydrolysis of starch into glucose is an organic chemical reaction. Rate of a physical or chemical process refers to the amount of product formed per unit time. It can be expressed as:

$$\text{rate} = \frac{\delta P}{\delta t}$$

Rate can also be called velocity if the direction is specified. Rates of physical and chemical processes are influenced by temperature among other factors. A general rule of thumb is that rate doubles or decreases by half for every 10°C change in either direction. Catalysed reactions proceed at rates vastly higher than that of uncatalysed ones. When enzyme catalysed reactions are observed, the rate would be vastly higher than the same but uncatalysed reaction. For example

$$\underset{\text{carbon dioxide}}{CO_2} + \underset{\text{water}}{H_2O} \xrightarrow{\text{Carbonic anhydrase}} \underset{\text{carbonic acid}}{H_2CO_3}$$

In the absence of any enzyme this reaction is very slow, with about 200 molecules of H_2CO_3 being formed in an hour. However, by using the enzyme present within the cytoplasm called carbonic anhydrase, the reaction speeds dramatically with about 600,000 molecules being formed every second. The enzyme has accelerated the reaction rate by about 10 million times. The power of enzymes is incredible indeed!

There are thousands of types of enzymes each catalysing a unique chemical or metabolic reaction. A multistep chemical reaction, when each of the steps is catalysed by the same enzyme complex or different enzymes, is called a metabolic pathway. For example,

$$\text{Glucose} \rightarrow 2 \text{ Pyruvic acid}$$

$$C_6H_{12}O_6 + O_2 \rightarrow 2C_3H_4O_3 + 2H_2O$$

is actually a metabolic pathway in which glucose becomes pyruvic acid through ten different enzyme catalysed metabolic reactions. When you study respiration in Chapter 14 you will study these reactions. At this stage you should know that this very metabolic pathway with one or two additional reactions gives rise to a variety of metabolic end products. In our skeletal muscle, under anaerobic conditions, lactic acid is formed. Under normal aerobic conditions, pyruvic acid is formed. In yeast, during fermentation, the same pathway leads to the production of ethanol (alcohol). Hence, in different conditions different products are possible.

9.12.2 How do Enzymes bring about such High Rates of Chemical Conversions?

To understand this we should study enzymes a little more. We have already understood the idea of an 'active site'. The chemical or metabolic conversion refers to a reaction. The chemical which is converted into a product is called a 'substrate'. Hence enzymes, i.e. proteins with three dimensional structures including an 'active site', convert a substrate (S) into a product (P). Symbolically, this can be depicted as:

$$S \rightarrow P$$

It is now understood that the substrate 'S' has to bind the enzyme at its 'active site' within a given cleft or pocket. The substrate has to diffuse

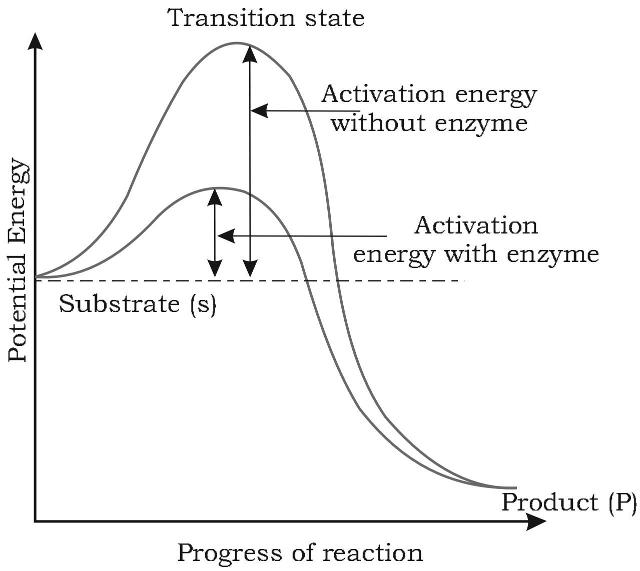


Figure 9.6 Concept of activation energy

towards the 'active site'. There is thus, an obligatory formation of an 'ES' complex. E stands for enzyme. This complex formation is a transient phenomenon. During the state where substrate is bound to the enzyme active site, a new structure of the substrate called transition state structure is formed. Very soon, after the expected bond breaking/making is completed, the product is released from the active site. In other words, the structure of substrate gets transformed into the structure of product(s). The pathway of this transformation must go through the so-called transition state structure. There could be many more 'altered structural states' between the stable substrate and the product. Implicit in this statement is the fact that all other intermediate structural states are unstable. Stability is something related to energy status of the molecule or the structure. Hence, when we look at this pictorially through a graph it looks like something as in Figure 9.6.

The y-axis represents the potential energy content. The x-axis represents the progression of the structural transformation or states through the 'transition state'. You would notice two things. The energy level difference between S and P. If 'P' is at a lower level than 'S', the reaction is an exothermic reaction. One need not supply energy (by heating) in order to form the product. However, whether it is an exothermic or spontaneous reaction or an endothermic or energy requiring reaction, the 'S' has to go through a much higher energy state or transition state. The difference in average energy content of 'S' from that of this transition state is called 'activation energy'.

Enzymes eventually bring down this energy barrier making the transition of 'S' to 'P' more easy.

9.12.3 Nature of Enzyme Action

Each enzyme (E) has a substrate (S) binding site in its molecule so that a highly reactive enzyme-substrate complex (ES) is produced. This complex is short-lived and dissociates into its product(s) P and the unchanged enzyme with an intermediate formation of the enzyme-product complex (EP).

The formation of the ES complex is essential for catalysis.

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

The catalytic cycle of an enzyme action can be described in the following steps:

1. First, the substrate binds to the active site of the enzyme, fitting into the active site.
2. The binding of the substrate induces the enzyme to alter its shape, fitting more tightly around the substrate.
3. The active site of the enzyme, now in close proximity of the substrate breaks the chemical bonds of the substrate and the new enzyme- product complex is formed.
4. The enzyme releases the products of the reaction and the free enzyme is ready to bind to another molecule of the substrate and run through the catalytic cycle once again.

9.12.4 Factors Affecting Enzyme Activity

The activity of an enzyme can be affected by a change in the conditions which can alter the tertiary structure of the protein. These include temperature, pH, change in substrate concentration or binding of specific chemicals that regulate its activity.

Temperature and pH

Enzymes generally function in a narrow range of temperature and pH (Figure 9.7). Each enzyme shows its highest activity at a particular temperature and pH called the optimum temperature and optimum pH. Activity declines both below and above the optimum value. Low temperature preserves the enzyme in a temporarily inactive state whereas high temperature destroys enzymatic activity because proteins are denatured by heat.

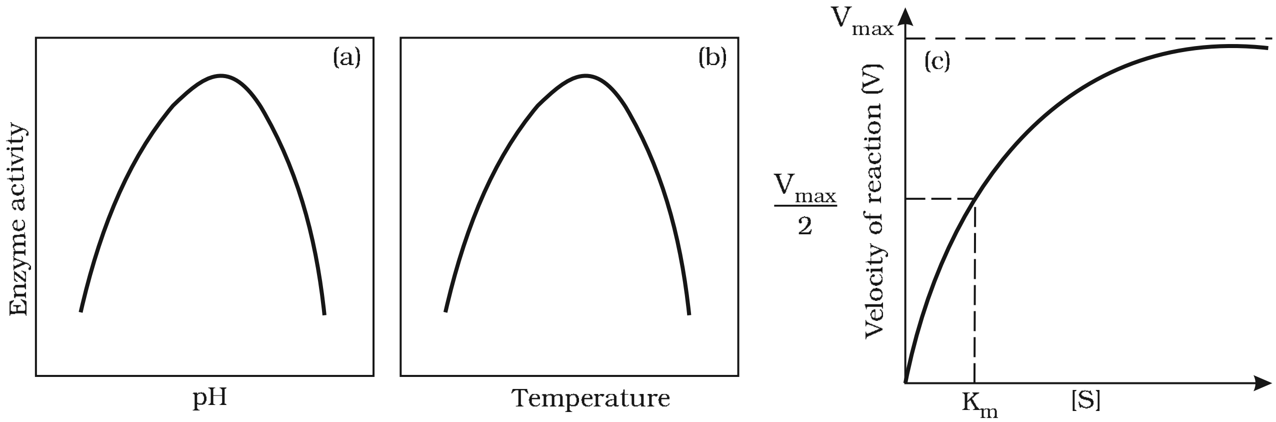


Figure 9.7 Effect of change in : (a) pH (b) Temperature and (c) Concentration of substrate on enzyme activity

Concentration of Substrate

With the increase in substrate concentration, the velocity of the enzymatic reaction rises at first. The reaction ultimately reaches a maximum velocity (V_{max}) which is not exceeded by any further rise in concentration of the substrate. This is because the enzyme molecules are fewer than the substrate molecules and after saturation of these molecules, there are no free enzyme molecules to bind with the additional substrate molecules (Figure 9.7).

The activity of an enzyme is also sensitive to the presence of specific chemicals that bind to the enzyme. When the binding of the chemical shuts off enzyme activity, the process is called **inhibition** and the chemical is called an **inhibitor**.

When the inhibitor closely resembles the substrate in its molecular structure and inhibits the activity of the enzyme, it is known as **competitive inhibitor**. Due to its close structural similarity with the substrate, the inhibitor competes with the substrate for the substrate-binding site of the enzyme. Consequently, the substrate cannot bind and as a result, the enzyme action declines, e.g., inhibition of succinic dehydrogenase by malonate which closely resembles the substrate succinate in structure. Such competitive inhibitors are often used in the control of bacterial pathogens.

9.12.5 Classification and Nomenclature of Enzymes

Thousands of enzymes have been discovered, isolated and studied. Most of these enzymes have been classified into different groups based on the type of reactions they catalyse. Enzymes are divided into 6 classes each with 4-13 subclasses and named accordingly by a four-digit number.

Oxidoreductases/dehydrogenases: Enzymes which catalyse oxidoreduction between two substrates S and S' e.g.,

$$\text{S reduced} + \text{S' oxidised} \longrightarrow \text{S oxidised} + \text{S' reduced.}$$

Transferases: Enzymes catalysing a transfer of a group, G (other than hydrogen) between a pair of substrate S and S' e.g.,

$$\text{S - G} + \text{S'} \longrightarrow \text{S} + \text{S' - G}$$

Hydrolases: Enzymes catalysing hydrolysis of ester, ether, peptide, glycosidic, C-C, C-halide or P-N bonds.

Lyases: Enzymes that catalyse removal of groups from substrates by mechanisms other than hydrolysis leaving double bonds.

$$\begin{matrix} \text{X} & \text{Y} \\ | & | \\ \text{C} & \!\!-\!\! & \text{C} \end{matrix} \longrightarrow \text{X - Y} + \text{C} = \text{C}$$

Isomerases: Includes all enzymes catalysing inter-conversion of optical, geometric or positional isomers.

Ligases: Enzymes catalysing the linking together of 2 compounds, e.g., enzymes which catalyse joining of C-O, C-S, C-N, P-O etc. bonds.

9.12.6 Co-factors

Enzymes are composed of one or several polypeptide chains. However, there are a number of cases in which non-protein constituents called co-factors are bound to the the enzyme to make the enzyme catalytically active. In these instances, the protein portion of the enzymes is called the apoenzyme. Three kinds of cofactors may be identified: prosthetic groups, co-enzymes and metal ions.

Prosthetic groups are organic compounds and are distinguished from other cofactors in that they are tightly bound to the apoenzyme. For example, in peroxidase and catalase, which catalyze the breakdown of hydrogen peroxide to water and oxygen, haem is the prosthetic group and it is a part of the active site of the enzyme.

Co-enzymes are also organic compounds but their association with the apoenzyme is only transient, usually occurring during the course of catalysis. Furthermore, co-enzymes serve as co-factors in a number of different enzyme catalyzed reactions. The essential chemical components of many coenzymes are vitamins, e.g., coenzyme nicotinamide adenine dinucleotide (NAD) and NADP contain the vitamin niacin.

A number of enzymes require metal ions for their activity which form coordination bonds with side chains at the active site and at the same time form one or more cordination bonds with the substrate, e.g., zinc is a cofactor for the proteolytic enzyme carboxypeptidase.

Catalytic activity is lost when the co-factor is removed from the enzyme which testifies that they play a crucial role in the catalytic activity of the enzyme.

SUMMARY

Although there is a bewildering diversity of living organisms, their chemical composition and metabolic reactions appear to be remarkably similar. The elemental composition of living tissues and non-living matter appear also to be similar when analysed qualitatively. However, a closer examination reveals that the relative abundance of carbon, hydrogen and oxygen is higher in living systems when compared to inanimate matter. The most abundant chemical in living organisms is water. There are thousands of small molecular weight (<1000 Da)

biomolecules. Amino acids, monosaccharide and disaccharide sugars, fatty acids, glycerol, nucleotides, nucleosides and nitrogen bases are some of the organic compounds seen in living organisms. There are 21 types of amino acids and 5 types of nucleotides. Fats and oils are glycerides in which fatty acids are esterified to glycerol. Phospholipids contain, in addition, a phosphorylated nitrogenous compound.

Only three types of macromolecules, i.e., proteins, nucleic acids and polysaccharides are found in living systems. Lipids, because of their association with membranes separate in the macromolecular fraction. Biomacromolecules are polymers. They are made of building blocks which are different. Proteins are heteropolymers made of amino acids. Nucleic acids (RNA and DNA) are composed of nucleotides. Biomacromolecules have a hierarchy of structures – primary, secondary, tertiary and quaternary. Nucleic acids serve as genetic material. Polysaccharides are components of cell wall in plants, fungi and also of the exoskeleton of arthropods. They also are storage forms of energy (e.g., starch and glycogen). Proteins serve a variety of cellular functions. Many of them are enzymes, some are antibodies, some are receptors, some are hormones and some others are structural proteins. Collagen is the most abundant protein in animal world and Ribulose bisphosphate Carboxylase-Oxygenase (RUBISCO) is the most abundant protein in the whole of the biosphere.

Enzymes are proteins which catalyse biochemical reactions in the cells. Ribozymes are nucleic acids with catalytic power. Proteinaceous enzymes exhibit substrate specificity, require optimum temperature and pH for maximal activity. They are denatured at high temperatures. Enzymes lower activation energy of reactions and enhance greatly the rate of the reactions. Nucleic acids carry hereditary information and are passed on from parental generation to progeny.

EXERCISES

1. What are macromolecules? Give examples.
2. Illustrate a glycosidic, peptide and a phospho-diester bond.
3. What is meant by tertiary structure of proteins?
4. Find and write down structures of 10 interesting small molecular weight biomolecules. Find if there is any industry which manufactures the compounds by isolation. Find out who are the buyers.
5. Proteins have primary structure. If you are given a method to know which amino acid is at either of the two termini (ends) of a protein, can you connect this information to purity or homogeneity of a protein?
6. Find out and make a list of proteins used as therapeutic agents. Find other applications of proteins (e.g., Cosmetics etc.)
7. Explain the composition of triglyceride.

8. Can you describe what happens when milk is converted into curd or yoghurt, from your understanding of proteins.
9. Can you attempt building models of biomolecules using commercially available atomic models (Ball and Stick models).
10. Attempt titrating an amino acid against a weak base and discover the number of dissociating (ionizable) functional groups in the amino acid.
11. Draw the structure of the amino acid, alanine.
12. What are gums made of? Is Fevicol different?
13. Find out a qualitative test for proteins, fats and oils, amino acids and test any fruit juice, saliva, sweat and urine for them.
14. Find out how much cellulose is made by all the plants in the biosphere and compare it with how much of paper is manufactured by man and hence what is the consumption of plant material by man annually. What a loss of vegetation!
15. Describe the important properties of enzymes.

Chapter 10

Cell Cycle and Cell Division

Are you aware that all organisms, even the largest, start their life from a single cell? You may wonder how a single cell then goes on to form such large organisms. Growth and reproduction are characteristics of cells, indeed of all living organisms. All cells reproduce by dividing into two, with each parental cell giving rise to two daughter cells each time they divide. These newly formed daughter cells can themselves grow and divide, giving rise to a new cell population that is formed by the growth and division of a single parental cell and its progeny. In other words, such cycles of growth and division allow a single cell to form a structure consisting of millions of cells.

10.1 Cell Cycle

Cell division is a very important process in all living organisms. During the division of a cell, DNA replication and cell growth also take place. All these processes, i.e., cell division, DNA replication, and cell growth, hence, have to take place in a coordinated way to ensure correct division and formation of progeny cells containing intact genomes. The sequence of events by which a cell duplicates its genome, synthesises the other constituents of the cell and eventually divides into two daughter cells is termed **cell cycle.** Although cell growth (in terms of cytoplasmic increase) is a continuous process, DNA synthesis occurs only during one specific stage in the cell cycle. The replicated chromosomes (DNA) are then distributed to daughter nuclei by a complex series of events during cell division. These events are themselves under genetic control.

10.1.1 Phases of Cell Cycle

A typical eukaryotic cell cycle is illustrated by human cells in culture. These cells divide once in approximately every 24 hours (Figure 10.1). However, this duration of cell cycle can vary from organism to organism and also from cell type to cell type. Yeast for example, can progress through the cell cycle in only about 90 minutes.

The cell cycle is divided into two basic phases:

- **Interphase**
- **M Phase (Mitosis phase)**

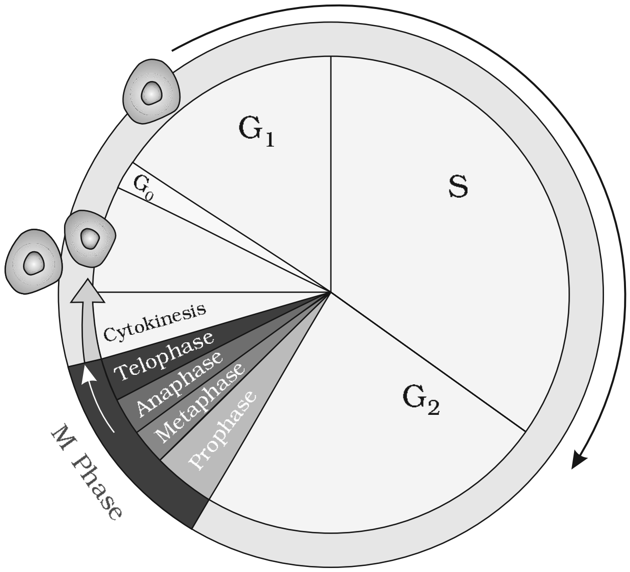


Figure 10.1 A diagrammatic view of cell cycle indicating formation of two cells from one cell

The M Phase represents the phase when the actual cell division or mitosis occurs and the interphase represents the phase between two successive M phases. It is significant to note that in the 24 hour average duration of cell cycle of a human cell, cell division proper lasts for only about an hour. The interphase lasts more than 95% of the duration of cell cycle.

The M Phase starts with the nuclear division, corresponding to the separation of daughter chromosomes **(karyokinesis)** and usually ends with division of cytoplasm **(cytokinesis).** The interphase, though called the resting phase, is the time during which the cell is preparing for division by undergoing both cell growth and DNA replication in an orderly manner. The interphase is divided into three further phases:

- **G_1 phase (Gap 1)**
- **S phase (Synthesis)**
- **G_2 phase (Gap 2)**

G_1 phase corresponds to the interval between mitosis and initiation of DNA replication. During G_1 phase the cell is metabolically active and continuously grows but does not replicate its DNA. S or **synthesis** phase marks the period during which DNA synthesis or replication takes place. During this time the amount of DNA per cell doubles. If the initial amount of DNA is denoted as 2C then it increases to 4C. However, there is no increase in the chromosome number; if the cell had diploid or 2n number of chromosomes at G_1, even after S phase the number of chromosomes remains the same, i.e., 2n.

In animal cells, during the S phase, DNA replication begins in the nucleus, and the centriole duplicates in the cytoplasm. During the G_2 phase, proteins are synthesised in preparation for mitosis while cell growth continues.

How do plants and animals continue to grow all their lives? Do all cells in a plant divide all the time? Do you think all cells continue to divide in all plants and animals? Can you tell the name and the location of tissues having cells that divide all their life in higher plants? Do animals have similar meristematic tissues?

You have studied mitosis in onion root tip cells. It has 14 chromosomes in each cell. Can you tell how many chromosomes will the cell have at G_1 phase, after S phase, and after M phase? Also, what will be the DNA content of the cells at G_1, after S and at G_2, if the content after M phase is 2C?

Some cells in the adult animals do not appear to exhibit division (e.g., heart cells) and many other cells divide only occasionally, as needed to replace cells that have been lost because of injury or cell death. These cells that do not divide further exit G_1 phase to enter an inactive stage called **quiescent stage (G_0)** of the cell cycle. Cells in this stage remain metabolically active but no longer proliferate unless called on to do so depending on the requirement of the organism.

In animals, mitotic cell division is only seen in the diploid somatic cells. Against this, the plants can show mitotic divisions in both haploid and diploid cells. From your recollection of examples of alternation of generations in plants (Chapter 3) identify plant species and stages at which mitosis is seen in haploid cells.

10.2 M Phase

This is the most dramatic period of the cell cycle, involving a major reorganisation of virtually all components of the cell. Since the number of chromosomes in the parent and progeny cells is the same, it is also called as **equational division.** Though for convenience mitosis has been divided into four stages of nuclear division, it is very essential to understand that cell division is a progressive process and very clear-cut lines cannot be drawn between various stages. Mitosis is divided into the following four stages:

- **Prophase**
- **Metaphase**
- **Anaphase**
- **Telophase**

10.2.1 Prophase

Prophase which is the first stage of mitosis follows the S and G_2 phases of interphase. In the S and G_2 phases the new DNA molecules formed are not distinct but interwined. Prophase is marked by the initiation of condensation of chromosomal material. The chromosomal material becomes untangled during the process of chromatin condensation (Figure 10.2 a). The centriole, which had undergone duplication during S phase of interphase, now begins to move towards opposite poles of the cell. The completion of prophase can thus be marked by the following characteristic events:

- Chromosomal material condenses to form compact mitotic chromosomes. Chromosomes are seen to be composed of two chromatids attached together at the centromere.
- Initiation of the assembly of mitotic spindle, the microtubules, the proteinaceous components of the cell cytoplasm help in the process.

Cells at the end of prophase, when viewed under the microscope, do not show golgi complexes, endoplasmic reticulum, nucleolus and the nuclear envelope.

10.2.2 Metaphase

The complete disintegration of the nuclear envelope marks the start of the second phase of mitosis, hence the chromosomes are spread through the cytoplasm of the cell. By this stage, condensation of chromosomes is completed and they can be observed clearly under the microscope. This then, is the stage at which morphology of chromosomes is most easily studied. At this stage, metaphase chromosome is made up of two sister chromatids, which are held together by the centromere (Figure 10.2 b). Small disc-shaped structures at the surface of the centromeres are called kinetochores. These structures serve as the sites of attachment of spindle fibres (formed by the spindle fibres) to the chromosomes that are moved into position at the centre of the cell. Hence, the metaphase is characterised by all the chromosomes coming to lie at the equator with one chromatid of each chromosome connected by its kinetochore to spindle fibres from one pole and its sister chromatid connected by its kinetochore to spindle fibres from the opposite pole (Figure 10.2 b). The plane of alignment of the chromosomes at metaphase is referred to as the **metaphase plate.** The key features of metaphase are:

- Spindle fibres attach to kinetochores of chromosomes.
- Chromosomes are moved to spindle equator and get aligned along metaphase plate through spindle fibres to both poles.

10.2.3 Anaphase

At the onset of anaphase, each chromosome arranged at the metaphase plate is split simultaneously and the two daughter chromatids, now referred to as chromosomes of the future daughter nuclei, begin their migration towards the two opposite poles. As each chromosome moves away from the equatorial plate, the centromere of each chromosome is towards the pole and hence at the leading edge, with the arms of the chromosome trailing behind (Figure 10.2 c). Thus, anaphase stage is characterised by

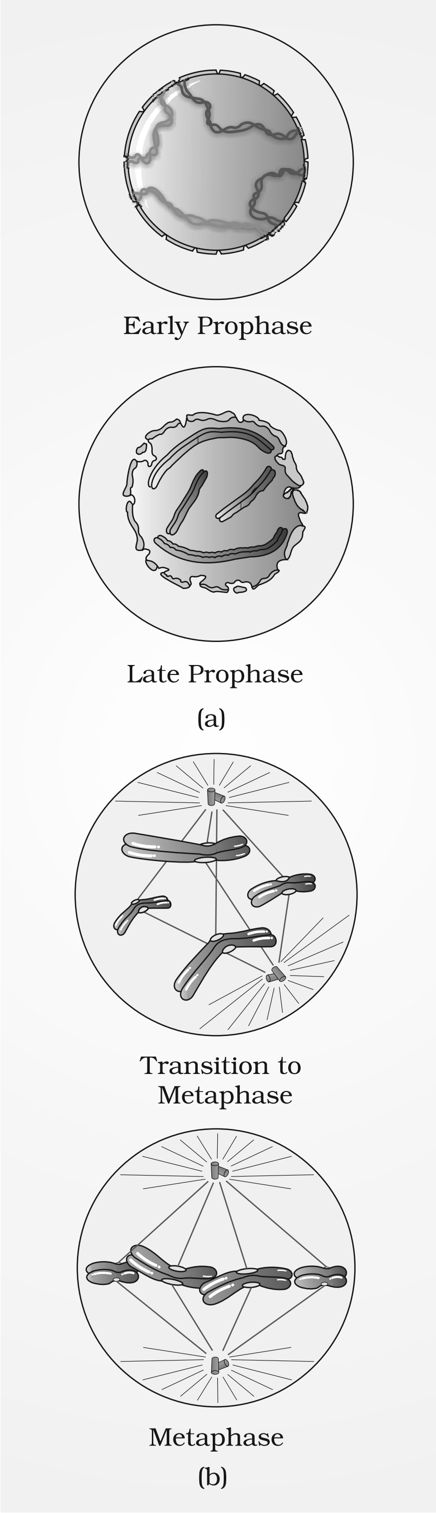


Figure 10.2 a and b : A diagrammatic view of stages in mitosis

the following key events:

- Centromeres split and chromatids separate.
- Chromatids move to opposite poles.

10.2.4 Telophase

At the beginning of the final stage of mitosis, i.e., telophase, the chromosomes that have reached their respective poles decondense and lose their individuality. The individual chromosomes can no longer be seen and chromatin material tends to collect in a mass in the two poles (Figure 10.2 d). This is the stage which shows the following key events:

- Chromosomes cluster at opposite spindle poles and their identity is lost as discrete elements.
- Nuclear envelope assembles around the chromosome clusters.
- Nucleolus, golgi complex and ER reform.

10.2.5 Cytokinesis

Mitosis accomplishes not only the segregation of duplicated chromosomes into daughter nuclei (karyokinesis), but the cell itself is divided into two daughter cells by a separate process called cytokinesis at the end of which cell division is complete (Figure 10.2 e). In an animal cell, this is achieved by the appearance of a furrow in the plasma membrane. The furrow gradually deepens and ultimately joins in the centre dividing the cell cytoplasm into two. Plant cells however, are enclosed by a relatively inextensible cell wall, thererfore they undergo cytokinesis by a different mechanism. In plant cells, wall formation starts in the centre of the cell and grows outward to meet the existing lateral walls. The formation of the new cell wall begins with the formation of a simple precursor, called the **cell-plate** that represents the middle lamella between the walls of two adjacent cells. At the time of cytoplasmic division, organelles like mitochondria and plastids get distributed between the two daughter cells. In some organisms karyokinesis is not followed by cytokinesis as a result of which multinucleate condition arises leading to the formation of syncytium (e.g., liquid endosperm in coconut).

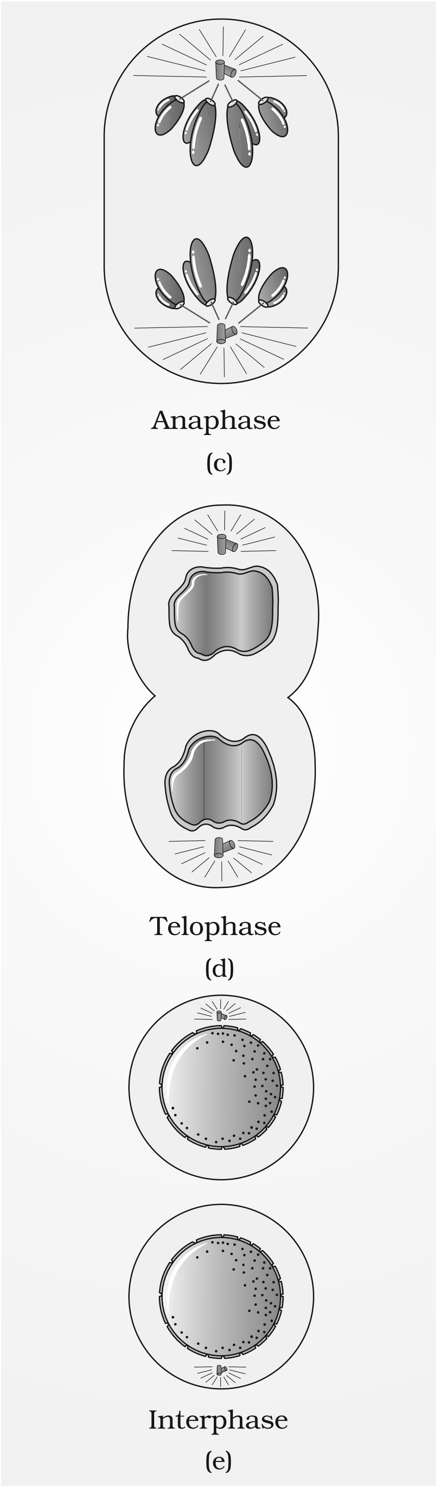


Figure 10.2 c to e : A diagrammatic view of stages in Mitosis

10.3 Significance of Mitosis

Mitosis or the equational division is usually restricted to the diploid cells only. However, in some lower plants and in some social insects haploid cells also divide by mitosis. It is very essential to understand the significance of this division in the life of an organism. Are you aware of some examples where you have studied about haploid and diploid insects?

Mitosis results in the production of diploid daughter cells with identical genetic complement usually. The growth of multicellular organisms is due to mitosis. Cell growth results in disturbing the ratio between the nucleus and the cytoplasm. It therefore becomes essential for the cell to divide to restore the nucleo-cytoplasmic ratio. A very significant contribution of mitosis is cell repair. The cells of the upper layer of the epidermis, cells of the lining of the gut, and blood cells are being constantly replaced. Mitotic divisions in the meristematic tissues – the apical and the lateral cambium, result in a continuous growth of plants throughout their life.

10.4 MEIOSIS

The production of offspring by sexual reproduction includes the fusion of two gametes, each with a complete haploid set of chromosomes. Gametes are formed from specialised diploid cells. This specialised kind of cell division that reduces the chromosome number by half results in the production of haploid daughter cells. This kind of division is called **meiosis.** Meiosis ensures the production of haploid phase in the life cycle of sexually reproducing organisms whereas fertilisation restores the diploid phase. We come across meiosis during gametogenesis in plants and animals. This leads to the formation of haploid gametes. The key features of meiosis are as follows:

- Meiosis involves two sequential cycles of nuclear and cell division called **meiosis I** and **meiosis II** but only a single cycle of DNA replication.
- Meiosis I is initiated after the parental chromosomes have replicated to produce identical sister chromatids at the S phase.
- Meiosis involves pairing of homologous chromosomes and recombination between them.
- Four haploid cells are formed at the end of meiosis II.

Meiotic events can be grouped under the following phases:

Meiosis I	**Meiosis II**
Prophase I	Prophase II
Metaphase I	Metaphase II
Anaphase I	Anaphase II
Telophase I	Telophase II

10.4.1 Meiosis I

Prophase I: Prophase of the first meiotic division is typically longer and more complex when compared to prophase of mitosis. It has been further subdivided into the following five phases based on chromosomal behaviour, i.e., Leptotene, Zygotene, Pachytene, Diplotene and Diakinesis.

During **leptotene** stage the chromosomes become gradually visible under the light microscope. The compaction of chromosomes continues throughout leptotene. This is followed by the second stage of prophase I called **zygotene**. During this stage chromosomes start pairing together and this process of association is called synapsis. Such paired chromosomes are called homologous chromosomes. Electron micrographs of this stage indicate that chromosome synapsis is accompanied by the formation of complex structure called **synaptonemal complex.** The complex formed by a pair of synapsed homologous chromosomes is called a **bivalent** or a tetrad. However, these are more clearly visible at the next stage. The first two stages of prophase I are relatively short-lived compared to the next stage that is **pachytene**. During this stage bivalent chromosomes now clearly appears as tetrads. This stage is characterised by the appearance of recombination nodules, the sites at which crossing over occurs between non-sister chromatids of the homologous chromosomes. Crossing over is the exchange of genetic material between two homologous chromosomes. Crossing over is also an enzyme-mediated process and the enzyme involved is called recombinase. Crossing over leads to recombination of genetic material on the two chromosomes. Recombination between homologous chromosomes is completed by the end of pachytene, leaving the chromosomes linked at the sites of crossing over.

The beginning of **diplotene** is recognised by the dissolution of the synaptonemal complex and the tendency of the recombined homologous chromosomes of the bivalents to separate from each other except at the sites of crossovers. These X-shaped structures, are called **chiasmata.** In oocytes of some vertebrates, diplotene can last for months or years.

The final stage of meiotic prophase I is **diakinesis.** This is marked by terminalisation of chiasmata. During this phase the chromosomes are fully condensed and the meiotic spindle is assembled to prepare the homologous chromosomes for separation. By the end of diakinesis, the nucleolus disappears and the nuclear envelope also breaks down. Diakinesis represents transition to metaphase.

Metaphase I: The bivalent chromosomes align on the equatorial plate (Figure 10.3). The microtubules from the opposite poles of the spindle attach to the pair of homologous chromosomes.

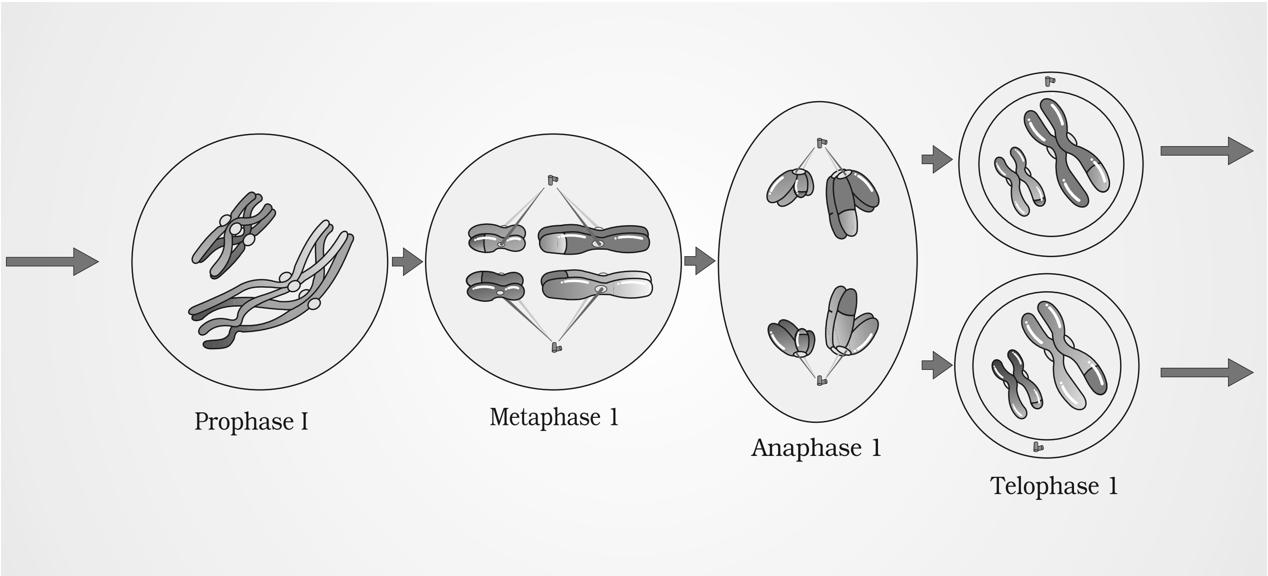


Figure 10.3 Stages of Meiosis I

Anaphase I: The homologous chromosomes separate, while sister chromatids remain associated at their centromeres (Figure 10.3).

Telophase I: The nuclear membrane and nucleolus reappear, cytokinesis follows and this is called as diad of cells (Figure 10.3). Although in many cases the chromosomes do undergo some dispersion, they do not reach the extremely extended state of the interphase nucleus. The stage between the two meiotic divisions is called interkinesis and is generally short lived. Interkinesis is followed by prophase II, a much simpler prophase than prophase I.

10.4.2 Meiosis II

Prophase II: Meiosis II is initiated immediately after cytokinesis, usually before the chromosomes have fully elongated. In contrast to meiosis I, meiosis II resembles a normal mitosis. The nuclear membrane disappears by the end of prophase II (Figure 10.4). The chromosomes again become compact.

Metaphase II: At this stage the chromosomes align at the equator and the microtubules from opposite poles of the spindle get attached to the kinetochores (Figure 10.4) of sister chromatids.

Anaphase II: It begins with the simultaneous splitting of the centromere of each chromosome (which was holding the sister chromatids together), allowing them to move toward opposite poles of the cell (Figure 10.4).

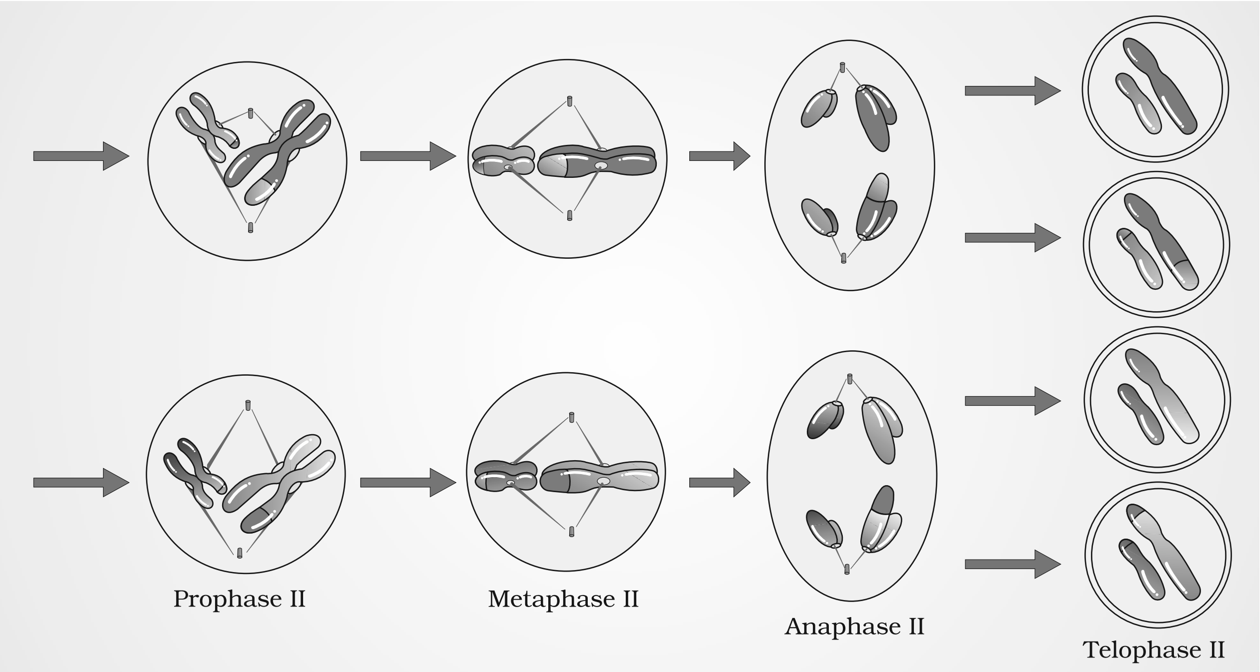


Figure 10.4 Stages of Meiosis II

Telophase II: Meiosis ends with telophase II, in which the two groups of chromosomes once again get enclosed by a nuclear envelope; cytokinesis follows resulting in the formation of tetrad of cells i.e., four haploid daughter cells (Figure 10.4).

10.5 Significance of Meiosis

Meiosis is the mechanism by which conservation of specific chromosome number of each species is achieved across generations in sexually reproducing organisms, even though the process, per se, paradoxically, results in reduction of chromosome number by half. It also increases the genetic variability in the population of organisms from one generation to the next. Variations are very important for the process of evolution.

Summary

According to the cell theory, cells arise from preexisting cells. The process by which this occurs is called cell division. Any sexually reproducing organism starts its life cycle from a single-celled zygote. Cell division does not stop with the formation of the mature organism but continues throughout its life cycle.

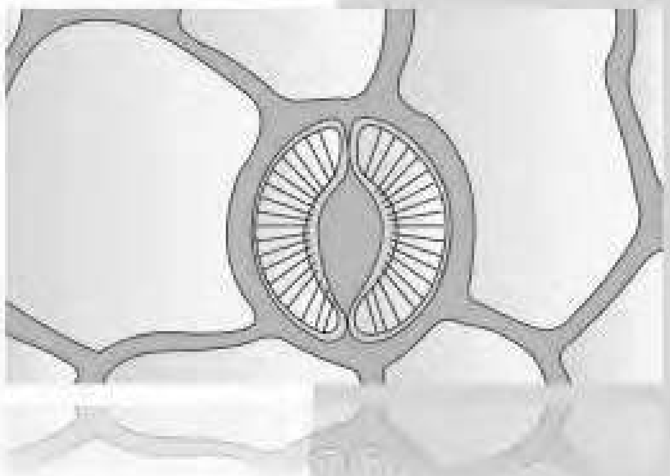
The stages through which a cell passes from one division to the next is called the cell cycle. Cell cycle is divided into two phases called (i) Interphase – a period of preparation for cell division, and (ii) Mitosis (M phase) – the actual period of cell division. Interphase is further subdivided into G_1, S and G_2. G_1 phase is the period when the cell grows and carries out normal metabolism. Most of the organelle duplication also occurs during this phase. S phase marks the phase of DNA replication and chromosome duplication. G_2 phase is the period of cytoplasmic growth. Mitosis is also divided into four stages namely prophase, metaphase, anaphase and telophase. Chromosome condensation occurs during prophase. Simultaneously, the centrioles move to the opposite poles. The nuclear envelope and the nucleolus disappear and the spindle fibres start appearing. Metaphase is marked by the alignment of chromosomes at the equatorial plate. During anaphase the centromeres divide and the chromatids start moving towards the two opposite poles. Once the chromatids reach the two poles, the chromosomal elongation starts, nucleolus and the nuclear membrane reappear. This stage is called the telophase. Nuclear division is then followed by the cytoplasmic division and is called cytokinesis. Mitosis thus, is the equational division in which the chromosome number of the parent is conserved in the daughter cell.

In contrast to mitosis, meiosis occurs in the diploid cells, which are destined to form gametes. It is called the reduction division since it reduces the chromosome number by half while making the gametes. In sexual reproduction when the two gametes fuse the chromosome number is restored to the value in the parent. Meiosis is divided into two phases – meiosis I and meiosis II. In the first meiotic division the homologous chromosomes pair to form bivalents, and undergo crossing over. Meiosis I has a long prophase, which is divided further into five phases. These are leptotene, zygotene, pachytene, diplotene and diakinesis. During metaphase I the bivalents arrange on the equatorial plate. This is followed by anaphase I in which homologous chromosomes move to the opposite poles with both their chromatids. Each pole receives half the chromosome number of the parent cell. In telophase I, the nuclear membrane and nucleolus reappear. Meiosis II is similar to mitosis. During anaphase II the sister chromatids separate. Thus at the end of meiosis four haploid cells are formed.

EXERCISES

1. What is the average cell cycle span for a mammalian cell?
2. Distinguish cytokinesis from karyokinesis.
3. Describe the events taking place during interphase.
4. What is G_o (quiescent phase) of cell cycle?

5. Why is mitosis called equational division?
6. Name the stage of cell cycle at which one of the following events occur:
   (i) Chromosomes are moved to spindle equator.
   (ii) Centromere splits and chromatids separate.
   (iii) Pairing between homologous chromosomes takes place.
   (iv) Crossing over between homologous chromosomes takes place.
7. Describe the following:
   (a) synapsis (b) bivalent (c) chiasmata
   Draw a diagram to illustrate your answer.
8. How does cytokinesis in plant cells differ from that in animal cells?
9. Find examples where the four daughter cells from meiosis are equal in size and where they are found unequal in size.
10. Distinguish anaphase of mitosis from anaphase I of meiosis.
11. List the main differences between mitosis and meiosis.
12. What is the significance of meiosis?
13. Discuss with your teacher about
    (i) haploid insects and lower plants where cell-division occurs, and
    (ii) some haploid cells in higher plants where cell-division does not occur.
14. Can there be mitosis without DNA replication in 'S' phase?
15. Can there be DNA replication without cell division?
16. Analyse the events during every stage of cell cycle and notice how the following two parameters change
    (i) number of chromosomes (N) per cell
    (ii) amount of DNA content (C) per cell



UNIT 4

PLANT PHYSIOLOGY

The description of structure and variation of living organisms over a period of time, ended up as two, apparently irreconcilable perspectives on biology. The two perspectives essentially rested on two levels of organisation of life forms and phenomena. One described at organismic and above level of organisation while the second described at cellular and molecular level of organisation. The first resulted in ecology and related disciplines. The second resulted in physiology and biochemistry. Description of physiological processes, in flowering plants as an example, is what is given in the chapters in this unit. The processes of mineral nutrition of plants, photosynthesis, transport, respiration and ultimately plant growth and development are described in molecular terms but in the context of cellular activities and even at organism level. Wherever appropriate, the relation of the physiological processes to environment is also discussed.

Melvin Calvin
(1911 –)

MELVIN CALVIN born in Minnesota in April, 1911 received his Ph.D. in Chemistry from the University of Minnesota. He served as Professor of Chemistry at the University of California, Berkeley.

Just after world war II, when the world was under shock after the Hiroshima-Nagasaki bombings, and seeing the ill-effects of radio-activity, Calvin and co-workers put radio-activity to beneficial use. He along with J.A. Bassham studied reactions in green plants forming sugar and other substances from raw materials like carbon dioxide, water and minerals by labelling the carbon dioxide with C^{14}. Calvin proposed that plants change light energy to chemical energy by transferring an electron in an organised array of pigment molecules and other substances. The mapping of the pathway of carbon assimilation in photosynthesis earned him Nobel Prize in 1961.

The principles of photosynthesis as established by Calvin are, at present, being used in studies on renewable resource for energy and materials and basic studies in solar energy research.

Chapter 11

Transport in Plants

Have you ever wondered how water reaches the top of tall trees, or for that matter how and why substances move from one cell to the other, whether all substances move in a similar way, in the same direction and whether metabolic energy is required for moving substances. Plants need to move molecules over very long distances, much more than animals do; they also do not have a circulatory system in place. Water taken up by the roots has to reach all parts of the plant, up to the very tip of the growing stem. The photosynthates or food synthesised by the leaves have also to be moved to all parts including the root tips embedded deep inside the soil. Movement across short distances, say within the cell, across the membranes and from cell to cell within the tissue has also to take place. To understand some of the transport processes that take place in plants, one would have to recollect one's basic knowledge about the structure of the cell and the anatomy of the plant body. We also need to revisit our understanding of diffusion, besides gaining some knowledge about chemical potential and ions.

When we talk of the movement of substances we need first to define what kind of movement we are talking about, and also what substances we are looking at. In a flowering plant the substances that would need to be transported are water, mineral nutrients, organic nutrients and plant growth regulators. Over small distances substances move by diffusion and by cytoplasmic streaming supplemented by active transport. Transport over longer distances proceeds through the vascular system (the xylem and the phloem) and is called **translocation.**

An important aspect that needs to be considered is the direction of transport. In rooted plants, transport in xylem (of water and minerals) is essentially unidirectional, from roots to the stems. Organic and mineral nutrients however, undergo multidirectional transport. Organic compounds synthesised in the photosynthetic leaves are exported to all other parts of the plant including storage organs. From the storage organs they are later re-exported. The mineral nutrients are taken up by the roots and transported upwards into the stem, leaves and the growing regions. When any plant part undergoes senescence, nutrients may be withdrawn from such regions and moved to the growing parts. Hormones or plant growth regulators and other chemical stimuli are also transported, though in very small amounts, sometimes in a strictly polarised or unidirectional manner from where they are synthesised to other parts. Hence, in a flowering plant there is a complex traffic of compounds (but probably very orderly) moving in different directions, each organ receiving some substances and giving out some others.

11.1 Means of Transport

11.1.1 Diffusion

Movement by **diffusion** is passive, and may be from one part of the cell to the other, or from cell to cell, or over short distances, say, from the inter-cellular spaces of the leaf to the outside. No energy expenditure takes place. In diffusion, molecules move in a random fashion, the net result being substances moving from regions of higher concentration to regions of lower concentration. Diffusion is a slow process and is not dependent on a 'living system'. Diffusion is obvious in gases and liquids, but diffusion *in solids* rather than *of solids* is more likely. Diffusion is very important to plants since it the only means for gaseous movement within the plant body.

Diffusion rates are affected by the gradient of concentration, the permeability of the membrane separating them, temperature and pressure.

11.1.2 Facilitated Diffusion

As pointed out earlier, a gradient must already be present for diffusion to occur. The diffusion rate depends on the size of the substances; obviously smaller substances diffuse faster. The diffusion of any substance across a membrane also depends on its solubility in lipids, the major constituent of the membrane. Substances soluble in lipids diffuse through the membrane faster. Substances that have a hydrophilic moiety, find it difficult to pass through the membrane; their movement has to be facilitated. Membrane proteins provide sites at which such molecules cross the membrane. They do not set up a concentration gradient: a concentration gradient must already be present for molecules to diffuse even if facilitated by the proteins. This process is called **facilitated diffusion**.

In facilitated diffusion special proteins help move substances across membranes without expenditure of ATP energy. Facilitated diffusion cannot cause net transport of molecules from a low to a high concentration – this would require input of energy. Transport rate reaches a maximum when all of the protein transporters are being used (saturation). Facilitated

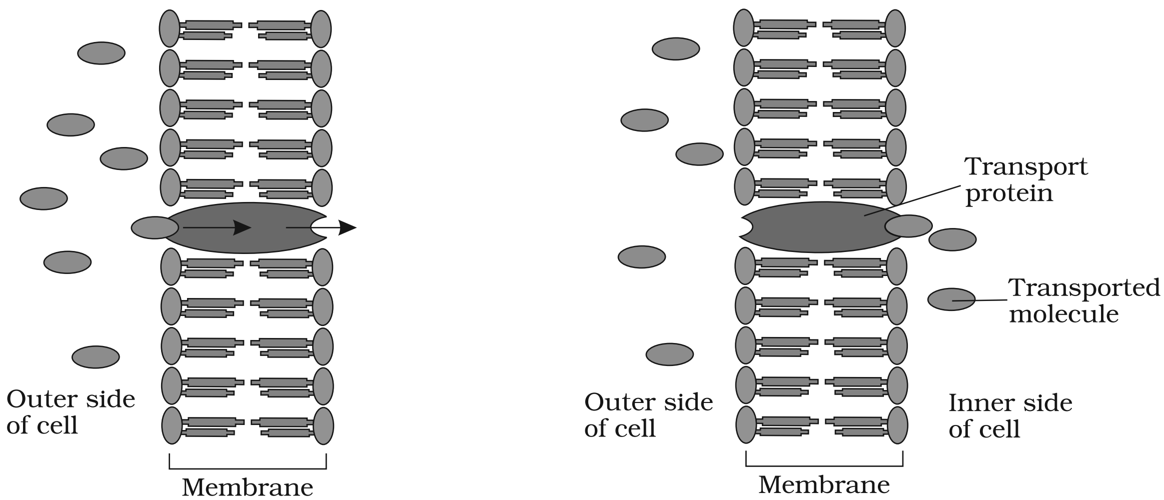


Figure 11.1 Facilitated diffusion

diffusion is very specific: it allows cell to select substances for uptake. It is sensitive to inhibitors which react with protein side chains.

The proteins form channels in the membrane for molecules to pass through. Some channels are always open; others can be controlled. Some are large, allowing a variety of molecules to cross. The **porins** are proteins that form huge pores in the outer membranes of the plastids, mitochondria and some bacteria allowing molecules up to the size of small proteins to pass through.

Figure 11.1 shows an extracellular molecule bound to the transport protein; the transport protein then rotates and releases the molecule inside the cell, e.g., water channels – made up of eight different types of **aquaporins**.

11.1.2.1 Passive symports and antiports

Some carrier or transport proteins allow diffusion only if two types of molecules move together. In a **symport**, both molecules cross the membrane in the same direction; in an **antiport**, they move in opposite directions (Figure 11.2). When a

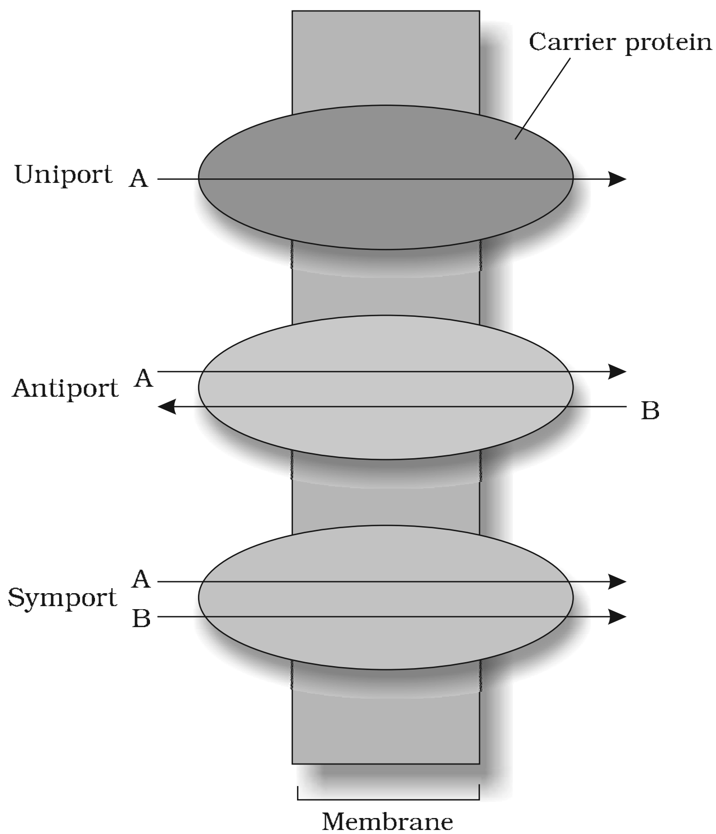


Figure 11.2 Facilitated diffusion

molecule moves across a membrane independent of other molecules, the process is called **uniport**.

11.1.3 Active Transport

Active transport uses energy to pump molecules against a concentration gradient. Active transport is carried out by membrane-proteins. Hence different proteins in the membrane play a major role in both active as well as passive transport. Pumps are proteins that use energy to carry substances across the cell membrane. These pumps can transport substances from a low concentration to a high concentration ('uphill' transport). Transport rate reaches a maximum when all the protein transporters are being used or are saturated. Like enzymes the carrier protein is very specific in what it carries across the membrane. These proteins are sensitive to inhibitors that react with protein side chains.

11.1.4 Comparison of Different Transport Processes

Table 11.1 gives a comparison of the different transport mechanisms. Proteins in the membrane are responsible for facilitated diffusion and active transport and hence show common characterstics of being highly selective; they are liable to saturate, respond to inhibitors and are under hormonal regulation. But diffusion whether facilitated or not – take place only along a gradient and do not use energy.

TABLE 11.1 Comparison of Different Transport Mechanisms

Property	Simple Diffusion	Facilitated Transport	Active Transport
Requires special membrane proteins	No	Yes	Yes
Highly selective	No	Yes	Yes
Transport saturates	No	Yes	Yes
Uphill transport	No	No	Yes
Requires ATP energy	No	No	Yes

11.2 PLANT-WATER RELATIONS

Water is essential for all physiological activities of the plant and plays a very important role in all living organisms. It provides the medium in which most substances are dissolved. The protoplasm of the cells is nothing but water in which different molecules are dissolved and (several particles) suspended. A watermelon has over 92 per cent water; most herbaceous plants have only about 10 to 15 per cent of its fresh weight as dry matter. Of course, distribution of water within a plant varies – woody parts have relatively very little water, while soft parts mostly contain water. A seed may appear dry but it still has water – otherwise it would not be alive and respiring!

Terrestrial plants take up huge amount water daily but most of it is lost to the air through evaporation from the leaves, i.e., **transpiration**. A mature corn plant absorbs almost three litres of water in a day, while a mustard plant absorbs water equal to its own weight in about 5 hours. Because of this high demand for water, it is not surprising that water is often the limiting factor for plant growth and productivity in both agricultural and natural environments.

11.2.1 Water Potential

To comprehend plant-water relations, an understanding of certain standard terms is necessary. **Water potential (Ψ_w)** is a concept fundamental to understanding water movement. **Solute potential (Ψ_s)** and **pressure potential (Ψ_p)** are the two main components that determine water potential.

Water molecules possess kinetic energy. In liquid and gaseous form they are in random motion that is both rapid and constant. The greater the concentration of water in a system, the greater is its kinetic energy or 'water potential'. Hence, it is obvious that pure water will have the greatest water potential. If two systems containing water are in contact, random movement of water molecules will result in net movement of water molecules from the system with higher energy to the one with lower energy. Thus water will move from the system containing water at higher water potential to the one having low water potential. This process of movement of substances down a gradient of free energy is called diffusion. Water potential is denoted by the Greek symbol Psi or **Ψ** and is expressed in pressure units such as pascals (Pa). By convention, the water potential of pure water at standard temperatures, which is not under any pressure, is taken to be zero.

If some solute is dissolved in pure water, the solution has fewer free water and the concentration of water decreases, reducing its water potential. Hence, all solutions have a lower water potential than pure water; the magnitude of this lowering due to dissolution of a solute is called **solute potential** or **Ψ_s**. **Ψ_s** is always negative. The more the solute molecules, the lower (more negative) is the Ψ_s. For a solution at atmospheric pressure (water potential) Ψ_w = (solute potential) Ψ_s.

If a pressure greater than atmospheric pressure is applied to pure water or a solution, its water potential increases. It is equivalent to pumping water from one place to another. Can you think of any system in our body where pressure is built up? Pressure can build up in a plant system when water enters a plant cell due to diffusion causing a pressure built up against the cell wall, it makes the cell **turgid** (see section 11.2.2);

this increases the **pressure potential**. Pressure potential is usually positive, though in plants negative potential or tension in the water column in the xylem plays a major role in water transport up a stem. Pressure potential is denoted as Ψ_p.

Water potential of a cell is affected by both solute and pressure potential. The relationship between them is as follows:

$$\Psi_w = \Psi_s + \Psi_p$$

11.2.2 Osmosis

The plant cell is surrounded by a cell membrane and a cell wall. The cell wall is freely permeable to water and substances in solution hence is not a barrier to movement. In plants the cells usually contain a large central vacuole, whose contents, the vacuolar sap, contribute to the solute potential of the cell. In plant cells, the cell membrane and the membrane of the vacuole, the tonoplast together are important determinants of movement of molecules in or out of the cell.

Osmosis is the term used to refer specifically to the diffusion of water across a differentially- or semi-permeable membrane. Osmosis occurs spontaneously in response to a driving force. The net direction and rate of osmosis depends on both the **pressure gradient** and **concentration gradient**. Water will move from its region of higher chemical potential (or concentration) to its region of lower chemical potential until equilibrium is reached. At equilibrium the two chambers should have the same water potential.

You may have made a potato osmometer at some earlier stage in school. If the tuber is placed in water, the cavity in the potato tuber containing a concentrated solution of sugar collects water due to osmosis.

Study Figure 11.3 in which the two chambers, A and B, containing solutions are separated by a semi-permeable membrane.

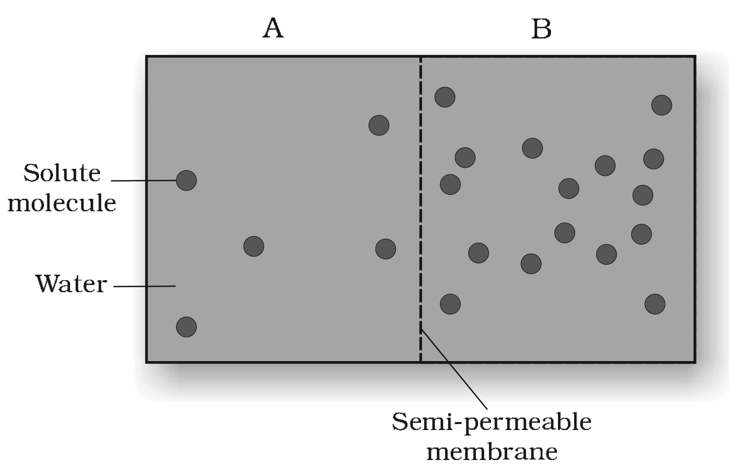


Figure 11.3

(a) Solution of which chamber has a lower water potential?

(b) Solution of which chamber has a lower solute potential?

(c) In which direction will osmosis occur?

(d) Which solution has a higher solute potential?

(e) At equilibrium which chamber will have lower water potential?

(f) If one chamber has a Ψ *of – 2000 kPa, and the other – 1000 kPa, which is the chamber that has the higher* Ψ*?*

Let us discuss another experiment where a solution of sucrose in water taken in a funnel is separated from pure water in a beaker through a semi-permeable membrane (Figure 11.4). *You can get this kind of a membrane in an egg. Remove the yolk and albumin through a small hole at one end of the egg, and place the shell in dilute solution of hydrochloric acid for a few hours. The egg shell dissolves leaving the membrane intact.* Water will move into the funnel, resulting in rise in the level of the solution in the funnel. This will continue till the equilibrium is reached. *In case sucrose does diffuse out through the membrane, will this equilibrium be ever reached?*

External pressure can be applied from the upper part of the funnel such that no water diffuses into the funnel through the membrane. This pressure required to prevent water from diffusing is in fact, the osmotic pressure and this is the function of the solute concentration; more the solute concentration, greater will be the pressure required to prevent water from diffusing in. Numerically osmotic pressure is equivalent to the osmotic potential, but the sign is opposite.Osmotic pressure is the positive pressure applied, while osmotic potential is negative.

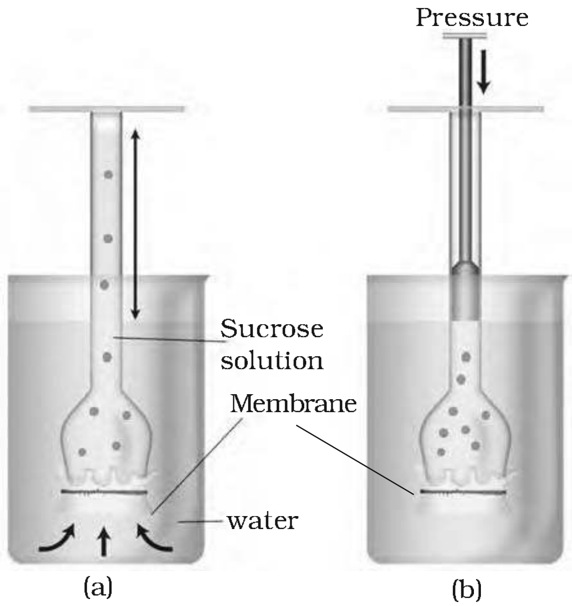


Figure 11.4 A demonstration of osmosis. A thistle funnel is filled with sucrose solution and kept inverted in a beaker containing water. (a) Water will diffuse across the membrane (as shown by arrows) to raise the level of the solution in the funnel (b) Pressure can be applied as shown to stop the water movement into the funnel

11.2.3 Plasmolysis

The behaviour of the plant cells (or tissues) with regard to water movement depends on the surrounding solution. If the external solution balances the osmotic pressure of the cytoplasm, it is said to be **isotonic**. If the external solution is more dilute than the cytoplasm, it is **hypotonic** and if the external solution is more concentrated, it is **hypertonic**. Cells swell in hypotonic solutions and shrink in hypertonic ones.

Plasmolysis occurs when water moves out of the cell and the cell membrane of a plant cell shrinks away from its cell wall. This occurs when

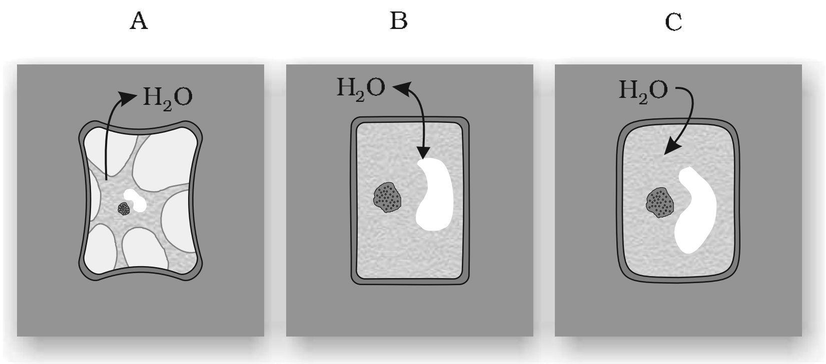


Figure 11.5 Plant cell plasmolysis

the cell (or tissue) is placed in a solution that is hypertonic (has more solutes) to the protoplasm. Water moves out; it is first lost from the cytoplasm and then from the vacuole. The water when drawn out of the cell through diffusion into the extracellular (outside cell) fluid causes the protoplast to shrink away from the walls. The cell is said to be plasmolysed. The movement of water occurred across the membrane moving from an area of high water potential (i.e., the cell) to an area of lower water potential outside the cell (Figure 11.5).

What occupies the space between the cell wall and the shrunken protoplast in the plasmolysed cell?

When the cell (or tissue) is placed in an **isotonic** solution, there is no net flow of water towards the inside or outside. If the external solution balances the osmotic pressure of the cytoplasm it is said to be isotonic. When water flows into the cell and out of the cell and are in equilibrium, the cells are said to be **flaccid**.

The process of plamolysis is usually reversible. When the cells are placed in a **hypotonic** solution (higher water potential or dilute solution as compared to the cytoplasm), water diffuses into the cell causing the cytoplasm to build up a pressure against the wall, that is called **turgor pressure**. The pressure exerted by the protoplasts due to entry of water against the rigid walls is called pressure potential $\Psi_{p.}$. Because of the rigidity of the cell wall, the cell does not rupture. This turgor pressure is ultimately responsible for enlargement and extension growth of cells.

What would be the Ψ_p of a flaccid cell? Which organisms other than plants possess cell wall ?

11.2.4 Imbibition

Imbibition is a special type of diffusion when water is absorbed by solids – colloids – causing them to enormously increase in volume. The classical examples of imbibition are absorption of water by seeds and dry wood. The pressure that is produced by the swelling of wood had been used by prehistoric man to split rocks and boulders. If it were not for the pressure due to imbibition, seedlings would not have been able to emerge out of the soil into the open; they probably would not have been able to establish!

Imbibition is also diffusion since water movement is along a concentration gradient; the seeds and other such materials have almost no water hence they absorb water easily. Water potential gradient between the absorbent and the liquid imbibed is essential for imbibition. In addition, for any substance to imbibe any liquid, affinity between the adsorbant and the liquid is also a pre-requisite.

11.3 LONG DISTANCE TRANSPORT OF WATER

At some earlier stage you might have carried out an experiment where you had placed a twig bearing white flowers in coloured water and had watched it turn colour. On examining the cut end of the twig after a few hours you had noted the region through which the coloured water moved. That experiment very easily demonstrates that the path of water movement is through the vascular bundles, more specifically, the xylem. Now we have to go further and try and understand the mechanism of movement of water and other substances up a plant.

Long distance transport of substances within a plant cannot be by diffusion alone. Diffusion is a slow process. It can account for only short distance movement of molecules. For example, the movement of a molecule across a typical plant cell (about 50 μm) takes approximately 2.5 s. *At this rate, can you calculate how many years it would take for the movement of molecules over a distance of 1 m within a plant by diffusion alone?*

In large and complex organisms, often substances have to be moved across very large distances. Sometimes the sites of production or absorption and sites of storage are too far from each other; diffusion or active transport would not suffice. Special long distance transport systems become necessary so as to move substances across long distances and at a much faster rate. Water and minerals, and food are generally moved by a **mass** or **bulk flow** system. Mass flow is the movement of substances in bulk or *en masse* from one point to another as a result of pressure differences between the two points. It is a characteristic of mass flow that substances, whether in solution or in suspension, are swept along at the same pace, as in a flowing river. This is unlike diffusion where different substances move independently depending on their concentration gradients. Bulk flow can be achieved either through a positive hydrostatic pressure gradient (e.g., a garden hose) or a negative hydrostatic pressure gradient (e.g., suction through a straw).

The bulk movement of substances through the conducting or vascular tissues of plants is called **translocation.**

Do you remember studying cross sections of roots, stems and leaves of higher plants and studying the vascular system? The higher plants have highly specialised vascular tissues – xylem and phloem. Xylem is associated with translocation of mainly water, mineral salts, some organic nitrogen and hormones, from roots to the aerial parts of the plants. The phloem translocates a variety of organic and inorganic solutes, mainly from the leaves to other parts of the plants.

11.3.1 How do Plants Absorb Water?

We know that the roots absorb most of the water that goes into plants; obviously that is why we apply water to the soil and not on the leaves. The responsibility of absorption of water and minerals is more specifically the function of the root hairs that are present in millions at the tips of the roots. Root hairs are thin-walled slender extensions of root epidermal cells that greatly increase the surface area for absorption. Water is absorbed along with mineral solutes, by the root hairs, purely by diffusion. Once water is absorbed by the root hairs, it can move deeper into root layers by two distinct pathways:

- apoplast pathway
- symplast pathway

The **apoplast** is the system of adjacent cell walls that is continuous throughout the plant, except at the **casparian** strips of the endodermis in the roots (Figure 11.6). The apoplastic movement of water occurs exclusively through the intercellular spaces and the walls of the cells. Movement through the apoplast does not involve crossing the cell

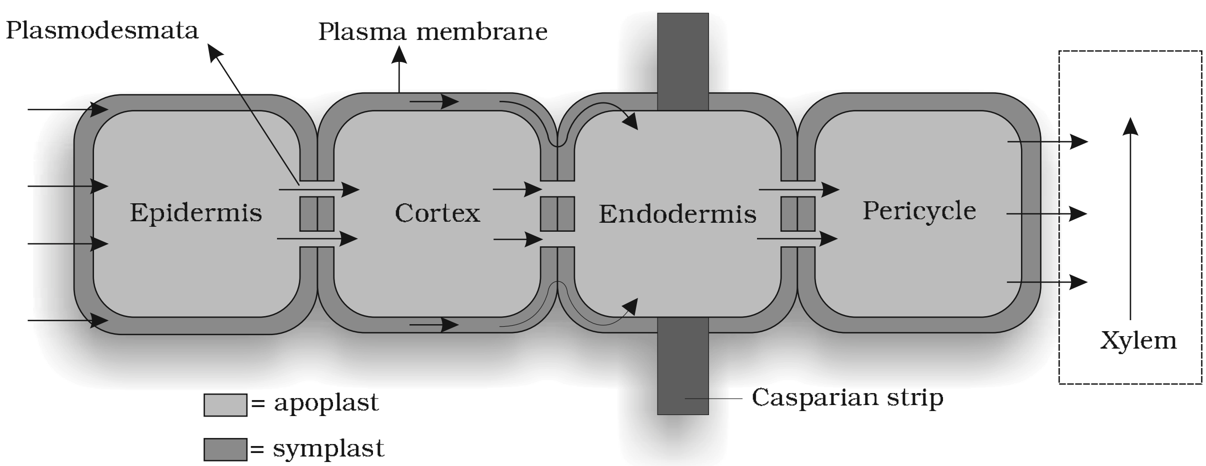


Figure 11.6 Pathway of water movement in the root

membrane. This movement is dependent on the gradient. The apoplast does not provide any barrier to water movement and water movement is through mass flow. As water evaporates into the intercellular spaces or the atmosphere, tension develop in the continuous stream of water in the apoplast, hence mass flow of water occurs due to the adhesive and cohesive properties of water.

The **symplastic** system is the system of interconnected protoplasts. Neighbouring cells are connected through cytoplasmic strands that extend through **plasmodesmata.** During symplastic movement, the water travels through the cells – their cytoplasm; intercellular movement is through the plasmodesmata. Water has to enter the cells through the cell membrane, hence the movement is relatively slower. Movement is again down a potential gradient. Symplastic movement may be aided by cytoplasmic streaming. You may have observed cytoplasmic streaming in cells of the *Hydrilla* leaf; the movement of chloroplast due to streaming is easily visible.

Most of the water flow in the roots occurs via the apoplast since the cortical cells are loosely packed, and hence offer no resistance to water movement. However, the inner boundary of the cortex, the **endodermis**, is impervious to water because of a band of suberised matrix called the **casparian strip**. Water molecules are unable to penetrate the layer, so they are directed to wall regions that are not suberised, into the cells proper through the membranes. The water then moves through the symplast and again crosses a membrane to reach the cells of the xylem. The movement of water through the root layers is ultimately symplastic in the endodermis. This is the only way water and other solutes can enter the vascular cylinder.

Once inside the xylem, water is again free to move between cells as well as through them. In young roots, water enters directly into the xylem vessels and/or tracheids. These are non-living conduits and so are parts of the apoplast. The path of water and mineral ions into the root vascular system is summarised in Figure 11.7.

Some plants have additional structures associated with them that help in water (and mineral) absorption. A **mycorrhiza** is a symbiotic association of a fungus with a root system. The fungal

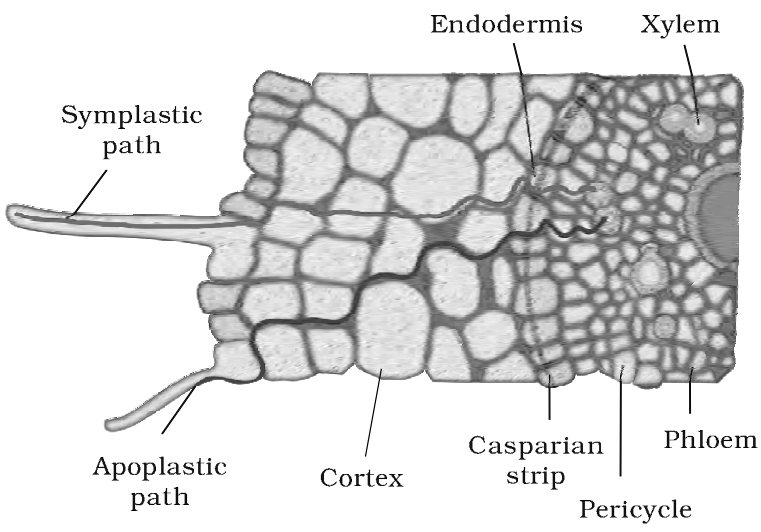


Figure 11.7 Symplastic and apoplastic pathways of water and ion absorption and movement in roots

filaments form a network around the young root or they penetrate the root cells. The hyphae have a very large surface area that absorb mineral ions and water from the soil from a much larger volume of soil that perhaps a root cannot do. The fungus provides minerals and water to the roots, in turn the roots provide sugars and N-containing compounds to the mycorrhizae. Some plants have an obligate association with the mycorrhizae. For example, *Pinus* seeds cannot germinate and establish without the presence of mycorrhizae.

11.3.2 Water Movement up a Plant

We looked at how plants absorb water from the soil, and move it into the vascular tissues. We now have to try and understand how this water is transported to various parts of the plant. Is the water movement active, or is it still passive? Since the water has to be moved up a stem against gravity, what provides the energy for this?

11.3.2.1 Root Pressure

As various ions from the soil are actively transported into the vascular tissues of the roots, water follows (its potential gradient) and increases the **pressure** inside the xylem. This positive pressure is called **root pressure,** and can be responsible for pushing up water to small heights in the stem. How can we see that root pressure exists? Choose a small soft-stemmed plant and on a day, when there is plenty of atmospheric moisture, cut the stem horizontally near the base with a sharp blade, early in the morning. You will soon see drops of solution ooze out of the cut stem; this comes out due to the positive root pressure. If you fix a rubber tube to the cut stem as a sleeve you can actually collect and measure the rate of exudation, and also determine the composition of the exudates. Effects of root pressure is also observable at night and early morning when evaporation is low, and excess water collects in the form of droplets around special openings of veins near the tip of grass blades, and leaves of many herbaceous parts. Such water loss in its liquid phase is known as **guttation**.

Root pressure can, at best, only provide a modest push in the overall process of water transport. They obviously do not play a major role in water movement up tall trees. The greatest contribution of root pressure may be to re-establish the continuous chains of water molecules in the xylem which often break under the enormous tensions created by transpiration. Root pressure does not account for the majority of water transport; most plants meet their need by transpiratory pull.

11.3.2.2 Transpiration pull

Despite the absence of a heart or a circulatory system in plants, the flow of water upward through the xylem in plants can achieve fairly high rates, up to 15 metres per hour. How is this movement accomplished? A long standing question is, whether water is 'pushed' or 'pulled' through the plant. Most researchers agree that water is mainly 'pulled' through the plant, and that the driving force for this process is transpiration from the leaves. This is referred to as the **cohesion-tension-transpiration pull model** of water transport. But, what generates this transpirational pull?

Water is transient in plants. Less than 1 per cent of the water reaching the leaves is used in photosynthesis and plant growth. Most of it is lost through the **stomata** in the leaves. This water loss is known as **transpiration**.

You have studied transpiration in an earlier class by enclosing a healthy plant in polythene bag and observing the droplets of water formed inside the bag. You could also study water loss from a leaf using cobalt chloride paper, which turns colour on absorbing water.

11.4 TRANSPIRATION

Transpiration is the evaporative loss of water by plants. It occurs mainly through the **stomata** in the leaves. Besides the loss of water vapour in transpiration, exchange of oxygen and carbon dioxide in the leaf also occurs through pores called stomata (sing. : stoma). Normally stomata are open in the day time and close during the night. The immediate cause of the opening or closing of the stomata is a change in the turgidity of the **guard cells**. The inner wall of each guard cell, towards the pore or **stomatal aperture,** is thick and elastic. When turgidity increases within the two guard cells flanking each stomatal aperture or pore, the thin outer walls bulge out and force the inner walls into a crescent shape. The opening of the stoma is also aided due to the orientation of the microfibrils in the cell walls of the guard cells. Cellulose microfibrils are oriented radially rather than longitudinally making it easier for the stoma to open. When the guard cells lose turgor, due to water loss (or water stress) the elastic inner walls regain their original shape, the guard cells become flaccid and the stoma closes.

Usually the lower surface of a dorsiventral (often dicotyledonous) leaf has a greater number of stomata while in an isobilateral (often monocotyledonous) leaf they are about equal on both surfaces. Transpiration is affected by several external factors: temperature, light, humidity, wind speed. Plant factors that affect transpiration include number and distribution of stomata, number of

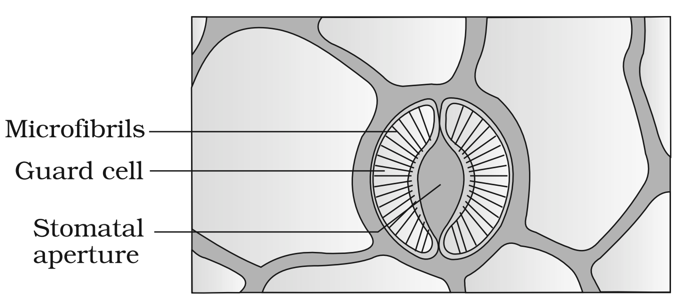


Figure11.8 A stomatal aperture with guard cells

stomata open, per cent, water status of the plant, canopy structure etc.

The transpiration driven ascent of xylem sap depends mainly on the following physical properties of water:

- **Cohesion** – mutual attraction between water molecules.
- **Adhesion** – attraction of water molecules to polar surfaces (such as the surface of tracheary elements).
- **Surface Tension** – water molecules are attracted to each other in the liquid phase more than to water in the gas phase.

These properties give water high **tensile strength**, i.e., an ability to resist a pulling force, and high **capillarity**, i.e., the ability to rise in thin tubes. In plants capillarity is aided by the small diameter of the tracheary elements – the **tracheids** and **vessel elements**.

The process of photosynthesis requires water. The system of xylem vessels from the root to the leaf vein can supply the needed water. But what force does a plant use to move water molecules into the leaf parenchyma cells where they are needed? As water evaporates through the stomata, since the thin film of water over the cells is continuous, it results in pulling of water, molecule by molecule, into the leaf from the xylem. Also, because of lower concentration of water vapour in the atmosphere as compared to the substomatal cavity and intercellular spaces, water diffuses into the surrounding air. This creates a 'pull' (Figure 11.9).

Measurements reveal that the forces generated by transpiration can create pressures sufficient to lift a xylem sized column of water over 130 metres high.

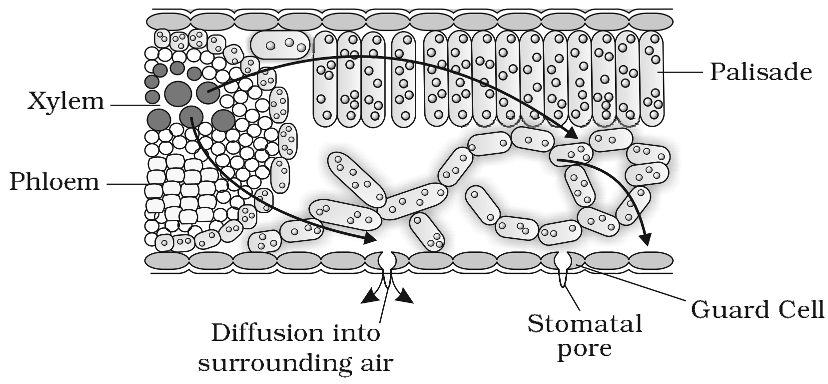


Figure 11.9 Water movement in the leaf. Evaporation from the leaf sets up a pressure gradient between the outside air and the air spaces of the leaf. The gradient is transmitted into the photosynthetic cells and on the water-filled xylem in the leaf vein.

11.4.1 Transpiration and Photosynthesis – a Compromise

Transpiration has more than one purpose; it

- creates transpiration pull for absorption and transport of plants
- supplies water for photosynthesis
- transports minerals from the soil to all parts of the plant
- cools leaf surfaces, sometimes 10 to 15 degrees, by evaporative cooling
- maintains the shape and structure of the plants by keeping cells turgid

An actively photosynthesising plant has an insatiable need for water. Photosynthesis is limited by available water which can be swiftly depleted by transpiration. The humidity of rainforests is largely due to this vast cycling of water from root to leaf to atmosphere and back to the soil.

The evolution of the C_4 photosynthetic system is probably one of the strategies for maximising the availability of CO_2 while minimising water loss. C_4 plants are twice as efficient as C_3 plants in terms of fixing carbon (making sugar). However, a C_4 plant loses only half as much water as a C_3 plant for the same amount of CO_2 fixed.

11.5 UPTAKE AND TRANSPORT OF MINERAL NUTRIENTS

Plants obtain their carbon and most of their oxygen from CO_2 in the atmosphere. However, their remaining nutritional requirements are obtained from minerals and water for hydrogen in the soil.

11.5.1 Uptake of Mineral Ions

Unlike water, all minerals cannot be passively absorbed by the roots. Two factors account for this: (i) minerals are present in the soil as charged particles (ions) which cannot move across cell membranes and (ii) the concentration of minerals in the soil is usually lower than the concentration of minerals in the root. Therefore, most minerals must enter the root by **active absorption** into the cytoplasm of epidermal cells. This needs energy in the form of ATP. The active uptake of ions is partly responsible for the water potential gradient in roots, and therefore for the uptake of water by osmosis. Some ions also move into the epidermal cells passively.

Ions are absorbed from the soil by both passive and active transport. Specific proteins in the membranes of root hair cells actively pump ions from the soil into the cytoplasms of the epidermal cells. Like all cells, the endodermal cells have many transport proteins embedded in their plasma membrane; they let some solutes cross the membrane, but not others. *Transport proteins of endodermal cells are control points, where a plant adjusts the quantity and types of solutes that reach the xylem.* Note that the root endodermis because of the layer of suberin has the ability to actively transport ions in one direction only.

11.5.2 Translocation of Mineral Ions

After the ions have reached xylem through active or passive uptake, or a combination of the two, their further transport up the stem to all parts of the plant is through the transpiration stream.

The chief sinks for the mineral elements are the growing regions of the plant, such as the apical and lateral meristems, young leaves, developing flowers, fruits and seeds, and the storage organs. Unloading of mineral ions occurs at the fine vein endings through diffusion and active uptake by these cells.

Mineral ions are frequently remobilised, particularly from older, senescing parts. Older dying leaves export much of their mineral content to younger leaves. Similarly, before leaf fall in decidous plants, minerals are removed to other parts. Elements most readily mobilised are phosphorus, sulphur, nitrogen and potassium. Some elements that are structural components like calcium are not remobilised.

An analysis of the xylem exudates shows that though some of the nitrogen travels as inorganic ions, much of it is carried in the organic form as amino acids and related compounds. Similarly, small amounts of P and S are carried as organic compounds. In addition, small amount of exchange of materials does take place between xylem and phloem. Hence, it is not that we can clearly make a distinction and say categorically that xylem transports only inorganic nutrients while phloem transports only organic materials, as was traditionally believed.

11.6 Phloem Transport: Flow from Source to Sink

Food, primarily sucrose, is transported by the vascular tissue phloem from a source to a sink. Usually the source is understood to be that part of the plant which synthesises the food, i.e., the leaf, and sink, the part that needs or stores the food. But, the source and sink may be reversed depending on the season, or the plant's needs. Sugar stored in roots may be mobilised to become a source of food in the early spring when the buds of trees, act as sink; they need energy for growth and development of the photosynthetic apparatus. Since the source-sink relationship is variable, the direction of movement in the phloem can be upwards or downwards, i.e., **bi-directional**. This contrasts with that of the xylem where the movement is always **unidirectional,** i.e., upwards. Hence, unlike one-way flow of water in transpiration, food in phloem sap can be transported in any required direction so long as there is a source of sugar and a sink able to use, store or remove the sugar.

Phloem sap is mainly water and sucrose, but other sugars, hormones and amino acids are also transported or **translocated** through phloem.

11.6.1 The Pressure Flow or Mass Flow Hypothesis

The accepted mechanism used for the translocation of sugars from source to sink is called the pressure flow hypothesis. (see Figure 11.10). As glucose is prepared at the source (by photosynthesis) it is converted to sucrose (a dissacharide). The sugar is then moved in the form of sucrose into the companion cells and then into the living phloem sieve tube cells by active transport. This process of loading at the source produces a hypertonic condition in the phloem. Water in the adjacent xylem moves into the phloem by osmosis. As osmotic pressure builds up the phloem sap will move to areas of lower pressure. At the sink osmotic pressure must be reduced. Again active transport is necessary to move the sucrose out of the phloem sap and into the cells which will use the sugar – converting it into energy, starch, or cellulose. As sugars are removed, the osmotic pressure decreases and water moves out of the phloem.

To summarise, the movement of sugars in the phloem begins at the source, where sugars are loaded (actively transported) into a sieve tube. Loading of the phloem sets up a water potential gradient that facilitates the mass movement in the phloem.

Phloem tissue is composed of sieve tube cells, which form long columns with holes in their end walls called sieve plates. Cytoplasmic strands pass through the holes in the sieve plates, so forming continuous filaments. As hydrostatic pressure in the phloem sieve tube increases, pressure flow begins, and the sap moves through the phloem. Meanwhile, at the sink, incoming sugars are actively transported out of the phloem and removed

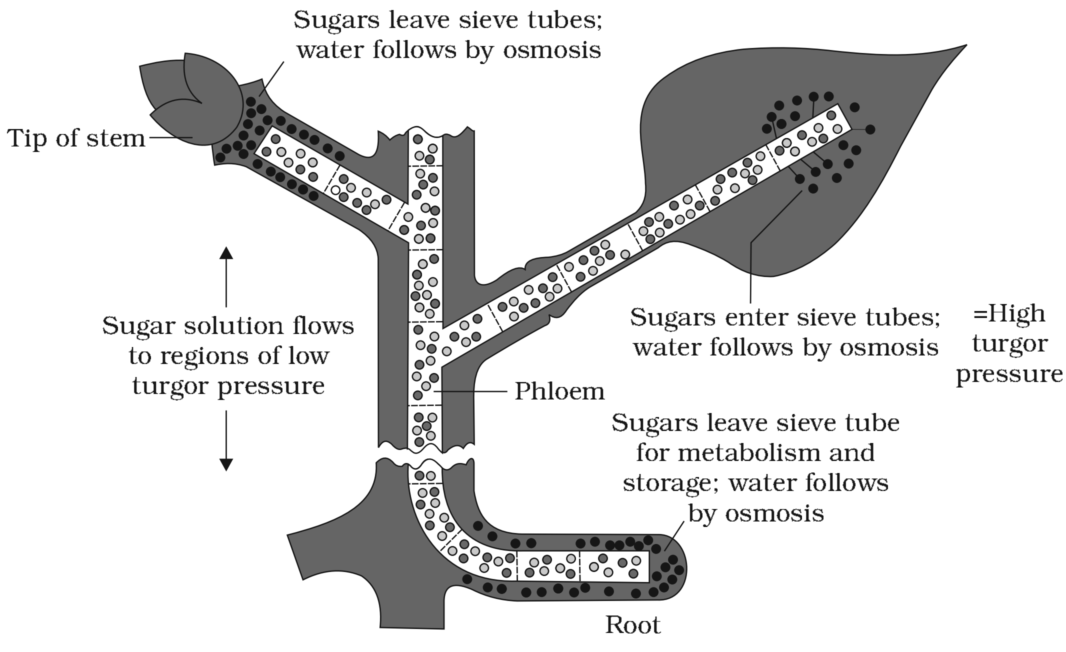


Figure11.10 Diagrammatic presentation of mechanism of translocation

as complex carbohydrates. The loss of solute produces a high water potential in the phloem, and water passes out, returning eventually to xylem.

A simple experiment, called girdling, was used to identify the tissues through which food is transported. On the trunk of a tree a ring of bark up to a depth of the phloem layer, can be carefully removed. In the absence of downward movement of food the portion of the bark above the ring on the stem becomes swollen after a few weeks. This simple experiment shows that phloem is the tissue responsible for translocation of food; and that transport takes place in one direction, i.e., towards the roots. This experiment can be performed by you easily.

Summary

Plants obtain a variety of inorganic elements (ions) and salts from their surroundings especially from water and soil. The movement of these nutrients from environment into the plant as well as from one plant cell to another plant cell essentially involves movement across a cell membrane. Transport across cell membrane can be through diffusion, facilitated transport or active transport. Water and minerals absorbed by roots are transported by xylem and the organic material synthesised in the leaves is transported to other parts of plant through phloem.

Passive transport (diffusion, osmosis) and active transport are the two modes of nutrient transport across cell membranes in living organisms. In passive transport, nutrients move across the membrane by diffusion, without any use of energy as it is always down the concentration gradient and hence entropy driven. This diffusion of substances depends on their size, solubility in water or organic solvents. Osmosis is the special type of diffusion of water across a semi-permeable membrane which depends on pressure gradient and concentration gradient. In active transport, energy in the form of ATP is utilised to pump molecules against a concentration gradient across membranes. Water potential is the potential energy of water which helps in the movement of water. It is determined by solute potential and pressure potential. The behaviour of the cells depends on the surrounding solution. If the surrounding solution of the cell is hypertonic, it gets plasmolysed. The absorption of water by seeds and drywood takes place by a special type of diffusion called imbibition.

In higher plants, there is a vascular system, xylem and phloem, responsible for translocation. Water minerals and food cannot be moved within the body of a plant by diffusion alone. They are therefore, transported by a mass flow system – movement of substance in bulk from one point to another as a result of pressure differences between the two points.

Water absorbed by root hairs moves deeper into the root by two distinct pathways, i.e., apoplast and symplast. Various ions, and water from soil can be transported upto a small height in stems by root pressure. Transpiration pull model is the most acceptable to explain the transport of water. Transpiration is the loss of water in the form of vapours from the plant parts through stomata. Temperature, light, humidity, wind speed and number of stomata affect the rate of transpiration. Excess water is also removed through tips of leaves of plants by guttation.

Phloem is responsible for transport of food (primarily) sucrose from the source to the sink. The translocation in phloem is bi-directional; the source-sink relationship is variable. The translocation in phloem is explained by the pressure-flow hypothesis.

EXERCISES

1. What are the factors affecting the rate of diffusion?
2. What are porins? What role do they play in diffusion?
3. Describe the role played by protein pumps during active transport in plants.
4. Explain why pure water has the maximum water potential.
5. Differentiate between the following:
   (a) Diffusion and Osmosis
   (b) Transpiration and Evaporation
   (c) Osmotic Pressure and Osmotic Potential
   (d) Imbibition and Diffusion
   (e) Apoplast and Symplast pathways of movement of water in plants.
   (f) Guttation and Transpiration.
6. Briefly describe water potential. What are the factors affecting it?
7. What happens when a pressure greater than the atmospheric pressure is applied to pure water or a solution?
8. (a) With the help of well-labelled diagrams, describe the process of plasmolysis in plants, giving appropriate examples.
   (b) Explain what will happen to a plant cell if it is kept in a solution having higher water potential.
9. How is the mycorrhizal association helpful in absorption of water and minerals in plants?
10. What role does root pressure play in water movement in plants?
11. Describe transpiration pull model of water transport in plants. What are the factors influencing transpiration? How is it useful to plants?
12. Discuss the factors responsible for ascent of xylem sap in plants.
13. What essential role does the root endodermis play during mineral absorption in plants?
14. Explain why xylem transport is unidirectional and phloem transport bi-directional.
15. Explain pressure flow hypothesis of translocation of sugars in plants.
16. What causes the opening and closing of guard cells of stomata during transpiration?

Chapter 12

Mineral Nutrition

The basic needs of all living organisms are essentially the same. They require macromolecules, such as carbohydrates, proteins and fats, and water and minerals for their growth and development.

This chapter focusses mainly on inorganic plant nutrition, wherein you will study the methods to identify elements essential to growth and development of plants and the criteria for establishing the essentiality. You will also study the role of the essential elements, their major deficiency symptoms and the mechanism of absorption of these essential elements. The chapter also introduces you briefly to the significance and the mechanism of biological nitrogen fixation.

12.1 Methods to Study the Mineral Requirements of Plants

In 1860, Julius von Sachs, a prominent German botanist, demonstrated, for the first time, that plants could be grown to maturity in a defined nutrient solution in complete absence of soil. This technique of growing plants in a nutrient solution is known as **hydroponics**. Since then, a number of improvised methods have been employed to try and determine the mineral nutrients essential for plants. The essence of all these methods involves the culture of plants in a soil-free, defined mineral solution. These methods require purified water and mineral nutrient salts. *Can you explain why this is so essential?*

After a series of experiments in which the roots of the plants were immersed in nutrient solutions and wherein an element was added / removed or given in varied concentration, a mineral solution suitable for the plant growth was obtained. By this method, essential elements were identified and their deficiency symptoms discovered. Hydroponics has been successfully employed as a technique for the commercial production of vegetables such as tomato, seedless cucumber and lettuce. It must be emphasised that the nutrient solutions must be adequately aerated to obtain the optimum growth. What would happen if solutions were poorly aerated? Diagrammatic views of the hydroponic technique is given in Figures 12.1 and 12.2.

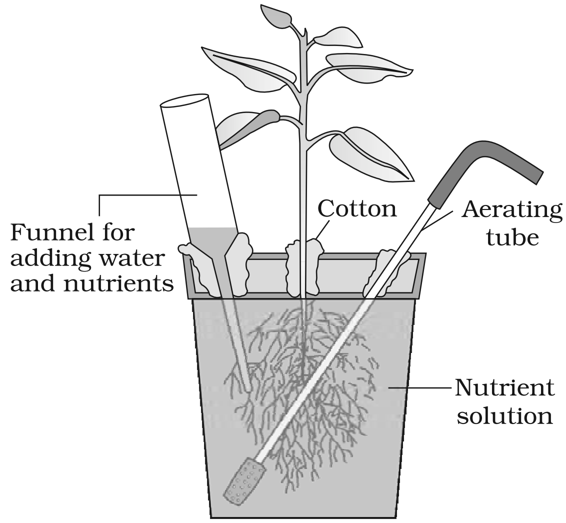


Figure 12.1 Diagram of a typical set-up for nutrient solution culture

12.2 ESSENTIAL MINERAL ELEMENTS

Most of the minerals present in soil can enter plants through roots. In fact, more than sixty elements of the 105 discovered so far are found in different plants. Some plant species accumulate selenium, some others gold, while some plants growing near nuclear test sites take up radioactive strontium. There are techniques that are able to detect the minerals even at a very low concentration (10^{-8} g/mL). The question is, whether all the diverse mineral elements present in a plant, for example, gold and selenium as mentioned above, are really necessary for plants? How do we decide what is essential for plants and what is not?

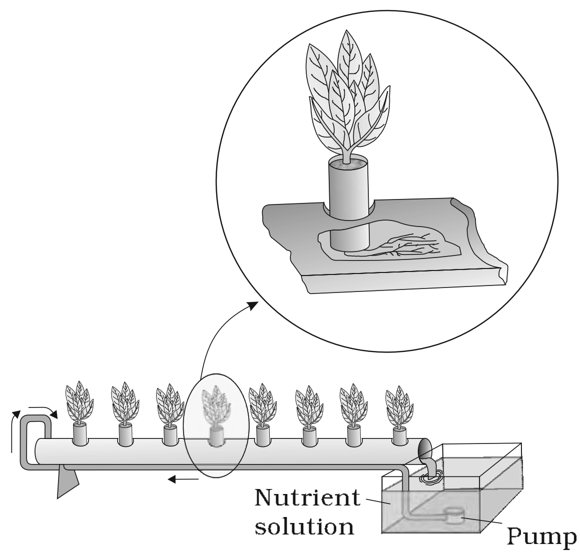


Figure 12.2 Hydroponic plant production. Plants are grown in a tube or trough placed on a slight incline. A pump circulates a nutrient solution from a reservoir to the elevated end of the tube. The solution flows down the tube and returns to the reservoir due to gravity. Inset shows a plant whose roots are continuously bathed in aerated nutrient solution. The arrows indicates the direction of the flow.

12.2.1 Criteria for Essentiality

The criteria for essentiality of an element are given below:

(a) The element must be absolutely necessary for supporting normal growth and reproduction. In the absence of the element the plants do not complete their life cycle or set the seeds.

(b) The requirement of the element must be specific and not replaceable by another element. In other words, deficiency of any one element cannot be met by supplying some other element.

(c) The element must be directly involved in the metabolism of the plant.

Based upon the above criteria only a few elements have been found to be absolutely essential for plant growth and metabolism. These elements are further divided into two broad categories based on their quantitative requirements.

(i) Macronutrients, and

(ii) Micronutrients

Macronutrients are generally present in plant tissues in large amounts (in excess of 10 mmole Kg^{-1} of dry matter). The macronutrients include carbon, hydrogen, oxygen, nitrogen, phosphorous, sulphur, potassium, calcium and magnesium. Of these, carbon, hydrogen and oxygen are mainly obtained from CO_2 and H_2O, while the others are absorbed from the soil as mineral nutrition.

Micronutrients or trace elements, are needed in very small amounts (less than 10 mmole Kg^{-1} of dry matter). These include iron, manganese, copper, molybdenum, zinc, boron, chlorine and nickel.

In addition to the 17 essential elements named above, there are some beneficial elements such as sodium, silicon, cobalt and selenium. They are required by higher plants.

Essential elements can also be grouped into four broad categories on the basis of their diverse functions. These categories are:

(i) Essential elements as components of biomolecules and hence structural elements of cells (e.g., carbon, hydrogen, oxygen and nitrogen).

(ii) Essential elements that are components of energy-related chemical compounds in plants (e.g., magnesium in chlorophyll and phosphorous in ATP).

(iii) Essential elements that activate or inhibit enzymes, for example Mg^{2+} is an activator for both ribulose bisphosphate carboxylase-oxygenase and phosphoenol pyruvate carboxylase, both of which are critical enzymes in photosynthetic carbon fixation; Zn^{2+} is an activator of alcohol dehydrogenase and Mo of nitrogenase during nitrogen metabolism. *Can you name a few more elements that fall in this category?* For this, you will need to recollect some of the biochemical pathways you have studied earlier.

(iv) Some essential elements can alter the osmotic potential of a cell. Potassium plays an important role in the opening and closing of stomata. You may recall the role of minerals as solutes in determining the water potential of a cell.

12.2.2 Role of Macro- and Micro-nutrients

Essential elements perform several functions. They participate in various metabolic processes in the plant cells such as permeability of cell membrane, maintenance of osmotic concentration of cell sap, electron-transport systems, buffering action, enzymatic activity and act as major constituents of macromolecules and co-enzymes.

Various forms and functions of mineral elements are given below.

Nitrogen : This is the mineral element required by plants in the greatest amount. It is absorbed mainly as NO_3^- though some are also taken up as NO_2^- or NH_4^+. Nitrogen is required by all parts of a plant, particularly the meristematic tissues and the metabolically active cells. Nitrogen is one of the major constituents of proteins, nucleic acids, vitamins and hormones.

Phosphorus: Phosphorus is absorbed by the plants from soil in the form of phosphate ions (either as $H_2PO_4^-$ or HPO_4^{2-}). Phosphorus is a constituent of cell membranes, certain proteins, all nucleic acids and nucleotides, and is required for all phosphorylation reactions.

Potassium: It is absorbed as potassium ion (K^+). In plants, this is required in more abundant quantities in the meristematic tissues, buds, leaves and root tips. Potassium helps to maintain an anion-cation balance in cells and is involved in protein synthesis, opening and closing of stomata, activation of enzymes and in the maintenance of the turgidity of cells.

Plant absorbs calcium from the soil in the form of calcium ions (Ca^{2+}). Calcium is required by meristematic and differentiating tissues. During cell division it is used in the synthesis of cell wall, particularly as calcium pectate in the middle lamella. It is also needed during the formation of mitotic spindle. It accumulates in older leaves. It is involved in the normal functioning of the cell membranes. It activates certain enzymes and plays an important role in regulating metabolic activities.

It is absorbed by plants in the form of divalent Mg^{2+}. It activates the enzymes of respiration, photosynthesis and are involved in the synthesis of DNA and RNA. Magnesium is a constituent of the ring structure of chlorophyll and helps to maintain the ribosome structure.

Plants obtain sulphur in the form of sulphate (SO_4^{2-}). Sulphur is present in two amino acids – cysteine and methionine and is the main constituent of several coenzymes, vitamins (thiamine, biotin, Coenzyme A) and ferredoxin.

Plants obtain iron in the form of ferric ions (Fe^{3+}). It is required in larger amounts in comparison to other micronutrients. It is an important constituent of proteins involved in the transfer of electrons like ferredoxin and cytochromes. It is reversibly oxidised from Fe^{2+} to Fe^{3+} during electron transfer. It activates catalase enzyme, and is essential for the formation of chlorophyll.

It is absorbed in the form of manganous ions (Mn^{2+}). It activates many enzymes involved in photosynthesis, respiration and nitrogen metabolism. The best defined function of manganese is in the splitting of water to liberate oxygen during photosynthesis.

Plants obtain zinc as Zn^{2+} ions. It activates various enzymes, especially carboxylases. It is also needed in the synthesis of auxin.

It is absorbed as cupric ions (Cu^{2+}). It is essential for the overall metabolism in plants. Like iron, it is associated with certain enzymes involved in redox reactions and is reversibly oxidised from Cu^{+} to Cu^{2+}.

It is absorbed as BO_3^{3-} or $B_4O_7^{2-}$. Boron is required for uptake and utilisation of Ca^{2+}, membrane functioning, pollen germination, cell elongation, cell differentiation and carbohydrate translocation.

Plants obtain it in the form of molybdate ions (MoO_2^{2+}). It is a component of several enzymes, including nitrogenase and nitrate reductase both of which participate in nitrogen metabolism.

It is absorbed in the form of chloride anion (Cl^{-}). Along with Na^{+} and K^{+}, it helps in determining the solute concentration and the anion-cation balance in cells. It is essential for the water-splitting reaction in photosynthesis, a reaction that leads to oxygen evolution.

12.2.3 Deficiency Symptoms of Essential Elements

Whenever the supply of an essential element becomes limited, plant growth is retarded. The concentration of the essential element below which plant growth is retarded is termed as The element is said to be deficient when present below the critical concentration.

Since each element has one or more specific structural or functional role in plants, in the absence of any particular element, plants show certain morphological changes. These morphological changes are indicative of certain element deficiencies and are called deficiency symptoms. The deficiency symptoms vary from element to element and they disappear when the deficient mineral nutrient is provided to the plant. However, if deprivation continues, it may eventually lead to the death of the plant. The parts of the plants that show the deficiency symptoms also depend on the mobility of the element in the plant. For elements that are actively mobilised within the plants and exported to young developing tissues, the deficiency symptoms tend to appear first in the older tissues. For example, the deficiency symptoms of nitrogen, potassium and magnesium are visible first in the senescent leaves. In the older leaves, biomolecules containing these elements are broken down, making these elements available for mobilising to younger leaves.

The deficiency symptoms tend to appear first in the young tissues whenever the elements are relatively immobile and are not transported out of the mature organs, for example, elements like sulphur and calcium are a part of the structural component of the cell and hence are not easily released. This aspect of mineral nutrition of plants is of a great significance and importance to agriculture and horticulture.

The kind of deficiency symptoms shown in plants include chlorosis, necrosis, stunted plant growth, premature fall of leaves and buds, and inhibition of cell division. Chlorosis is the loss of chlorophyll leading to yellowing in leaves. This symptom is caused by the deficiency of elements N, K, Mg, S, Fe, Mn, Zn and Mo. Likewise, necrosis, or death of tissue, particularly leaf tissue, is due to the deficiency of Ca, Mg, Cu, K. Lack or low level of N, K, S, Mo causes an inhibition of cell division. Some elements like N, S, Mo delay flowering if their concentration in plants is low.

You can see from the above that the deficiency of any element can cause multiple symptoms and that the same symptoms may be caused by the deficiency of one of several different elements. Hence, to identify the deficient element, one has to study all the symptoms developed in all the various parts of the plant and compare them with the available standard tables. We must also be aware that different plants also respond differently to the deficiency of the same element.

12.2.4 Toxicity of Micronutrients

The requirement of micronutrients is always in low amounts while their moderate decrease causes the deficiency symptoms and a moderate increase causes toxicity. In other words, there is a narrow range of concentration at which the elements are optimum. Any mineral ion concentration in tissues that reduces the dry weight of tissues by about 10 per cent is considered toxic. Such critical concentrations vary widely among different micronutrients. The toxicity symptoms are difficult to identify. Toxicity levels for any element also vary for different plants. Many a times, excess of an element may inhibit the uptake of another element. For example, the prominent symptom of manganese toxicity is the appearance of brown spots surrounded by chlorotic veins. It is important to know that manganese competes with iron and magnesium for uptake and with magnesium for binding with enzymes. Manganese also inhibit calcium translocation in shoot apex. Therefore, excess of manganese may, in fact, induce deficiencies of iron, magnesium and calcium. Thus, what appears as symptoms of manganese toxicity may actually be the deficiency symptoms of iron, magnesium and calcium. Can this knowledge be of some importance to a farmer? a gardener? or even for you in your kitchen-garden?

12.3 Mechanism of Absorption of Elements

Much of the studies on mechanism of absorption of elements by plants has been carried out in isolated cells, tissues or organs. These studies revealed that the process of absorption can be demarcated into two main phases. In the first phase, an initial rapid uptake of ions into the 'free space' or 'outer space' of cells – the apoplast, is passive. In the second phase of uptake, the ions are taken in slowly into the 'inner space' – the symplast of the cells. The passive movement of ions into the apoplast usually occurs through ion-channels, the trans-membrane proteins that function as selective pores. On the other hand, the entry or exit of ions to and from the symplast requires the expenditure of metabolic energy, which is an process. The movement of ions is usually called the inward movement into the cells is influx and the outward movement, efflux. You have read the aspects of mineral nutrient uptake and translocation in plants in Chapter 11.

12.4 Translocation of Solutes

Mineral salts are translocated through xylem along with the ascending stream of water, which is pulled up through the plant by transpirational pull. Analysis of xylem sap shows the presence of mineral salts in it. Use of radioisotopes of mineral elements also substantiate the view that they are transported through the xylem. You have already discussed the movement of water in xylem in Chapter 11.

12.5 Soil as Reservoir of Essential Elements

Majority of the nutrients that are essential for the growth and development of plants become available to the roots due to weathering and breakdown of rocks. These processes enrich the soil with dissolved ions and inorganic salts. Since they are derived from the rock minerals, their role in plant nutrition is referred to as mineral nutrition. Soil consists of a wide variety of substances. Soil not only supplies minerals but also harbours nitrogen-fixing bacteria, other microbes, holds water, supplies air to the roots and acts as a matrix that stabilises the plant. Since deficiency of essential minerals affect the crop-yield, there is often a need for supplying them through fertilisers. Both macro-nutrients (N, P, K, S, etc.) and micro-nutrients (Cu, Zn, Fe, Mn, etc.) form components of fertilisers and are applied as per need.

12.6 Metabolism of Nitrogen

12.6.1 Nitrogen Cycle

Apart from carbon, hydrogen and oxygen, nitrogen is the most prevalent element in living organisms. Nitrogen is a constituent of amino acids, proteins, hormones, chlorophylls and many of the vitamins. Plants compete with microbes for the limited nitrogen that is available in soil. Thus, nitrogen is a limiting nutrient for both natural and agricultural eco-systems. Nitrogen exists as two nitrogen atoms joined by a very strong triple covalent bond (N ≡ N). The process of conversion of nitrogen (N_2) to ammonia is termed as

In nature, lightning and ultraviolet radiation provide enough energy to convert nitrogen to nitrogen oxides (NO, NO_2, N_2O). Industrial combustions, forest fires, automobile exhausts and power-generating stations are also sources of atmospheric nitrogen oxides. Decomposition of organic nitrogen of dead plants and animals into ammonia is called ammonification. Some of this ammonia volatilises and re-enters the atmosphere but most of it is converted into nitrate by soil bacteria in the following steps:

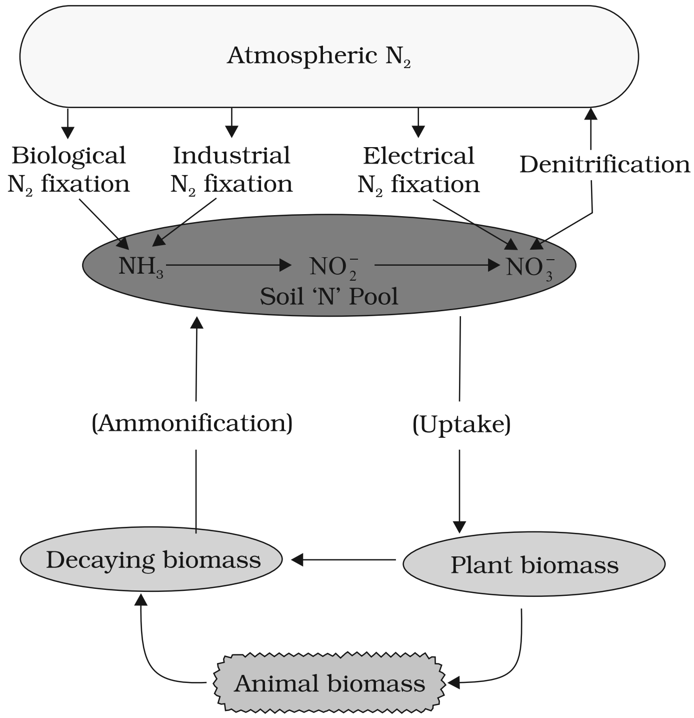


Figure 12.3 The nitrogen cycle showing relationship between the three main nitrogen pools – atmospheric soil, and biomass

$$2NH_3 + 3O_2 \longrightarrow 2NO_2^- + 2H^+ + 2H_2O \quad \text{.... (i)}$$

$$2NO_2^- + O_2 \longrightarrow 2NO_3^- \quad \text{...... (ii)}$$

Ammonia is first oxidised to nitrite by the bacteria *Nitrosomonas* and/or *Nitrococcus*. The nitrite is further oxidised to nitrate with the help of the bacterium *Nitrobacter*

Pseudomonas *Thiobacillus*

12.6.2 Biological Nitrogen Fixation

$_2$, available abundantly in the air. Only certain prokaryotic species are capable of fixing nitrogen. Reduction of nitrogen to ammonia by living organisms is

$_2$- fixers.

$$N \equiv N \xrightarrow{\text{Nitrogenase}} NH_3$$

The nitrogen-fixing microbes could be free-living or symbiotic. Examples of free-living nitrogen-fixing aerobic microbes are *Azotobacter*
Beijernickia *Rhodospirillum* *Bacillus*
Anabaena *Nostoc*

Rhizobium

Frankia,
Rhizobium *Frankia*

Rhizobium

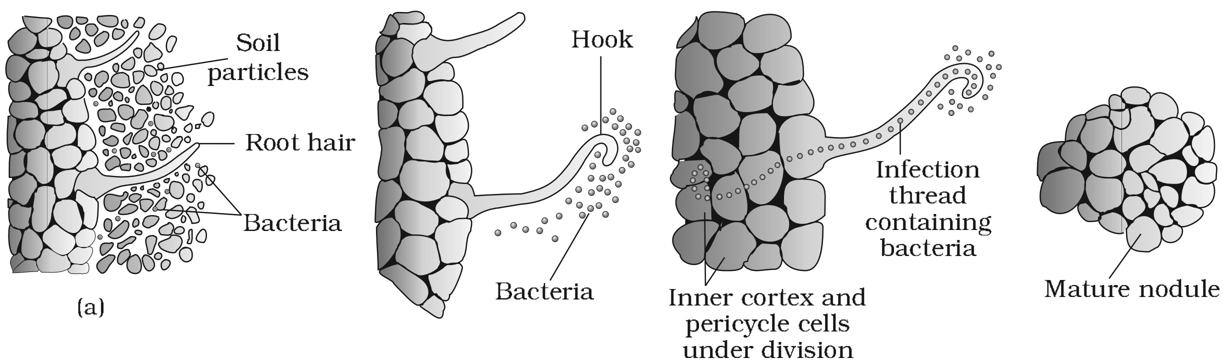


Figure 12.4 Development of root nodules in soyabean : (a) *Rhizobium* bacteria contact a susceptible root hair, divide near it, (b) Upon successful infection of the root hair cause it to curl, (c) Infected thread carries the bacteria to the inner cortex. The bacteria get modified into rod-shaped bacteroids and cause inner cortical and pericycle cells to divide. Division and growth of cortical and pericycle cells lead to nodule formation, (d) A mature nodule is complete with vascular tissues continuous with those of the root

$$N_2 + 8e^- + 8H^+ + 16ATP \longrightarrow 2NH_3 + H_2 + 16ADP + 16P_i$$

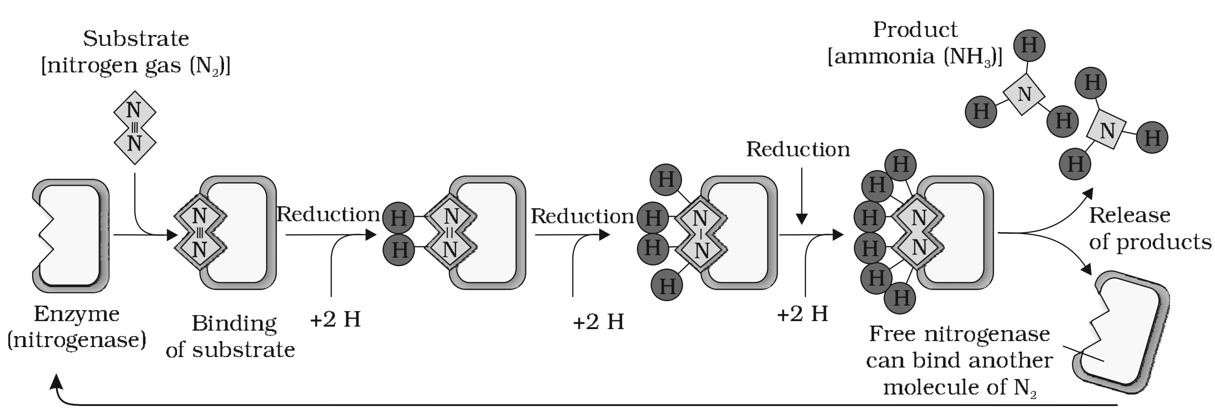


Figure 12.5 Steps of conversion of atmospheric nitrogen to ammonia by nitrogenase enzyme complex found in nitrogen-fixing bacteria

$_3$ produced). The energy required, thus, is obtained from the respiration of the host cells.

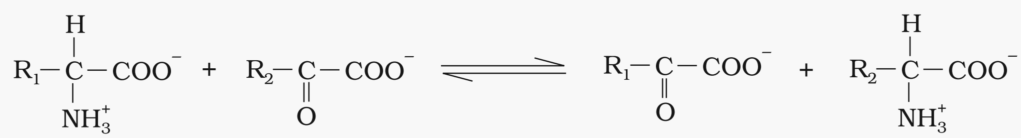
NH_4^+

NH_4^+

α

ketoglutaric acid NH_4 NADPH $\xrightarrow[\text{Dehydrogenase}]{\text{Glutamate}}$ glutamate H_2O NADP

$_2$, the amino group takes place and other amino acids are formed through transamination. The enzyme



Amino-donor Amino-acceptor

$_2^-$ radicle. Since amides contain more nitrogen than the amino acids, they are transported to other parts of the plant via xylem vessels. In addition, along with the transpiration stream the nodules of some plants (e.g., soyabean) export the fixed nitrogen as ureides. These compounds also have a particularly high nitrogen to carbon ratio.

SUMMARY

$_2$-fixing bacteria, especially roots of legumes, can fix this atmospheric nitrogen into biologically usable forms. Nitrogen fixation requires a strong reducing agent and energy in the form of ATP. N_2-fixation is accomplished with the help of nitrogen-fixing microbes, mainly *Rhizobium.*

$_2$ fixation is very sensitive to oxygen. Most of the processes take place in anaerobic environment. The energy, ATP, required is provided by the respiration of the host cells. Ammonia produced following N_2 fixation is incorporated into amino acids as the amino group.

EXERCISES

1. 'All elements that are present in a plant need not be essential to its survival'. Comment.
2. Why is purification of water and nutrient salts so important in studies involving mineral nutrition using hydroponics.
3. Explain with examples: macronutrients, micronutrients, beneficial nutrients, toxic elements and essential elements.
4. Name at least five different deficiency symptoms in plants. Describe them and correlate them with the concerned mineral deficiency.
5. If a plant shows a symptom which could develop due to deficiency of more than one nutrient, how would you find out experimentally, the real deficient mineral element?
6. Why is that in certain plants deficiency symptoms appear first in younger parts of the plant while in others they do so in mature organs?
7. How are the minerals absorbed by the plants?
8. What are the conditions necessary for fixation of atmospheric nitrogen by *Rhizobium*. What is their role in N_2-fixation?
9. What are the steps involved in formation of a root nodule?
10. Which of the following statements are true? If false, correct them:
    (a) Boron deficiency leads to stout axis.
    (b) Every mineral element that is present in a cell is needed by the cell.
    (c) Nitrogen as a nutrient element, is highly immobile in the plants.
    (d) It is very easy to establish the essentiality of micronutrients because they are required only in trace quantities.

CHAPTER 13

PHOTOSYNTHESIS IN HIGHER PLANTS

All animals including human beings depend on plants for their food. Have you ever wondered from where plants get their food? Green plants, in fact, have to make or rather synthesise the food they need and all other organisms depend on them for their needs. Green plants carry out 'photosynthesis', a physico-chemical process by which they use light energy to drive the synthesis of organic compounds. Ultimately, all living forms on earth depend on sunlight for energy. The use of energy from sunlight by plants doing photosynthesis is the basis of life on earth. Photosynthesis is important due to two reasons: it is the primary source of all food on earth. It is also responsible for the release of oxygen into the atmosphere by green plants. *Have you ever thought what would happen if there were no oxygen to breath?* This chapter focusses on the structure of the photosynthetic machinery and the various reactions that transform light energy into chemical energy.

13.1 WHAT DO WE KNOW?

Let us try to find out what we already know about photosynthesis. Some simple experiments you may have done in the earlier classes have shown that chlorophyll (green pigment of the leaf), light and CO_2 are required for photosynthesis to occur.

You may have carried out the experiment to look for starch formation in two leaves – a variegated leaf or a leaf that was partially covered with black paper, and one that was exposed to light. On testing these leaves for starch it was clear that photosynthesis occurred only in the green parts of the leaves in the presence of light.

Another experiment you may have carried out is the half-leaf experiment, where a part of a leaf is enclosed in a test tube containing some KOH soaked cotton (which absorbs CO_2), while the other half is exposed to air. The setup is then placed in light for some time. On testing for starch later in the two halves of the leaf, you must have found that the exposed part of the leaf tested positive for starch while the portion that was in the tube, tested negative. This showed that CO_2 was required for photosynthesis. *Can you explain how this conclusion could be drawn?*

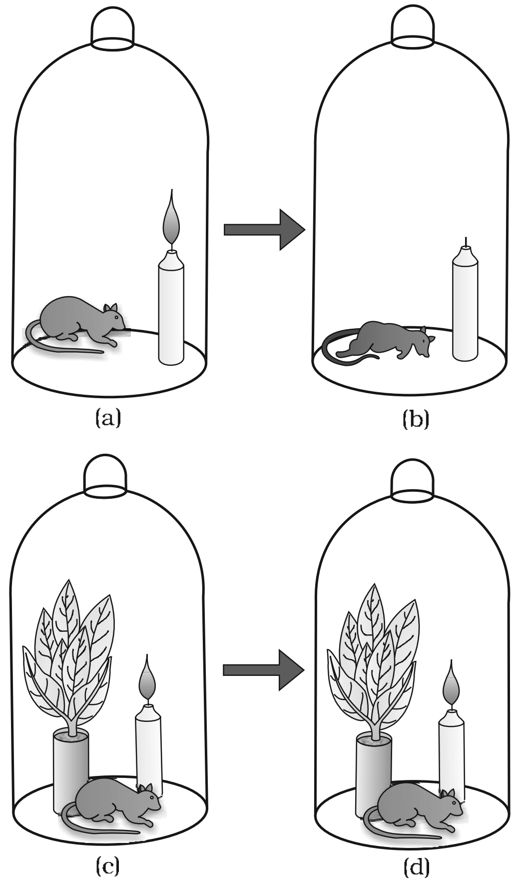


Figure 13.1 Priestley's experiment

13.2 EARLY EXPERIMENTS

It is interesting to learn about those simple experiments that led to a gradual development in our understanding of photosynthesis.

Joseph Priestley (1733-1804) in 1770 performed a series of experiments that revealed the essential role of air in the growth of green plants. Priestley, you may recall, discovered oxygen in 1774. Priestley observed that a candle burning in a closed space – a bell jar, soon gets extinguished (Figure 13.1 a, b, c, d). Similarly, a mouse would soon suffocate in a closed space. He concluded that a burning candle or an animal that breathe the air, both somehow, damage the air. But when he placed a mint plant in the same bell jar, he found that the mouse stayed alive and the candle continued to burn. Priestley hypothesised as follows: Plants restore to the air whatever breathing animals and burning candles remove.

Can you imagine how Priestley would have conducted the experiment using a candle and a plant? Remember, he would need to rekindle the candle to test whether it burns after a few days. *How many different ways can you think of to light the candle without disturbing the set-up?*

Using a similar setup as the one used by Priestley, but by placing it once in the dark and once in the sunlight, Jan Ingenhousz (1730-1799) showed that sunlight is essential to the plant process that somehow purifies the air fouled by burning candles or breathing animals. Ingenhousz in an elegant experiment with an aquatic plant showed that in bright sunlight, small bubbles were formed around the green parts while in the dark they did not. Later he identified these bubbles to be of oxygen. Hence he showed that it is only the green part of the plants that could release oxygen.

It was not until about 1854 that Julius von Sachs provided evidence for production of glucose when plants grow. Glucose is usually stored as starch. His later studies showed that the green substance in plants (chlorophyll as we know it now) is located in special bodies (later called chloroplasts) within plant cells. He found that the green parts in plants is where glucose is made, and that the glucose is usually stored as starch.

Now consider the interesting experiments done by T.W Engelmann (1843 – 1909). Using a prism he split light into its spectral components and then illuminated a green alga, *Cladophora*, placed in a suspension of aerobic bacteria. The bacteria were used to detect the sites of O_2 evolution. He observed that the bacteria accumulated mainly in the region of blue and red light of the split spectrum. A first action spectrum of photosynthesis was thus described. It resembles roughly the absorption spectra of chlorophyll *a* and *b* (discussed in section 13.4).

By the middle of the nineteenth century the key features of plant photosynthesis were known, namely, that plants could use light energy to make carbohydrates from CO_2 and water. The empirical equation representing the total process of photosynthesis for oxygen evolving organisms was then understood as:

$$CO_2 + H_2O \xrightarrow{\text{Light}} [CH_2O] + O_2$$

where $[CH_2O]$ represented a carbohydrate (e.g., glucose, a six-carbon sugar).

A milestone contribution to the understanding of photosynthesis was that made by a microbiologist, Cornelius van Niel (1897-1985), who, based on his studies of purple and green bacteria, demonstrated that photosynthesis is essentially a light-dependent reaction in which hydrogen from a suitable oxidisable compound reduces carbon dioxide to carbohydrates. This can be expressed by:

$$2H_2A + CO_2 \xrightarrow{\text{Light}} 2A + CH_2O + H_2O$$

In green plants H_2O is the hydrogen donor and is oxidised to O_2. Some organisms do not release O_2 during photosynthesis. When H_2S, instead is the hydrogen donor for purple and green sulphur bacteria, the 'oxidation' product is sulphur or sulphate depending on the organism and not O_2. Hence, he inferred that the O_2 evolved by the green plant comes from H_2O, not from carbon dioxide. This was later proved by using radioisotopic techniques. The correct equation, that would represent the overall process of photosynthesis is therefore:

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

where $C_6 H_{12} O_6$ represents glucose. The O_2 released is from water; this was proved using radio isotope techniques. Note that this is not a single reaction but description of a multistep process called photosynthesis. *Can you explain why twelve molecules of water as substrate are used in the equation given above?*

13.3 WHERE DOES PHOTOSYNTHESIS TAKE PLACE?

You would of course answer: in 'the green leaf' or you may add, 'in the chloroplasts' based on what you earlier read in Chapter 8. You are definitely right. Photosynthesis does take place in the green leaves of plants but it does so also in other green parts of the plants. *Can you name some other parts where you think photosynthesis may occur?*

You would recollect from previous unit that the mesophyll cells in the leaves, have a large number of chloroplasts. Usually the chloroplasts align themselves along the walls of the mesophyll cells, such that they get the optimum quantity of the incident light. *When do you think the chloroplasts will be aligned with their flat surfaces parallel to the walls? When would they be perpendicular to the incident light?*

You have studied the structure of chloroplast in Chapter 8. Within the chloroplast there is the membranous system consisting of grana, the stroma lamellae, and the fluid stroma (Figure 13.2). There is a clear division of labour within the chloroplast. The membrane system is responsible for trapping the light energy and also for the synthesis of ATP and NADPH. In stroma, enzymatic reactions incorporate CO_2 into the plant leading to the synthesis of sugar, which in turn forms starch. The former set of reactions, since they are directly light driven are called **light reactions.** The latter are not directly light driven but are dependent on the products of light reactions (ATP and NADPH). Hence, to distinguish the latter they are called, by convention, as **dark reactions**. However, this should not be construed to mean that they occur in darkness or that they are not light-dependent.

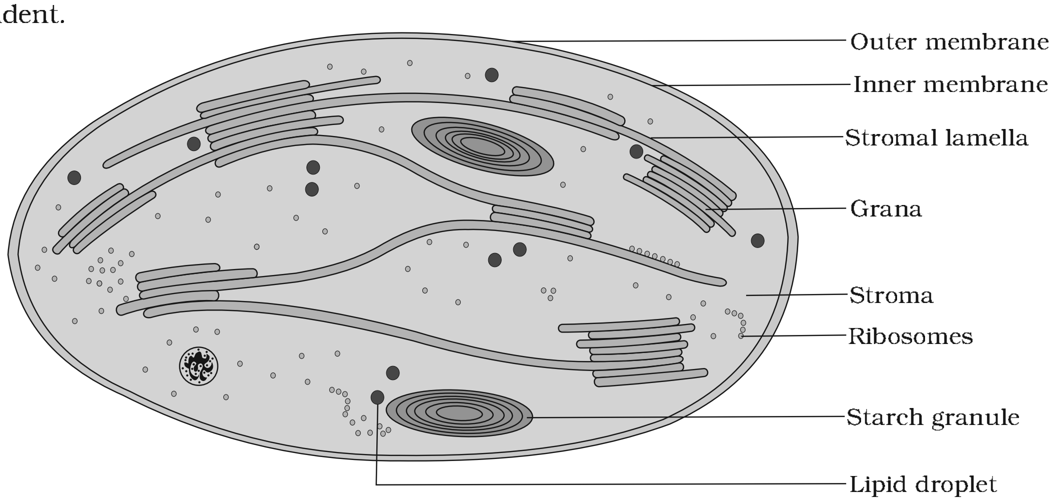


Figure 13.2 Diagrammatic representation of an electron micrograph of a section of chloroplast

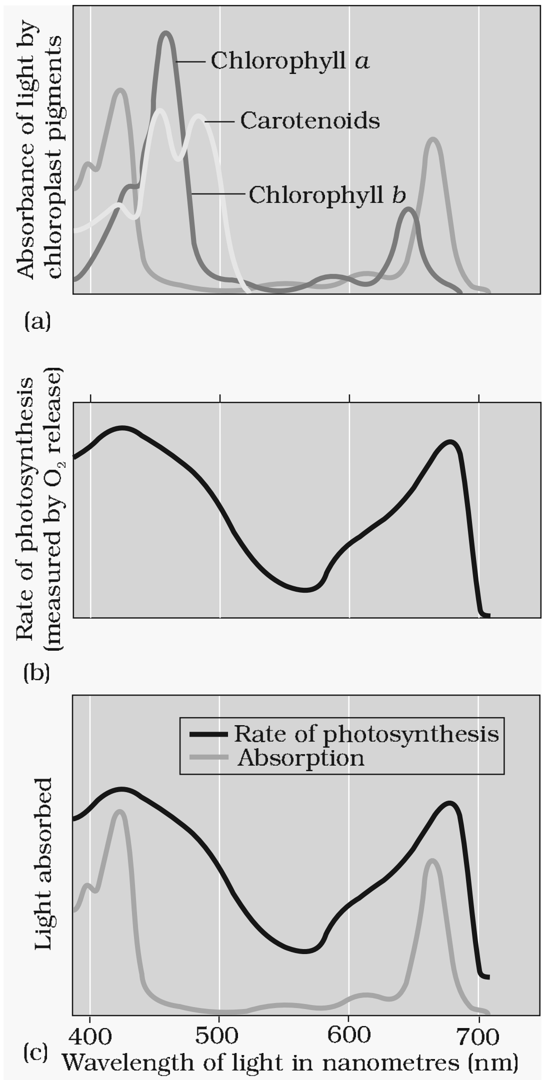


Figure 13.3a Graph showing the absorption spectrum of chlorophyll *a*, *b* and the carotenoids
Figure 13.3b Graph showing action spectrum of photosynthesis
Figure 13.3c Graph showing action spectrum of photosynthesis superimposed on absorption spectrum of chlorophyll *a*

13.4 How many Pigments are Involved in Photosynthesis?

Looking at plants have you ever wondered why and how there are so many shades of green in their leaves – even in the same plant? We can look for an answer to this question by trying to separate the leaf pigments of any green plant through paper chromatography. A chromatographic separation of the leaf pigments shows that the colour that we see in leaves is not due to a single pigment but due to four pigments: **Chlorophyll *a*** (bright or blue green in the chromatogram), **chlorophyll *b*** (yellow green), **xanthophylls** (yellow) and **carotenoids** (yellow to yellow-orange). Let us now see what roles various pigments play in photosynthesis.

Pigments are substances that have an ability to absorb light, at specific wavelengths. *Can you guess which is the most abundant plant pigment in the world?* Let us study the graph showing the ability of chlorophyll *a* pigment to absorb lights of different wavelengths (Figure 13.3 a). Of course, you are familiar with the wavelength of the visible spectrum of light as well as the VIBGYOR.

From Figure 13.3a can you determine the wavelength (colour of light) at which chlorophyll a shows the maximum absorption? Does it show another absorption peak at any other wavelengths too? If yes, which one?

Now look at Figure 13.3b showing the wavelengths at which maximum photosynthesis occurs in a plant. Can you see that the wavelengths at which there is maximum absorption by chlorophyll *a*, i.e., in the blue and the red regions, also shows higher rate of photosynthesis. Hence, we can conclude that chlorophyll *a* is the chief pigment associated with photosynthesis. *But by looking at Figure 13.3c can you say that there is a complete one-to-one overlap between the absorption spectrum of chlorophyll a and the action spectrum of photosynthesis?*

These graphs, together, show that most of the photosynthesis takes place in the blue and red regions of the spectrum; some photosynthesis does take place at the other wavelengths of the visible spectrum. Let us see how this happens. Though chlorophyll is the major pigment responsible for trapping light, other thylakoid pigments like chlorophyll *b*, xanthophylls and carotenoids, which are called accessory pigments, also absorb light and transfer the energy to chlorophyll *a*. Indeed, they not only enable a wider range of wavelength of incoming light to be utilised for photosyntesis but also protect chlorophyll *a* from photo-oxidation.

13.5 WHAT IS LIGHT REACTION?

Light reactions or the 'Photochemical' phase include light absorption, water splitting, oxygen release, and the formation of high-energy chemical intermediates, ATP and NADPH. Several complexes are involved in the process. The pigments are organised into two discrete photochemical **light harvesting complexes** (**LHC**) within the **Photosystem I (PS I)** and **Photosystem II (PS II)**. These are named in the sequence of their discovery, and not in the sequence in which they function during the light reaction. The LHC are made up of hundreds of pigment molecules bound to proteins. Each photosystem has all the pigments (except one molecule of chlorophyll *a*) forming a light harvesting system also called **antennae** (Figure 13.4). These pigments help to make photosynthesis more efficient by absorbing different wavelengths of light. The single chlorophyll *a* molecule forms the **reaction centre.** The reaction centre is different in both the photosystems. In PS I the reaction centre chlorophyll *a* has an absorption peak at 700 nm, hence is called **P700,** while in PS II it has absorption maxima at 680 nm, and is called **P680**.

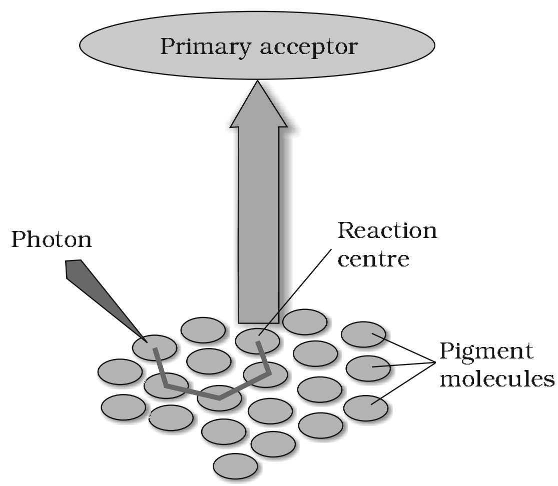


Figure 13.4 The light harvesting complex

13.6 THE ELECTRON TRANSPORT

In photosystem II the reaction centre chlorophyll *a* absorbs 680 nm wavelength of red light causing electrons to become excited and jump into an orbit farther from the atomic nucleus. These electrons are picked up by an electron acceptor which passes them to an **electrons transport**

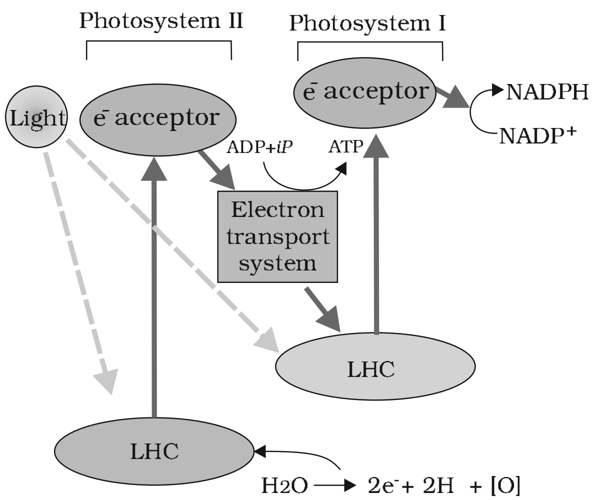


Figure 13.5 Z scheme of light reaction

system consisting of cytochromes (Figure 13.5). This movement of electrons is downhill, in terms of an oxidation-reduction or redox potential scale. The electrons are not used up as they pass through the electron transport chain, but are passed on to the pigments of photosystem PS I. Simultaneously, electrons in the reaction centre of PS I are also excited when they receive red light of wavelength 700 nm and are transferred to another accepter molecule that has a greater redox potential. These electrons then are moved downhill again, this time to a molecule of energy-rich $NADP^+$. The addition of these electrons reduces $NADP^+$ to NADPH + H^+. This whole scheme of transfer of electrons, starting from the PS II, uphill to the accepter, down the electron transport chain to PS I, excitation of electrons, transfer to another accepter, and finally down hill to $NADP^+$ causing it to be reduced to NADPH + H^+ is called the **Z scheme**, due to its characterstic shape (Figure 13.5). This shape is formed when all the carriers are placed in a sequence on a redox potential scale.

13.6.1 Splitting of Water

You would then ask, *How does PS II supply electrons continuously?* The electrons that were moved from photosystem II must be replaced. This is achieved by electrons available due to splitting of water. The splitting of water is associated with the PS II; water is split into H^+, [O] and electrons. This creates oxygen, one of the net products of photosynthesis. The electrons needed to replace those removed from photosystem I are provided by photosystem II.

$$2H_2O \longrightarrow 4H^+ + O_2 + 4e^-$$

We need to emphasise here that the water splitting complex is associated with the PS II, which itself is physically located on the inner side of the membrane of the thylakoid. *Then, where are the protons and O_2 formed likely to be released – in the lumen? or on the outer side of the membrane?*

13.6.2 Cyclic and Non-cyclic Photo-phosphorylation

Living organisms have the capability of extracting energy from oxidisable substances and store this in the form of bond energy. Special substances like ATP, carry this energy in their chemical bonds. The process of which

ATP is synthesised by cells (in mitochondria and chloroplasts) is named phosphorylation. Photo-phosphorylation is the synthesis of ATP from ADP and inorganic phosphate in the presence of light. When the two photosystems work in a series, first PS II and then the PS I, a process called non-cyclic photo-phosphorylation occurs. The two photosystems are connected through an electron transport chain, as seen earlier – in the Z scheme. Both ATP and NADPH + H^+ are synthesised by this kind of electron flow (Figure 13.5).

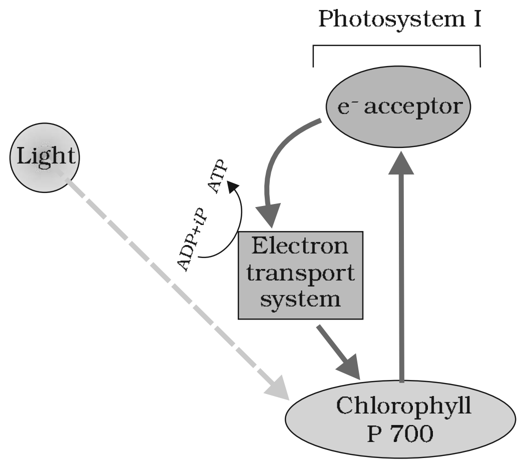


Figure 13.6 Cyclic photophosphorylation

When only PS I is functional, the electron is circulated within the photosystem and the phosphorylation occurs due to cyclic flow of electrons (Figure 13.6). A possible location where this could be happening is in the stroma lamellae. While the membrane or lamellae of the grana have both PS I and PS II the stroma lamellae membranes lack PS II as well as NADP reductase enzyme. The excited electron does not pass on to $NADP^+$ but is cycled back to the PS I complex through the electron transport chain (Figure 13.6). The cyclic flow hence, results only in the synthesis of ATP, but not of NADPH + H^+. Cyclic photophosphorylation also occurs when only light of wavelengths beyond 680 nm are available for excitation.

13.6.3 Chemiosmotic Hypothesis

Let us now try and understand how actually ATP is synthesised in the chloroplast. The chemiosmotic hypothesis has been put forward to explain the mechanism. Like in respiration, in photosynthesis too, ATP synthesis is linked to development of a proton gradient across a membrane. This time these are membranes of the thylakoid. There is one difference though, here the proton accumulation is towards the inside of the membrane, i.e., in the lumen. In respiration, protons accumulate in the intermembrane space of the mitochondria when electrons move through the ETS (Chapter 14).

Let us understand what causes the proton gradient across the membrane. We need to consider again the processes that take place during the activation of electrons and their transport to determine the steps that cause a proton gradient to develop (Figure 13.7).

(a) Since splitting of the water molecule takes place on the inner side of the membrane, the protons or hydrogen ions that are produced by the splitting of water accumulate within the lumen of the thylakoids.

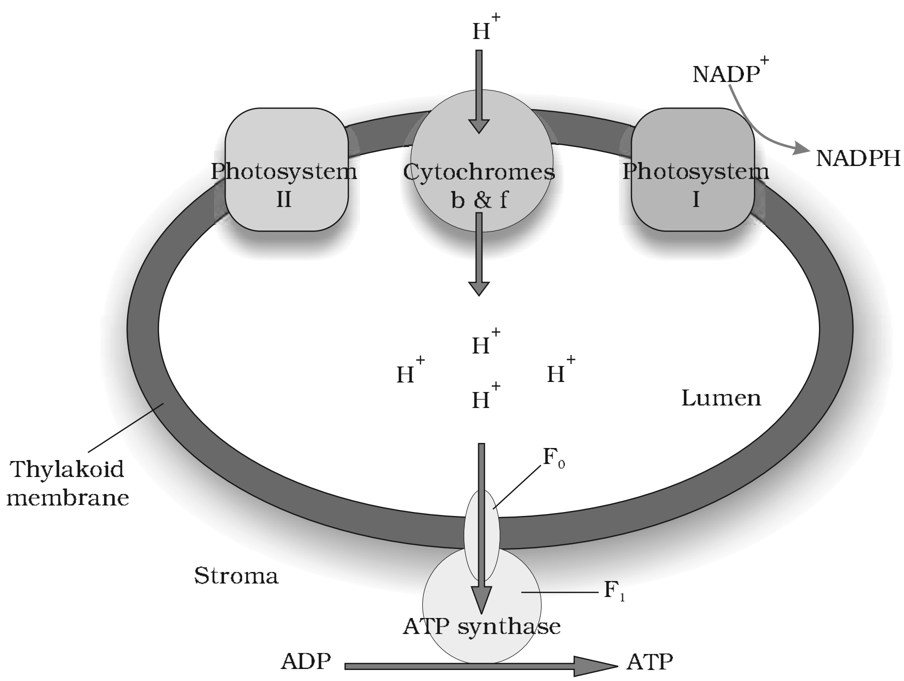


Figure 13.7 ATP synthesis through chemiosmosis

(b) As electrons move through the photosystems, protons are transported across the membrane. This happens because the primary accepter of electron which is located towards the outer side of the membrane transfers its electron not to an electron carrier but to an H carrier. Hence, this molecule removes a proton from the stroma while transporting an electron. When this molecule passes on its electron to the electron carrier on the inner side of the membrane, the proton is released into the inner side or the lumen side of the membrane.

(c) The NADP reductase enzyme is located on the stroma side of the membrane. Along with electrons that come from the accepter of electrons of PS I, protons are necessary for the reduction of $NADP^+$ to NADPH+ H^+. These protons are also removed from the stroma.

Hence, within the chloroplast, protons in the stroma decrease in number, while in the lumen there is accumulation of protons. This creates a proton gradient across the thylakoid membrane as well as a measurable decrease in pH in the lumen.

Why are we so interested in the proton gradient? This gradient is important because it is the breakdown of this gradient that leads to release of energy. The gradient is broken down due to the movement of protons across the membrane to the stroma through the transmembrane channel of the F_0 of the ATPase. The ATPase enzyme consists of two parts: one called the F_0 is embedded in the membrane and forms a transmembrane channel that carries out facilitated diffusion of protons across the membrane. The other portion is called F_1 and protrudes on the outer surface of the thylakoid membrane on the side that faces the stroma. The break down of the gradient provides enough energy to cause a conformational change in the F_1 particle of the ATPase, which makes the enzyme synthesise several molecules of energy-packed ATP.

Chemiosmosis requires a membrane, a proton pump, a proton gradient and ATPase. Energy is used to pump protons across a membrane, to create a gradient or a high concentration of protons within the thylakoid lumen. ATPase has a channel that allows diffusion of protons back across the membrane; this releases enough energy to activate ATPase enzyme that catalyses the formation of ATP.

Along with the NADPH produced by the movement of electrons, the ATP will be used immediately in the biosynthetic reaction taking place in the stroma, responsible for fixing CO_2, and synthesis of sugars.

13.7 WHERE ARE THE ATP AND NADPH USED?

We learnt that the products of light reaction are ATP, NADPH and O_2. Of these O_2 diffuses out of the chloroplast while ATP and NADPH are used to drive the processes leading to the synthesis of food, more accurately, sugars. This is the **biosynthetic phase** of photosynthesis. This process does not directly depend on the presence of light but is dependent on the products of the light reaction, i.e., ATP and NADPH, besides CO_2 and H_2O. You may wonder how this could be verified; it is simple: immediately after light becomes unavailable, the biosynthetic process continues for some time, and then stops. If then, light is made available, the synthesis starts again.

*Can we, hence, say that calling the biosynthetic phase as the **dark reaction** is a misnomer? Discuss this amongst yourselves.*

Let us now see how the ATP and NADPH are used in the biosynthetic phase. We saw earlier that CO_2 is combined with H_2O to produce $(CH_2O)_n$ or sugars. It was of interest to scientists to find out how this reaction proceeded, or rather what was the first product formed when CO_2 is taken into a reaction or fixed. Just after world war II, among the several efforts to put radioisotopes to beneficial use, the work of Melvin Calvin is exemplary. The use of radioactive ^{14}C by him in algal photosynthesis studies led to the discovery that the first CO_2 fixation product was a 3-carbon organic acid. He also contributed to working out the complete biosynthetic pathway; hence it was called **Calvin cycle** after him. The first product identified was **3-phosphoglyceric** acid or in short **PGA**. *How many carbon atoms does it have?*

Scientists also tried to know whether all plants have PGA as the first product of CO_2 fixation, or whether any other product was formed in other plants. Experiments conducted over a wide range of plants led to the discovery of another group of plants, where the first stable product of CO_2 fixation was again an organic acid, but one which had 4 carbon atoms in it. This acid was identified to be **oxaloacetic acid** or OAA. Since then CO_2 assimilation during photosynthesis was said to be of two main types: those plants in which the first product of CO_2 fixation is a C_3 acid (PGA), i.e., the **C_3 pathway,** and those in which the first product was a C_4 acid (OAA), i.e., the **C_4 pathway**. These two groups of plants showed other associated characteristics that we will discuss later.

13.7.1 The Primary Acceptor of CO_2

Let us now ask ourselves a question that was asked by the scientists who were struggling to understand the 'dark reaction'. *How many carbon atoms would a molecule have which after accepting (fixing) CO_2, would have 3 carbons (of PGA)?*

The studies very unexpectedly showed that the accepter molecule was a 5-carbon ketose sugar – it was ribulose bisphosphate (RuBP). *Did any of you think of this possibility?* Do not worry; the scientists also took a long time and conducted many experiments to reach this conclusion. They also believed that since the first product was a C_3 acid, the primary acceptor would be a 2-carbon compound; they spent many years trying to identify a 2-carbon compound before they discovered the 5-carbon RuBP.

13.7.2 The Calvin Cycle

Calvin and his co-workers then worked out the whole pathway and showed that the pathway operated in a cyclic manner; the RuBP was regenerated. Let us now see how the Calvin pathway operates and where the sugar is synthesised. Let us at the outset understand very clearly that the Calvin pathway occurs in **all photosynthetic plants**; it does not matter whether they have C_3 or C_4 (or any other) pathways (Figure 13.8).

For ease of understanding, the Calvin cycle can be described under three stages: carboxylation, reduction and regeneration.

1. **Carboxylation** – Carboxylation is the fixation of CO_2 into a stable organic intermediate. Carboxylation is the most crucial step of the Calvin cycle where CO_2 is utilised for the carboxylation of RuBP. This reaction is catalysed by the enzyme RuBP carboxylase which results in the formation of two molecules of 3-PGA. Since this enzyme also has an oxygenation activity it would be more correct to call it RuBP carboxylase-oxygenase or **RuBisCO**.

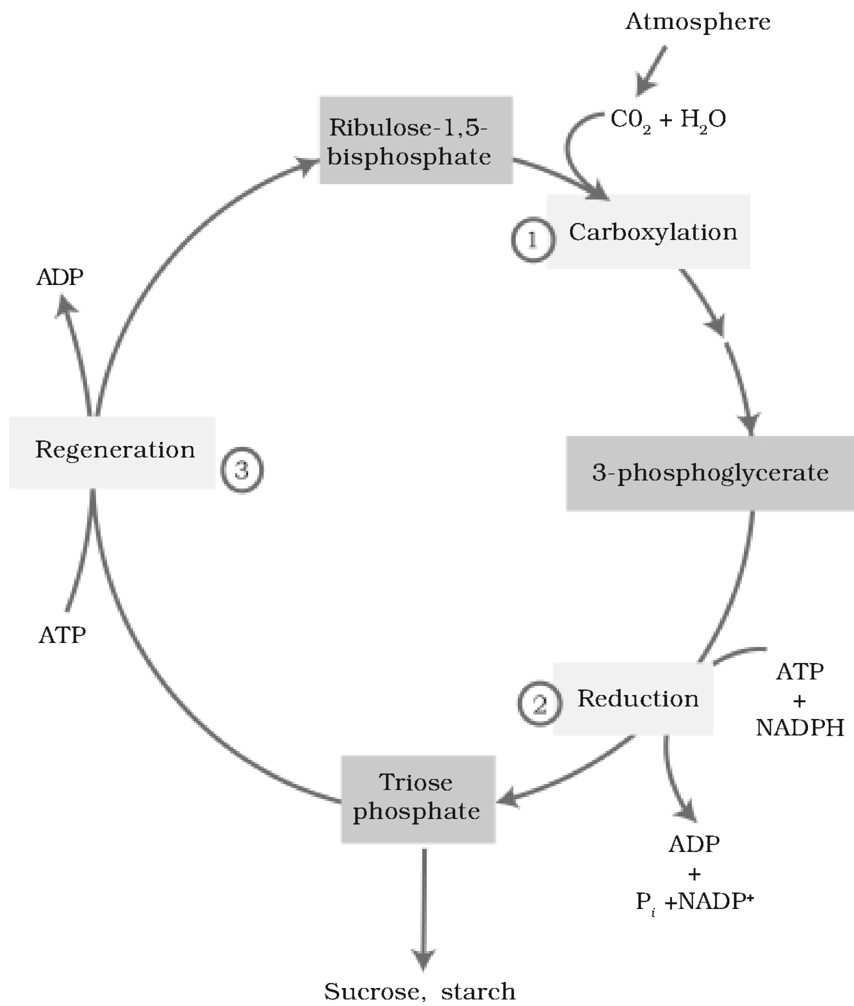


Figure 13.8 The Calvin cycle proceeds in three stages : (1) carboxylation, during which CO_2 combines with ribulose-1,5-bisphosphate; (2) reduction, during which carbohydrate is formed at the expense of the photochemically made ATP and NADPH; and (3) regeneration during which the CO_2 acceptor ribulose-1,5-bisphosphate is formed again so that the cycle continues

2. **Reduction** – These are a series of reactions that lead to the formation of glucose. The steps involve utilisation of 2 molecules of ATP for phosphorylation and two of NADPH for reduction per CO_2 molecule fixed. The fixation of six molecules of CO_2 and 6 turns of the cycle are required for the removal of one molecule of glucose from the pathway.

3. **Regeneration** – Regeneration of the CO_2 acceptor molecule RuBP is crucial if the cycle is to continue uninterrupted. The regeneration steps require one ATP for phosphorylation to form RuBP.

Hence for every CO_2 molecule entering the Calvin cycle, 3 molecules of ATP and 2 of NADPH are required. It is probably to meet this difference in number of ATP and NADPH used in the dark reaction that the cyclic phosphorylation takes place.

To make one molecule of glucose 6 turns of the cycle are required. *Work out how many ATP and NADPH molecules will be required to make one molecule of glucose through the Calvin pathway.*

It might help you to understand all of this if we look at what goes in and what comes out of the Calvin cycle.

In	Out
Six CO_2	One glucose
18 ATP	18 ADP
12 NADPH	12 NADP

13.8 The C_4 Pathway

Plants that are adapted to dry tropical regions have the C_4 pathway mentioned earlier. Though these plants have the C_4 oxaloacetic acid as the first CO_2 fixation product they use the C_3 pathway or the Calvin cycle as the main biosynthetic pathway. Then, in what way are they different from C_3 plants? This is a question that you may reasonably ask.

C_4 plants are special: They have a special type of leaf anatomy, they tolerate higher temperatures, they show a response to highlight intensities, they lack a process called photorespiration and have greater productivity of biomass. Let us understand these one by one.

Study vertical sections of leaves, one of a C_3 plant and the other of a C_4 plant. *Did you notice the differences? Do both have the same types of mesophylls? Do they have similar cells around the vascular bundle sheath?*

The particularly large cells around the vascular bundles of the C_4 pathway plants are called **bundle sheath cells**, and the leaves which have such anatomy are said to have **'Kranz' anatomy**. 'Kranz' means 'wreath' and is a reflection of the arrangement of cells. The bundle sheath cells may form **several layers** around the vascular bundles; they are characterised by having a large number of chloroplasts, thick walls impervious to gaseous exchange and no intercellular spaces. You may like to cut a section of the leaves of C_4 plants – maize or sorghum – to observe the Kranz anatomy and the distribution of mesophyll cells.

It would be interesting for you to collect leaves of diverse species of plants around you and cut vertical sections of the leaves. Observe under the microscope – look for the bundle sheath around the vascular bundles. The presence of the bundle sheath would help you identify the C_4 plants.

Now study the pathway shown in Figure 13.9. This pathway that has been named the Hatch and Slack Pathway, is again a cyclic process. Let us study the pathway by listing the steps.

The primary CO_2 acceptor is a 3-carbon molecule **phosphoenol pyruvate (PEP)** and is present in the mesophyll cells. The enzyme responsible for this fixation is **PEP carboxylase** or PEPcase. It is important to register that the mesophyll cells lack RuBisCO enzyme. The C_4 acid OAA is formed in the mesophyll cells.

It then forms other 4-carbon compounds like malic acid or aspartic acid in the mesophyll cells itself, which are transported to the bundle sheath cells. In the bundle sheath cells these C_4 acids are broken down to release CO_2 and a 3-carbon molecule.

The 3-carbon molecule is transported back to the mesophyll where it is converted to PEP again, thus, completing the cycle.

The CO_2 released in the bundle sheath cells enters the C_3 or the Calvin pathway, a pathway common to all plants. The bundle sheath cells are

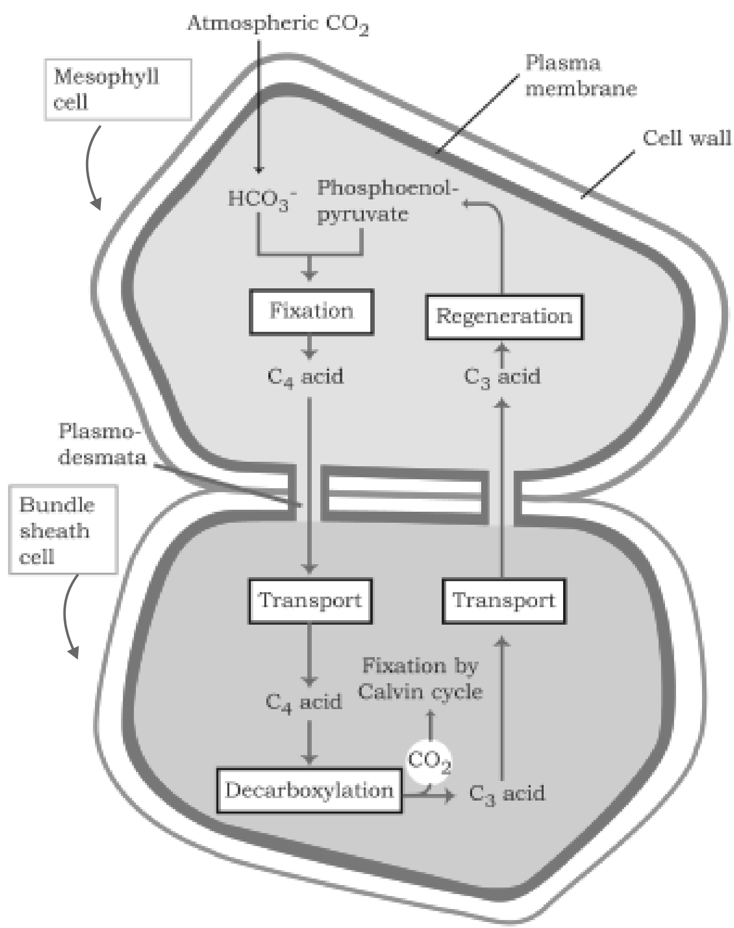


Figure 13.9 Diagrammatic representation of the Hatch and Slack Pathway

rich in an enzyme Ribulose bisphosphate carboxylase-oxygenase **(RuBisCO)**, but lack PEPcase. Thus, the basic pathway that results in the formation of the sugars, the Calvin pathway, is common to the C_3 and C_4 plants.

Did you note that the Calvin pathway occurs in all the mesophyll cells of the C_3 plants? In the C_4 plants it does not take place in the mesophyll cells but does so only in the bundle sheath cells.

13.9 PHOTORESPIRATION

Let us try and understand one more process that creates an important difference between C_3 and C_4 plants – **Photorespiration**. To understand photorespiration we have to know a little bit more about the first step of the Calvin pathway – the first CO_2 fixation step. This is the reaction where RuBP combines with CO_2 to form 2 molecules of 3PGA, that is catalysed by RuBisCO.

$$\text{RuBP} + CO_2 \xrightarrow{\text{Rubisco}} 2\times\ \text{3PGA}$$

RuBisCO that is the most abundant enzyme in the world (Do you wonder why?) is characterised by the fact that its active site can bind to both CO_2 and O_2 – hence the name. *Can you think how this could be possible?* RuBisCO has a much greater affinity for CO_2 than for O_2. Imagine what would happen if this were not so! This binding is competitive. It is the relative concentration of O_2 and CO_2 that determines which of the two will bind to the enzyme.

In C_3 plants some O_2 does bind to RuBisCO, and hence CO_2 fixation is decreased. Here the RuBP instead of being converted to 2 molecules of PGA binds with O_2 to form one molecule and phosphoglycolate in a pathway called photorespiration. In the photorespiratory pathway, there is neither synthesis of sugars, nor of ATP. Rather it results in the release of CO_2 with the utilisation of ATP. In the photorespiratory pathway there is no synthesis of ATP or NADPH. Therefore, photorespiration is a wasteful process.

In C_4 plants photorespiration does not occur. This is because they have a mechanism that increases the concentration of CO_2 at the enzyme site. This takes place when the C_4 acid from the mesophyll is broken down in the bundle cells to release CO_2 – this results in increasing the intracellular concentration of CO_2. In turn, this ensures that the RuBisCO functions as a carboxylase minimising the oxygenase activity.

Now that you know that the C_4 plants lack photorespiration, you probably can understand why productivity and yields are better in these plants. In addition these plants show tolerance to higher temperatures.

Based on the above discussion can you compare plants showing the C_3 and the C_4 pathway? Use the table format given and fill in the information.

TABLE 13.1 Fill in the Columns 2 and 3 in this table to bring the Differences between C_3 and C_4 Plants

Characteristics	**C_3 Plants**	**C_4 Plants**	**Choose from**
Cell type in which the Calvin cycle takes place			Mesophyll/Bundle sheath/both
Cell type in which the initial carboxylation reaction occurs			Mesophyll/Bundle sheath /both
How many cell types does the leaf have that fix CO_2.			Two: Bundle sheath and mesophyll One: Mesophyll Three: Bundle sheath, palisade, spongy mesophyll
Which is the primary CO_2 acceptor			RuBP/PEP/PGA
Number of carbons in the primary CO_2 acceptor			5 / 4 / 3
Which is the primary CO_2 fixation product			PGA/OAA/RuBP/PEP
No. of carbons in the primary CO_2 fixation product			3 / 4 / 5
Does the plant have RuBisCO?			Yes/No/Not always
Does the plant have PEP Case?			Yes/No/Not always
Which cells in the plant have Rubisco?			Mesophyll/Bundle sheath/none
CO_2 fixation rate under high light conditions			Low/ high/ medium
Whether photorespiration is present at low light intensities			High/negligible/sometimes
Whether photorespiration is present at high light intensities			High/negligible/sometimes
Whether photorespiration would be present at low CO_2 concentrations			High/negligible/sometimes
Whether photorespiration would be present at high CO_2 concentrations			High/negligible/sometimes
Temperature optimum			30-40 C/20-25C/above 40 C
Examples			Cut vertical sections of leaves of different plants and observe under the microscope for Kranz anatomy and list them in the appropriate columns.

13.10 Factors affecting Photosynthesis

An understanding of the factors that affect photosynthesis is necessary. The rate of photosynthesis is very important in determining the yield of plants including crop plants. Photosynthesis is under the influence of several factors, both internal (plant) and external. The plant factors include the number, size, age and orientation of leaves, mesophyll cells and chloroplasts, internal CO_2 concentration and the amount of chlorophyll. The plant or internal factors are dependent on the genetic predisposition and the growth of the plant.

The external factors would include the availability of sunlight, temperature, CO_2 concentration and water. As a plant photosynthesises, all these factors will simultaneously affect its rate. Hence, though several factors interact and simultaneously affect photosynthesis or CO_2 fixation, usually one factor is the major cause or is the one that limits the rate. Hence, at any point the rate will be determined by the factor available at sub-optimal levels.

When several factors affect any [bio] chemical process, Blackman's (1905) **Law of Limiting Factors** comes into effect. This states the following:

If a chemical process is affected by more than one factor, then its rate will be determined by the factor which is nearest to its minimal value: it is the factor which directly affects the process if its quantity is changed.

For example, despite the presence of a green leaf and optimal light and CO_2 conditions, the plant may not photosynthesise if the temperature is very low. This leaf, if given the optimal temperature, will start photosynthesising.

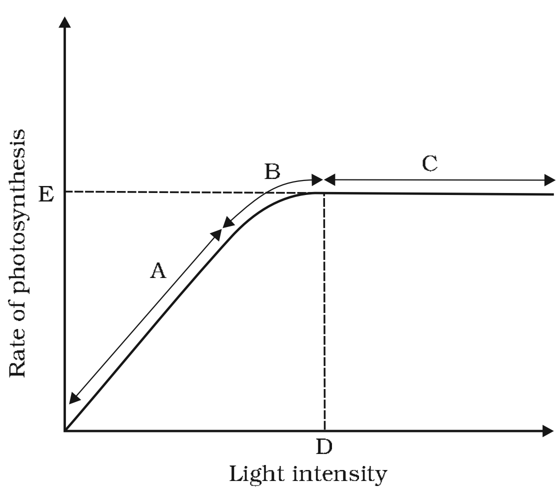


Figure 13.10 Graph of light intensity on the rate of photosynthesis

13.10.1 Light

We need to distinguish between light quality, light intensity and the duration of exposure to light, while discussing light as a factor that affects photosynthesis. There is a linear relationship between incident light and CO_2 fixation rates at low light intensities. At higher light intensities, gradually the rate does not show further increase as other factors become limiting (Figure 13.10). What is interesting to note is that light saturation occurs at 10 per cent of the full sunlight. Hence, except for plants in shade or in dense forests, light is rarely a limiting factor in nature. Increase in incident light beyond a point causes the breakdown of chlorophyll and a decrease in photosynthesis.

13.10.2 Carbon dioxide Concentration

Carbon dioxide is the major limiting factor for photosynthesis. The concentration of CO_2 is very low in the atmosphere (between 0.03 and 0.04 per cent). Increase in concentration upto 0.05 per cent can cause an increase in CO_2 fixation rates; beyond this the levels can become damaging over longer periods.

The C_3 and C_4 plants respond differently to CO_2 concentrations. At low light conditions neither group responds to high CO_2 conditions. At high light intensities, both C_3 and C_4 plants show increase in the rates of photosynthesis. What is important to note is that the C_4 plants show saturation at about 360 μlL^{-1} while C_3 responds to increased CO_2 concentration and saturation is seen only beyond 450 μlL^{-1}. Thus, current availability of CO_2 levels is limiting to the C_3 plants.

The fact that C_3 plants respond to higher CO_2 concentration by showing increased rates of photosynthesis leading to higher productivity has been used for some greenhouse crops such as tomatoes and bell pepper. They are allowed to grow in carbon dioxide enriched atmosphere that leads to higher yields.

13.10.3 Temperature

The dark reactions being enzymatic are temperature controlled. Though the light reactions are also temperature sensitive they are affected to a much lesser extent. The C_4 plants respond to higher temperatures and show higher rate of photosynthesis while C_3 plants have a much lower temperature optimum.

The temperature optimum for photosynthesis of different plants also depends on the habitat that they are adapted to. Tropical plants have a higher temperature optimum than the plants adapted to temperate climates.

13.10.4 Water

Even though water is one of the reactants in the light reaction, the effect of water as a factor is more through its effect on the plant, rather than directly on photosynthesis. Water stress causes the stomata to close hence reducing the CO_2 availability. Besides, water stress also makes leaves wilt, thus, reducing the surface area of the leaves and their metabolic activity as well.

SUMMARY

Green plants make their own food by photosynthesis. During this process carbon dioxide from the atmosphere is taken in by leaves through stomata and used for making carbohydrates, principally glucose and starch. Photosynthesis takes place only in the green parts of the plants, mainly the leaves. Within the leaves, the mesophyll cells have a large number of chloroplasts that are responsible for CO_2 fixation. Within the chloroplasts, the membranes are sites for the light reaction, while the chemosynthetic pathway occurs in the stromatal aperture. Photosynthesis has two stages: the light reaction and the carbon fixing reactions. In the light reaction the light energy is absorbed by the pigments present in the antenna, and funnelled to special chlorophyll *a* molecules called reaction centre chlorophylls. There are two photosystems, PS I and PS II. PS I has a 700 nm absorbing chlorophyll *a* P700 molecule at its reaction centre, while PS II has a P680 reaction centre that absorbs red light at 680 nm. After absorbing light, electrons are excited and transferred through PS II and PS I and finally to NAD forming NADH. During this process a proton gradient is created across the membrane of the thylakoid. The breakdown of the protons gradient due to movement through the F_0 part of the ATPase enzyme releases enough energy for synthesis of ATP. Splitting of water molecules is associated with PS II resulting in the release of O_2, protons and transfer of electrons to PS II.

In the carbon fixation cycle, CO_2 is added by the enzyme, RuBisCO, to a 5-carbon compound RuBP that is converted to 2 molecules of 3-carbon PGA. This is then converted to sugar by the Calvin cycle, and the RuBP is regenerated. During this process ATP and NADPH synthesised in the light reaction are utilised. RuBisCO also catalyses a wasteful oxygenation reaction in C_3 plants: photorespiration.

Some tropical plants show a special type of photosynthesis called C_4 pathway. In these plants the first product of CO_2 fixation that takes place in the mesophyll, is a 4-carbon compound. In the bundle sheath cells the Calvin pathway is carried out for the synthesis of carbohydrates.

EXERCISES

1. By looking at a plant externally can you tell whether a plant is C_3 or C_4? Why and how?
2. By looking at which internal structure of a plant can you tell whether a plant is C_3 or C_4? Explain.
3. Even though a very few cells in a C_4 plant carry out the biosynthetic – Calvin pathway, yet they are highly productive. Can you discuss why?

4. RuBisCO is an enzyme that acts both as a carboxylase and oxygenase. Why do you think RuBisCO carries out more carboxylation in C_4 plants?
5. Suppose there were plants that had a high concentration of Chlorophyll *b*, but lacked chlorophyll *a*, would it carry out photosynthesis? Then why do plants have chlorophyll *b* and other accessory pigments?
6. Why is the colour of a leaf kept in the dark frequently yellow, or pale green? Which pigment do you think is more stable?
7. Look at leaves of the same plant on the shady side and compare it with the leaves on the sunny side. Or, compare the potted plants kept in the sunlight with those in the shade. Which of them has leaves that are darker green ? Why?
8. Figure shows the effect of light on the rate of photosynthesis. Based on the graph, answer the following questions:

   (a) At which point/s (A, B or C) in the curve is light a limiting factor?
   (b) What could be the limiting factor/s in region A?
   (c) What do C and D represent on the curve?
9. Give comparison between the following:

   (a) C_3 and C_4 pathways
   (b) Cyclic and non-cyclic photophosphorylation
   (c) Anatomy of leaf in C_3 and C_4 plants

CHAPTER 14

RESPIRATION IN PLANTS

All of us breathe to live, but why is breathing so essential to life? What happens when we breathe? Also, do all living organisms, including plants and microbes, breathe? If so, how?

All living organisms need energy for carrying out daily life activities, be it absorption, transport, movement, reproduction or even breathing. Where does all this energy come from? We know we eat food for energy – but how is this energy taken from food? How is this energy utilised? Do all foods give the same amount of energy? Do plants 'eat'? Where do plants get their energy from? And micro-organisms – for their energy requirements, do they eat 'food'?

You may wonder at the several questions raised above – they may seem to be very disconnected. But in reality, the process of breathing is very much connected to the process of release of energy from food. Let us try and understand how this happens.

All the energy required for 'life' processes is obtained by oxidation of some macromolecules that we call 'food'. Only green plants and cyanobacteria can prepare their own food; by the process of photosynthesis they trap light energy and convert it into chemical energy that is stored in the bonds of carbohydrates like glucose, sucrose and starch. We must remember that in green plants too, not all cells, tissues and organs photosynthesise; only cells containing chloroplasts, that are most often located in the superficial layers, carry out photosynthesis. Hence, even in green plants all other organs, tissues and cells that are non-green, need food for oxidation. Hence, food has to be translocated to all non-green parts. Animals are heterotrophic, i.e., they obtain food from plants directly (herbivores) or indirectly (carnivores). Saprophytes like fungi are dependent on dead and decaying matter. What is important to recognise is that ultimately all the food that is respired for life processes comes from photosynthesis. This chapter deals with **cellular respiration** or the mechanism of breakdown of food materials within the cell to release energy, and the trapping of this energy for synthesis of ATP.

Photosynthesis, of course, takes place within the chloroplasts (in the eukaryotes), whereas the breakdown of complex molecules to yield energy takes place in the cytoplasm and in the mitochondria (also only in eukaryotes). The breaking of the C-C bonds of complex compounds through oxidation within the cells, leading to release of considerable amount of energy is called **respiration**. The compounds that are oxidised during this process are known as **respiratory substrates.** Usually carbohydrates are oxidised to release energy, but proteins, fats and even organic acids can be used as respiratory substances in some plants, under certain conditions. During oxidation within a cell, all the energy contained in respiratory substrates is not released free into the cell, or in a single step. It is released in a series of slow step-wise reactions controlled by enzymes, and it is trapped as chemical energy in the form of ATP. Hence, it is important to understand that the energy released by oxidation in respiration is not (or rather cannot be) used directly but is used to synthesise ATP, which is broken down whenever (and wherever) energy needs to be utilised. Hence, ATP acts as the energy currency of the cell. This energy trapped in ATP is utilised in various energy-requiring processes of the organisms, and the carbon skeleton produced during respiration is used as precursors for biosynthesis of other molecules in the cell.

14.1 DO PLANTS BREATHE?

Well, the answer to this question is not quite so direct. Yes, plants require O_2 for respiration to occur and they also give out CO_2. Hence, plants have systems in place that ensure the availability of O_2. Plants, unlike animals, have no specialised organs for gaseous exchange but they have stomata and lenticels for this purpose. There are several reasons why plants can get along without respiratory organs. First, each plant part takes care of its own gas-exchange needs. There is very little transport of gases from one plant part to another. Second, plants do not present great demands for gas exchange. Roots, stems and leaves respire at rates far lower than animals do. Only during photosynthesis are large volumes of gases exchanged and, each leaf is well adapted to take care of its own needs during these periods. When cells photosynthesise, availability of O_2 is not a problem in these cells since O_2 is released within the cell. Third, the distance that gases must diffuse even in large, bulky plants is not great. Each living cell in a plant is located quite close to the surface of the plant. 'This is true for leaves', you may ask, 'but what about thick, woody stems and roots?' In stems, the 'living' cells are organised in thin layers inside and beneath the bark. They also have openings called lenticels. The cells in the interior are dead and provide only mechanical support. Thus, most cells of a plant have at least a part of their surface in contact with air. This is also facilitated by the loose packing of parenchyma cells in leaves, stems and roots, which provide an interconnected network of air spaces.

The complete combustion of glucose, which produces CO_2 and H_2O as end products, yields energy most of which is given out as heat.

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

If this energy is to be useful to the cell, it should be able to utilise it to synthesise other molecules that the cell requires. The strategy that the plant cell uses is to catabolise the glucose molecule in such a way that not all the liberated energy goes out as heat. The key is to oxidise glucose not in one step but in several small steps enabling some steps to be just large enough such that the energy released can be coupled to ATP synthesis. How this is done is, essentially, the story of respiration.

During the process of respiration, oxygen is utilised, and carbon dioxide, water and energy are released as products. The combustion reaction requires oxygen. But some cells live where oxygen may or may not be available. *Can you think of such situations (and organisms) where O_2 is not available?* There are sufficient reasons to believe that the first cells on this planet lived in an atmosphere that lacked oxygen. Even among present-day living organisms, we know of several that are adapted to anaerobic conditions. Some of these organisms are facultative anaerobes, while in others the requirement for anaerobic condition is obligate. In any case, all living organisms retain the enzymatic machinery to partially oxidise glucose without the help of oxygen. This breakdown of glucose to pyruvic acid is called **glycolysis.**

14.2 Glycolysis

The term glycolysis has originated from the Greek words, *glycos* for sugar, and *lysis* for splitting. The scheme of glycolysis was given by Gustav Embden, Otto Meyerhof, and J. Parnas, and is often referred to as the EMP pathway. In anaerobic organisms, it is the only process in respiration. Glycolysis occurs in the cytoplasm of the cell and is present in all living organisms. In this process, glucose undergoes partial oxidation to form two molecules of pyruvic acid. In plants, this glucose is derived from sucrose, which is the end product of photosynthesis, or from storage carbohydrates. Sucrose is converted into glucose and fructose by the enzyme, invertase, and these two monosaccharides readily enter the glycolytic pathway. Glucose and fructose are phosphorylated to give rise to glucose-6-phosphate by the activity of the enzyme hexokinase. This phosphorylated form of glucose then isomerises to produce fructose-6-phosphate. Subsequent steps of metabolism of glucose and fructose are same. The various steps of glycolysis are depicted in Figure 14.1. In glycolysis, a chain of ten reactions, under the control of different enzymes, takes place to produce pyruvate from glucose. While studying the steps of glycolysis, please note the steps at which utilisation (ATP energy) or synthesis of ATP or (in this case of) NADH + H^+ take place.

ATP is utilised at two steps: first in the conversion of glucose into glucose 6-phosphate and second in the conversion of fructose 6-phosphate to fructose 1, 6-diphosphate.

The fructose 1, 6-diphosphate is split into dihydroxyacetone phosphate and 3-phosphoglyceraldehyde (PGAL). We find that there is one step where NADH + H^+ is formed from NAD^+; this is when 3-phosphoglyceraldehyde (PGAL) is converted to 1, 3-bisphosphoglycerate (DPGA). Two redox-equivalents are removed (in the form of two hydrogen atoms) from PGAL and transferred to a molecule of NAD^+. PGAL is oxidised and with inorganic phosphate to get converted into DPGA. The conversion of DPGA to 3-phosphoglyceric acid (PGA), is also an energy yielding process; this energy is trapped by the formation of ATP. Another ATP is synthesised during the conversion of PEP to pyruvic acid. *Can you then calculate how many ATP molecules are directly synthesised in this pathway from one glucose molecule?*

Pyruvic acid is then the key product of glycolysis. What is the metabolic fate of

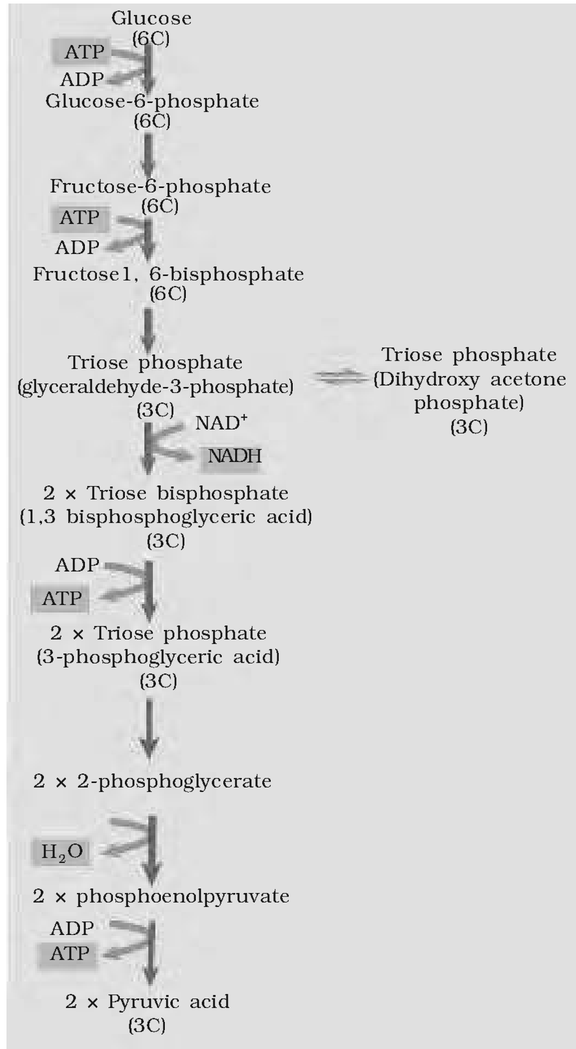


Figure 14.1 Steps of glycolysis

pyruvate? This depends on the cellular need. There are three major ways in which different cells handle pyruvic acid produced by glycolysis. These are lactic acid fermentation, alcoholic fermentation and aerobic respiration. Fermentation takes place under anaerobic conditions in many prokaryotes and unicellular eukaryotes. For the complete oxidation of glucose to CO_2 and H_2O, however, organisms adopt Krebs' cycle which is also called as aerobic respiration. This requires O_2 supply.

14.3 Fermentation

In fermentation, say by yeast, the incomplete oxidation of glucose is achieved under anaerobic conditions by sets of reactions where pyruvic acid is converted to CO_2 and ethanol. The enzymes, pyruvic acid decarboxylase and alcohol dehydrogenase catalyse these reactions. Other organisms like some bacteria produce lactic acid from pyruvic acid. The steps involved are shown in Figure 14.2. In animal cells also, like muscles during exercise, when oxygen is inadequate for cellular respiration pyruvic acid is reduced to lactic acid by lactate dehydrogenase. The reducing agent is $NADH+H^+$ which is reoxidised to NAD^+ in both the processes.

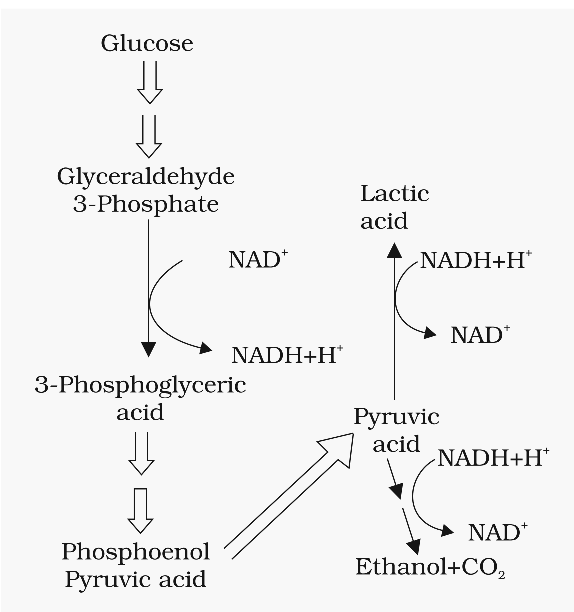


Figure 14.2 Major pathways of anaerobic respiration

In both lactic acid and alcohol fermentation not much energy is released; less than seven per cent of the energy in glucose is released and not all of it is trapped as high energy bonds of ATP. Also, the processes are hazardous – either acid or alcohol is produced. What is the net ATPs that is synthesised (calculate how many ATP are synthesised and deduct the number of ATP utilised during glycolysis) when one molecule of glucose is fermented to alcohol or lactic acid? Yeasts poison themselves to death when the concentration of alcohol reaches about 13 per cent. *What then would be the maximum concentration of alcohol in beverages that are naturally fermented?* How do you think alcoholic beverages of alcohol content greater than this concentration are obtained?

What then is the process by which organisms can carryout complete oxidation of glucose and extract the energy stored to synthesise a larger number of ATP molecules needed for cellular metabolism? In eukaryotes these steps take place within the mitochondria and this requires O_2. **Aerobic respiration** is the process that leads to a complete oxidation of organic substances in the presence of oxygen, and releases CO_2, water and a large amount of energy present in the substrate. This type of respiration is most common in higher organisms. We will look at these processes in the next section.

14.4 AEROBIC RESPIRATION

For aerobic respiration to take place within the mitochondria, the final product of glycolysis, pyruvate is transported from the cytoplasm into the mitochondria. The crucial events in aerobic respiration are:

- The complete oxidation of pyruvate by the stepwise removal of all the hydrogen atoms, leaving three molecules of CO_2.
- The passing on of the electrons removed as part of the hydrogen atoms to molecular O_2 with simultaneous synthesis of ATP.

What is interesting to note is that the first process takes place in the matrix of the mitochondria while the second process is located on the inner membrane of the mitochondria.

Pyruvate, which is formed by the glycolytic catabolism of carbohydrates in the cytosol, after it enters mitochondrial matrix undergoes oxidative decarboxylation by a complex set of reactions catalysed by pyruvic dehydrogenase. The reactions catalysed by pyruvic dehydrogenase require the participation of several coenzymes, including NAD^+ and Coenzyme A.

$$\text{Pyruvic acid} + \text{CoA} + \text{NAD}^+ \xrightarrow[\text{Pyruvate dehydrogenase}]{\text{Mg}^{2+}} \text{Acetyl CoA} + \text{CO}_2 + \text{NADH} + \text{H}^+$$

During this process, two molecules of NADH are produced from the metabolism of two molecules of pyruvic acid (produced from one glucose molecule during glycolysis).

The acetyl CoA then enters a cyclic pathway, tricarboxylic acid cycle, more commonly called as Krebs' cycle after the scientist Hans Krebs who first elucidated it.

14.4.1 Tricarboxylic Acid Cycle

The TCA cycle starts with the condensation of acetyl group with oxaloacetic acid (OAA) and water to yield citric acid (Figure 14.3). The reaction is catalysed by the enzyme citrate synthase and a molecule of CoA is released. Citrate is then isomerised to isocitrate. It is followed by two successive steps of decarboxylation, leading to the formation of α-ketoglutaric acid

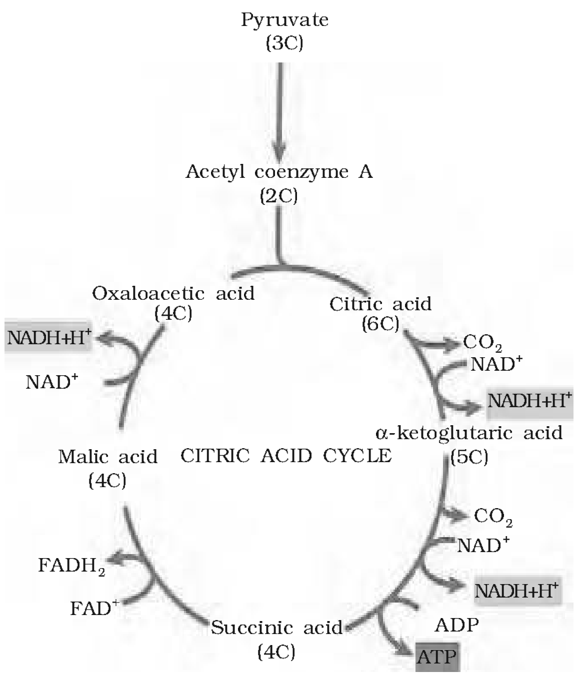


Figure 14.3 The Citric acid cycle

and then succinyl-CoA. In the remaining steps of citric acid cycle, succinyl-CoA is oxidised to OAA allowing the cycle to continue. During the conversion of succinyl-CoA to succinic acid a molecule of GTP is synthesised. This is a substrate level phosphorylation. In a coupled reaction GTP is converted to GDP with the simultaneous synthesis of ATP from ADP. Also there are three points in the cycle where NAD^+ is reduced to $NADH + H^+$ and one point where FAD^+ is reduced to $FADH_2$. The continued oxidation of acetic acid via the TCA cycle requires the continued replenishment of oxaloacetic acid, the first member of the cycle. In addition it also requires regeneration of NAD^+ and FAD^+ from NADH and $FADH_2$ respectively. The summary equation for this phase of respiration may be written as follows:

$$\text{Pyruvic acid} + 4NAD^+ + FAD^+ + 2H_2O + ADP + Pi \xrightarrow{\text{Mitochondrial Matrix}} 3CO_2 + 4NADH + 4H^+ + FADH_2 + ATP$$

We have till now seen that glucose has been broken down to release CO_2 and eight molecules of $NADH + H^+$; two of $FADH_2$ have been synthesised besides just two molecules of ATP. You may be wondering why we have been discussing respiration at all – neither O_2 has come into the picture nor the promised large number of ATP has yet been synthesised. Also what is the role of the $NADH + H^+$ and $FADH_2$ that is synthesised? Let us now understand the role of O_2 in respiration and how ATP is synthesised.

14.4.2 Electron Transport System (ETS) and Oxidative Phosphorylation

The following steps in the respiratory process are to release and utilise the energy stored in $NADH+H^+$ and $FADH_2$. This is accomplished when they are oxidised through the electron transport system and the electrons are passed on to O_2 resulting in the formation of H_2O. The metabolic pathway through which the electron passes from one carrier to another, is called the **electron transport system** (ETS) (Figure 14.4) and it is present in the inner mitochondrial membrane. Electrons from NADH produced in the mitochondrial matrix during citric acid cycle are oxidised by an NADH dehydrogenase (complex I), and electrons are then transferred to ubiquinone located within the inner membrane. Ubiquinone also receives reducing equivalents via $FADH_2$ (complex II) that is generated during oxidation of succinate in the citric acid cycle. The reduced ubiquinone (ubiquinol) is then oxidised with the transfer of electrons to cytochrome *c* via cytochrome bc_1 complex (complex III). Cytochrome *c* is a small protein attached to the outer surface of the inner membrane and acts as a mobile carrier for transfer of electrons between complex III and IV. Complex IV refers to cytochrome *c* oxidase complex containing cytochromes *a* and a_3, and two copper centres.

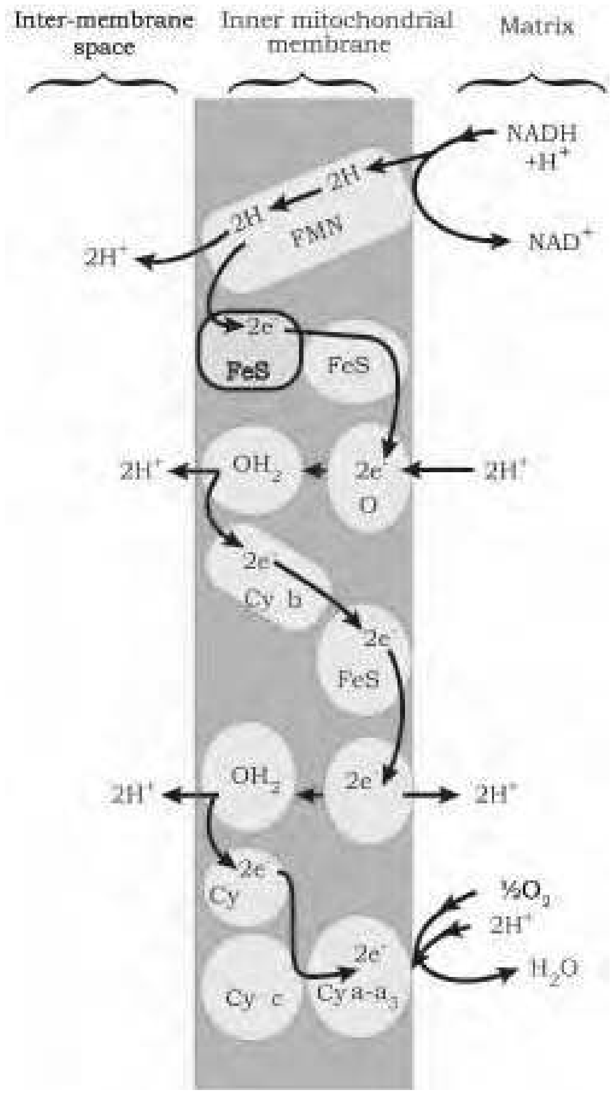


Figure 14.4 Electron Transport System (ETS)

When the electrons pass from one carrier to another via complex I to IV in the electron transport chain, they are coupled to ATP synthase (complex V) for the production of ATP from ADP and inorganic phosphate. The number of ATP molecules synthesised depends on the nature of the electron donor. Oxidation of one molecule of NADH gives rise to 3 molecules of ATP, while that of one molecule of $FADH_2$ produces 2 molecules of ATP. Although the aerobic process of respiration takes place only in the presence of oxygen, the role of oxygen is limited to the terminal stage of the process. Yet, the presence of oxygen is vital, since it drives the whole process by removing hydrogen from the system. Oxygen acts as the final hydrogen acceptor. Unlike photophosphorylation where it is the light energy that is utilised for the production of proton gradient required for phosphorylation, in respiration it is the energy of oxidation-reduction utilised for the same process. It is for this reason that the process is called oxidative phosphorylation.

You have already studied about the mechanism of membrane-linked ATP synthesis as explained by chemiosmotic hypothesis in the earlier chapter. As mentioned earlier, the energy released during the electron

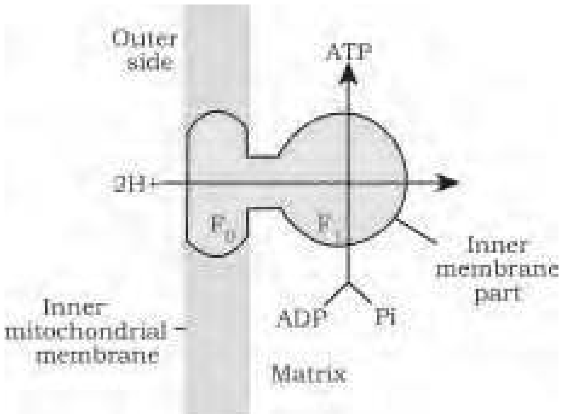


Figure 14.5 Diagramatic presentation of ATP synthesis in mitochondria

transport system is utilised in synthesising ATP with the help of ATP synthase (complex V). This complex consists of two major components, F_1 and F_0 (Figure 14.5). The F_1 headpiece is a peripheral membrane protein complex and contains the site for synthesis of ATP from ADP and inorganic phosphate. F_0 is an integral membrane protein complex that forms the channel through which protons cross the inner membrane. The passage of protons through the channel is coupled to the catalytic site of the F_1 component for the production of ATP. For each ATP produced, $2H^+$ passes through F_0 from the intermembrane space to the matrix down the electrochemical proton gradient.

14.5 The Respiratory Balance Sheet

It is possible to make calculations of the net gain of ATP for every glucose molecule oxidised; but in reality this can remain only a theoretical exercise. These calculations can be made only on certain assumptions that:

- There is a sequential, orderly pathway functioning, with one substrate forming the next and with glycolysis, TCA cycle and ETS pathway following one after another.
- The NADH synthesised in glycolysis is transferred into the mitochondria and undergoes oxidative phosphorylation.
- None of the intermediates in the pathway are utilised to synthesise any other compound.
- Only glucose is being respired – no other alternative substrates are entering in the pathway at any of the intermediary stages.

But this kind of assumptions are not really valid in a living system; all pathways work simultaneously and do not take place one after another; substrates enter the pathways and are withdrawn from it as and when necessary; ATP is utilised as and when needed; enzymatic rates are controlled by multiple means. Yet, it is useful to do this exercise to appreciate the beauty and efficiency of the living system in extraction and storing energy. Hence, there can be a net gain of 36 ATP molecules during aerobic respiration of one molecule of glucose.

Now let us compare fermentation and aerobic respiration:

- Fermentation accounts for only a partial breakdown of glucose whereas in aerobic respiration it is completely degraded to CO_2 and H_2O.
- In fermentation there is a net gain of only two molecules of ATP for each molecule of glucose degraded to pyruvic acid whereas many more molecules of ATP are generated under aerobic conditions.
- NADH is oxidised to NAD^+ rather slowly in fermentation, however the reaction is very vigorous in case of aerobic respiration.

14.6 AMPHIBOLIC PATHWAY

Glucose is the favoured substrate for respiration. All carbohydrates are usually first converted into glucose before they are used for respiration. Other substrates can also be respired, as has been mentioned earlier, but then they do not enter the respiratory pathway at the first step. See Figure 14.6 to see the points of entry of different substrates in the respiratory pathway. Fats would need to be broken down into glycerol and fatty acids first. If fatty acids were to be respired they would first be degraded to acetyl CoA and enter the pathway. Glycerol would enter the pathway after being converted to PGAL. The proteins would be degraded by proteases and the individual amino acids (after deamination) depending on their structure would enter the pathway at some stage within the Krebs' cycle or even as pyruvate or acetyl CoA.

Since respiration involves breakdown of substrates, the respiratory process has traditionally been considered a catabolic process and the respiratory pathway as a catabolic pathway. But is this understanding correct? We have discussed above, at which points in the respiratory pathway different substrates would enter if they were to be respired and used to derive energy. What is important to recognise is that it is these very compounds that would be withdrawn from the respiratory pathway for the synthesis of the said substrates. Hence, fatty acids would be broken down to acetyl CoA before entering the respiratory pathway when it is used as a substrate. But when the organism needs to synthesise fatty acids, acetyl CoA would be withdrawn from the respiratory pathway for it. Hence, the respiratory pathway comes into the picture both during breakdown and synthesis of fatty acids. Similarly, during breakdown and synthesis of protein too, respiratory intermediates form the link. Breaking down processes within the living organism is catabolism, and synthesis is anabolism. Because the respiratory pathway is involved in both anabolism and catabolism, it would hence be better to consider the respiratory pathway

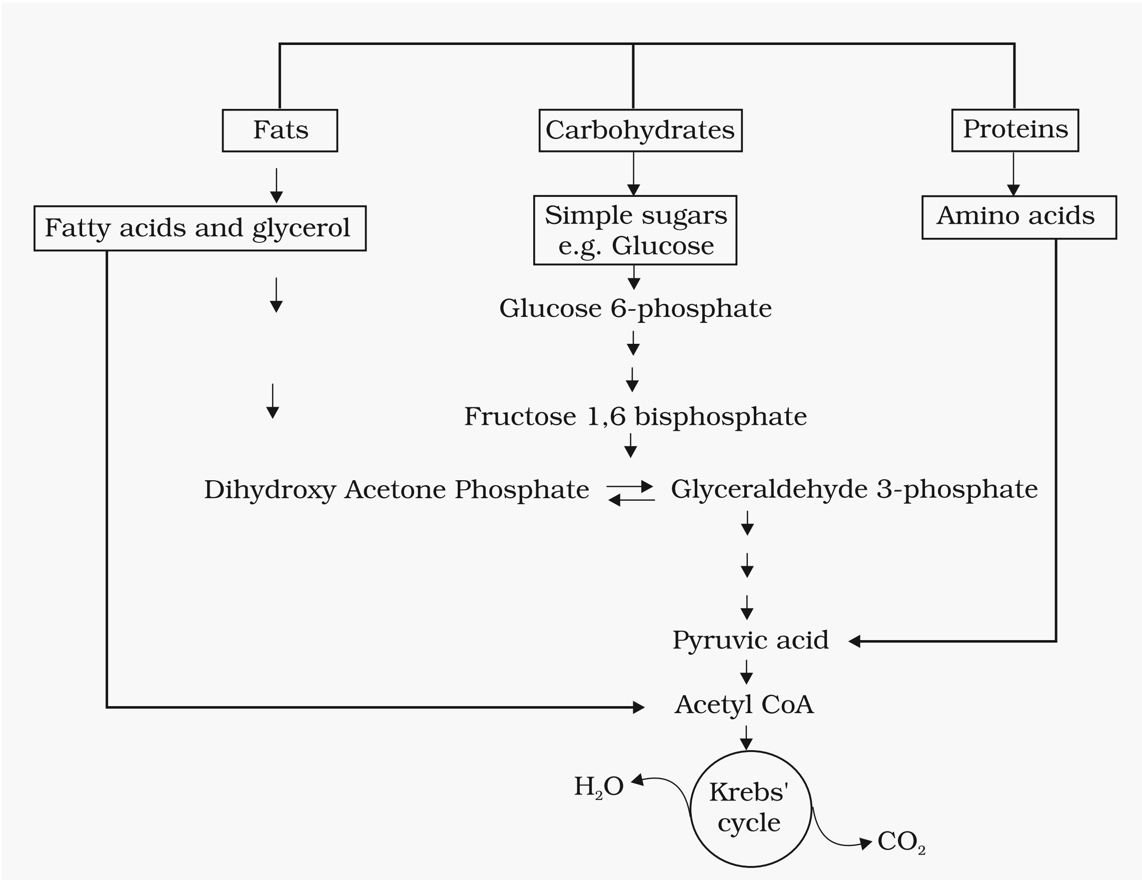


Figure 14.6 Interrelationship among metabolic pathways showing respiration mediated breakdown of different organic molecules to CO_2 and H_20

as an **amphibolic pathway** rather than as a catabolic one.

14.7 Respiratory Quotient

Let us now look at another aspect of respiration. As you know, during aerobic respiration, O_2 is consumed and CO_2 is released. The ratio of the volume of CO_2 evolved to the volume of O_2 consumed in respiration is called the **respiratory quotient** (RQ) or respiratory ratio.

$$RQ = \frac{\text{volume of } CO_2 \text{ evolved}}{\text{volume of } O_2 \text{ consumed}}$$

The respiratory quotient depends upon the type of respiratory substrate used during respiration.

When carbohydrates are used as substrate and are completely oxidised, the RQ will be 1, because equal amounts of CO_2 and O_2 are evolved and consumed, respectively, as shown in the equation below :

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

$$RQ = \frac{6CO_2}{6O_2} = 1.0$$

When fats are used in respiration, the RQ is less than 1. Calculations for a fatty acid, tripalmitin, if used as a substrate is shown:

$$\underset{\text{Tripalmitin}}{2(C_{51}H_{98}O_6)} + 145O_2 \longrightarrow 102CO_2 + 98H_2O + \text{energy}$$

$$RQ = \frac{102CO_2}{145O_2} = 0.7$$

When proteins are respiratory substrates the ratio would be about 0.9.

What is important to recognise is that in living organisms respiratory substances are often more than one; pure proteins or fats are never used as respiratory substrates.

SUMMARY

Plants unlike animals have no special systems for breathing or gaseous exchange. Stomata and lenticels allow gaseous exchange by diffusion. Almost all living cells in a plant have their surfaces exposed to air.

The breaking of C-C bonds of complex organic molecules by oxidation cells leading to the release of a lot of energy is called cellular respiration. Glucose is the favoured substrate for respiration. Fats and proteins can also be broken down to yield energy. The initial stage of cellular respiration takes place in the cytoplasm. Each glucose molecule is broken through a series of enzyme catalysed reactions into two molecules of pyruvic acid. This process is called glycolysis. The fate of the pyruvate depends on the availability of oxygen and the organism. Under anaerobic conditions either lactic acid fermentation or alcohol fermentation occurs. Fermentation takes place under anerobic conditions in many prokaryotes, unicellular eukaryotes and in germinating seeds. In eukaryotic organisms aerobic respiration occurs in the presence of oxygen. Pyruvic acid is transported into the mitochondria where it is converted into acetyl CoA with the release of CO_2. Acetyl CoA then enters the tricarboxylic acid pathway or Krebs' cycle operating in the matrix of the mitochondria. NADH + H^+ and $FADH_2$ are generated in the Krebs'

cycle. The energy in these molecules as well as that in the NADH+ H^+ synthesised during glycolysis are used to synthesise ATP. This is accomplished through a system of electron carriers called electron transport system (ETS) located on the inner membrane of the mitochondria. The electrons, as they move through the system, release enough energy that are trapped to synthesise ATP. This is called oxidative phosphorylation. In this process O_2 is the ultimate acceptor of electrons and it gets reduced to water.

The respiratory pathway is an amphibolic pathway as it involves both anabolism and catabolism. The respiratory quotient depends upon the type of respiratory substance used during respiration.

EXERCISES

1. Differentiate between
   (a) Respiration and Combustion
   (b) Glycolysis and Krebs' cycle
   (c) Aerobic respiration and Fermentation
2. What are respiratory substrates? Name the most common respiratory substrate.
3. Give the schematic representation of glyolysis?
4. What are the main steps in aerobic respiration? Where does it take place?
5. Give the schematic representation of an overall view of Krebs' cycle.
6. Explain ETS.
7. Distinguish between the following:
   (a) Aerobic respiration and Anaerobic respiration
   (b) Glycolysis and Fermentation
   (c) Glycolysis and Citric acid Cycle
8. What are the assumptions made during the calculation of net gain of ATP?
9. Discuss "The respiratory pathway is an amphibolic pathway."
10. Define RQ. What is its value for fats?
11. What is oxidative phosphorylation?
12. What is the significance of step-wise release of energy in respiration?

Chapter 15

Plant Growth and Development

You have already studied the organisation of a flowering plant in Chapter 5. Have you ever thought about where and how the structures like roots, stems, leaves, flowers, fruits and seeds arise and that too in an orderly sequence? You are, by now, aware of the terms seed, seedling plantlet, mature plant. You have also seen that trees continue to increase in height or girth over a period of time. However, the leaves, flowers and fruits of the same tree not only have limited dimensions but also appear and fall periodically and some time repeatedly. Why does vegetative phase precede flowering in a plant? All plant organs are made up of a variety of tissues; is there any relationship between the structure of a cell, a tissue, an organ and the function they perform? Can the structure and the function of these be altered? All cells of a plant are descendents of the zygote. The question is, then, why and how do they have different structural and functional attributes? Development is the sum of two processes: growth and differentiation. To begin with, it is essential and sufficient to know that the development of a mature plant from a zygote (fertilised egg) follow a precise and highly ordered succession of events. During this process a complex body organisation is formed that produces roots, leaves, branches, flowers, fruits, and seeds, and eventually they die (Figure 15.1).

In this chapter, you shall also study some of the factors which govern and control these developmental processes. These factors are both intrinsic (internal) and extrinsic (external) to the plant.

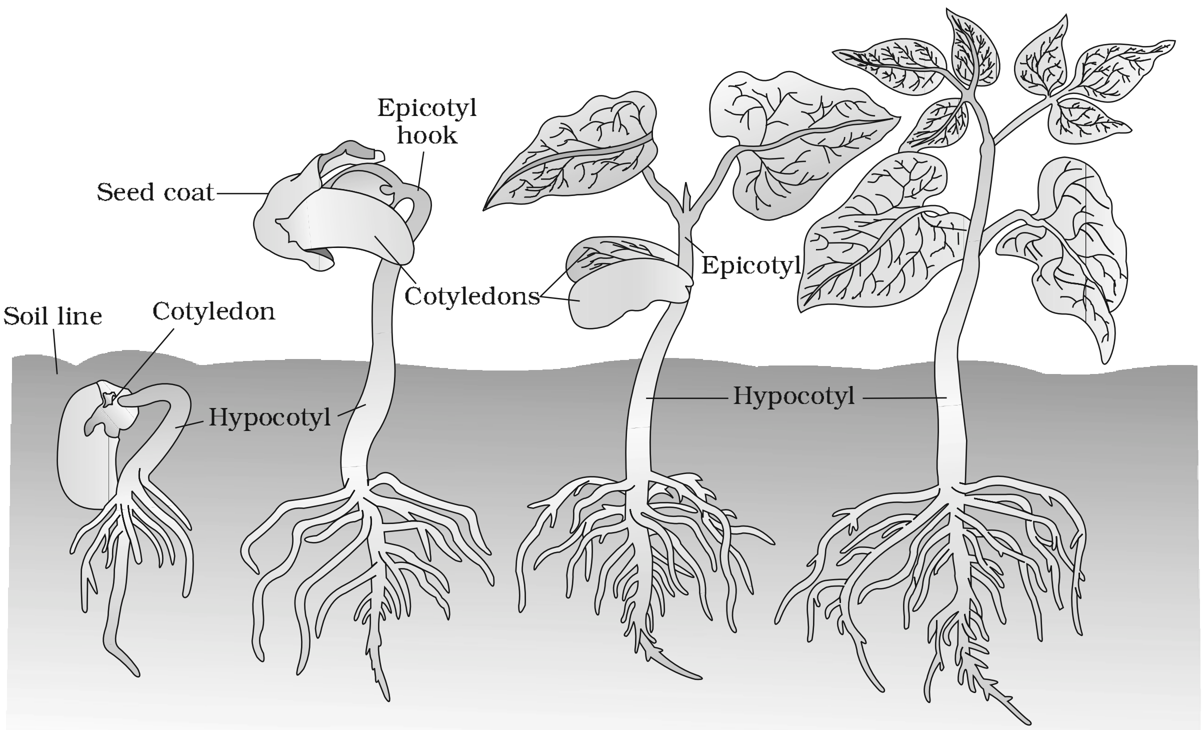


Figure 15.1 Germination and seedling development in bean

15.1 Growth

Growth is regarded as one of the most fundamental and conspicuous characteristics of a living being. What is growth? Growth can be defined as an irreversible permanent increase in size of an organ or its parts or even of an individual cell. Generally, growth is accompanied by metabolic processes (both anabolic and catabolic), that occur at the expense of energy. Therefore, for example, expansion of a leaf is growth. How would you describe the swelling of piece of wood when placed in water?

15.1.1 Plant Growth Generally is Indeterminate

Plant growth is unique because plants retain the capacity for unlimited growth throughout their life. This ability of the plants is due to the presence of meristems at certain locations in their body. The cells of such meristems have the capacity to divide and self-perpetuate. The product, however, soon loses the capacity to divide and such cells make up the plant body. This form of growth wherein new cells are always being added to the plant body by the activity of the meristem is called the open form of growth. What would happen if the meristem ceases to divide? Does this ever happen?

In Chapter 6, you have studied about the root apical meristem and the shoot apical meristem. You know that they are responsible for the primary growth of the plants and principally contribute to the elongation of the plants along their axis. You also know that in dicotyledonous plants and gymnosperms, the lateral meristems, vascular cambium and cork-cambium appear later in life. These are the meristems that cause the increase in the girth of the organs in which they are active. This is known as secondary growth of the plant (see Figure 15.2).

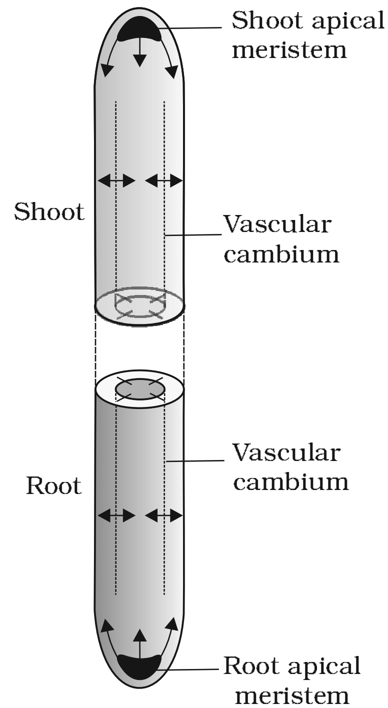


Figure 15.2 Diagrammatic representation of locations of root apical meristem, shoot aplical meristem and vascular cambium. Arrows exhibit the direction of growth of cells and organ

15.1.2 Growth is Measurable

Growth, at a cellular level, is principally a consequence of increase in the amount of protoplasm. Since increase in protoplasm is difficult to measure directly, one generally measures some quantity which is more or less proportional to it. Growth is, therefore, measured by a variety of parameters some of which are: increase in fresh weight, dry weight, length, area, volume and cell number. You may find it amazing to know that one single maize root apical mersitem can give rise to more than 17,500 new cells per hour, whereas cells in a watermelon may increase in size by upto 3,50,000 times. In the former, growth is expressed as increase in cell number; the latter expresses growth as increase in size of the cell. While the growth of a pollen tube is measured in terms of its length, an increase in surface area denotes the growth in a dorsiventral leaf.

15.1.3 Phases of Growth

The period of growth is generally divided into three phases, namely, meristematic, elongation and maturation (Figure 15.3). Let us understand this by looking at the root tips. The constantly dividing cells, both at the root apex and the shoot apex, represent the meristematic phase of growth. The cells in this region are rich in protoplasm, possess large conspicuous nuclei. Their cell walls are primary in nature, thin and cellulosic with abundant plasmodesmatal connections. The cells proximal (just next, away from the tip) to the

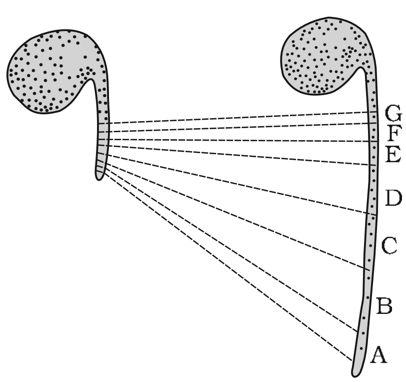


Figure 15.3 Detection of zones of elongation by the parallel line technique. Zones A, B, C, D immediately behind the apex have elongated most.

meristematic zone represent the phase of elongation. Increased vacuolation, cell enlargement and new cell wall deposition are the characteristics of the cells in this phase. Further away from the apex, i.e., more proximal to the phase of elongation, lies the portion of axis which is undergoing the phase of maturation. The cells of this zone, attain their maximal size in terms of wall thickening and protoplasmic modifications. Most of the tissues and cell types you have studied in Chapter 6 represent this phase.

15.1.4 Growth Rates

The increased growth per unit time is termed as growth rate. Thus, rate of growth can be expressed mathematically. An organism, or a part of the organism can produce more cells in a variety of ways.

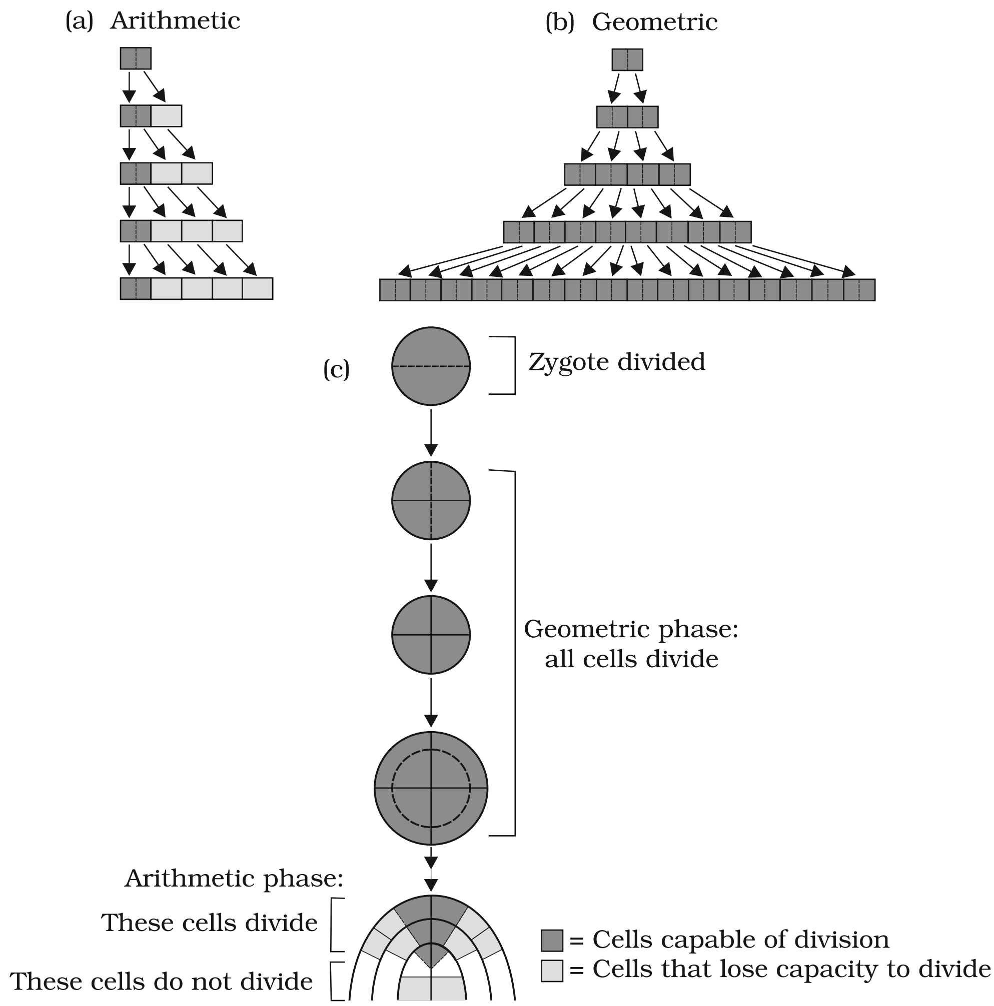


Figure15.4 Diagrammatic representation of : (a) Arithmetic (b) Geometric growth and (c) Stages during embryo development showing geometric and arithematic phases

The growth rate shows an increase that may be arithmetic or geometrical (Figure 15.4).

In arithmetic growth, following mitotic cell division, only one daughter cell continues to divide while the other differentiates and matures. The simplest expression of arithmetic growth is exemplified by a root elongating at a constant rate. Look at Figure 15.5. On plotting the length of the organ against time, a linear curve is obtained. Mathematically, it is expressed as

$L_t = L_0 + rt$

L_t = length at time 't'

L_0 = length at time 'zero'

r = growth rate / elongation per unit time.

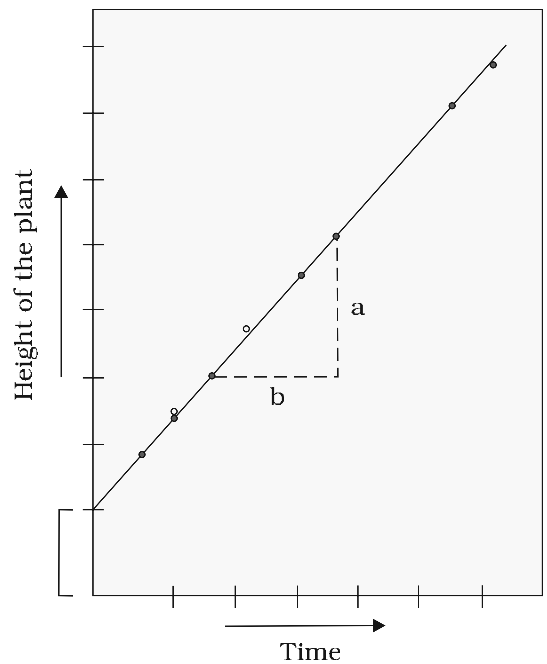


Figure 15.5 Constant linear growth, a plot of length L against time t

Let us now see what happens in geometrical growth. In most systems, the initial growth is slow (lag phase), and it increases rapidly thereafter – at an exponential rate (log or exponential phase). Here, both the progeny cells following mitotic cell division retain the ability to divide and continue to do so. However, with limited nutrient supply, the growth slows down leading to a stationary phase. If we plot the parameter of growth against time, we get a typical sigmoid or S-curve (Figure 15.6). A sigmoid curve is a characteristic of living organism growing in a natural environment. It is typical for all cells, tissues and organs of a plant. *Can you think of more similar examples? What kind of a curve can you expect in a tree showing seasonal activities?*

The exponential growth can be expressed as

$W_1 = W_0 e^{rt}$

W_1 = final size (weight, height, number etc.)

W_0 = initial size at the beginning of the period

r = growth rate

t = time of growth

e = base of natural logarithms

Here, r is the relative growth rate and is also the measure of the ability of the plant to produce new plant material, referred to as efficiency index. Hence, the final size of W_1 depends on the initial size, W_0.

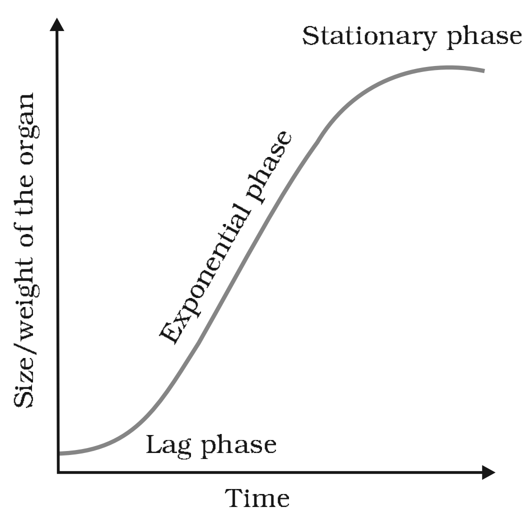


Figure 15.6 An idealised sigmoid growth curve typical of cells in culture, and many higher plants and plant organs

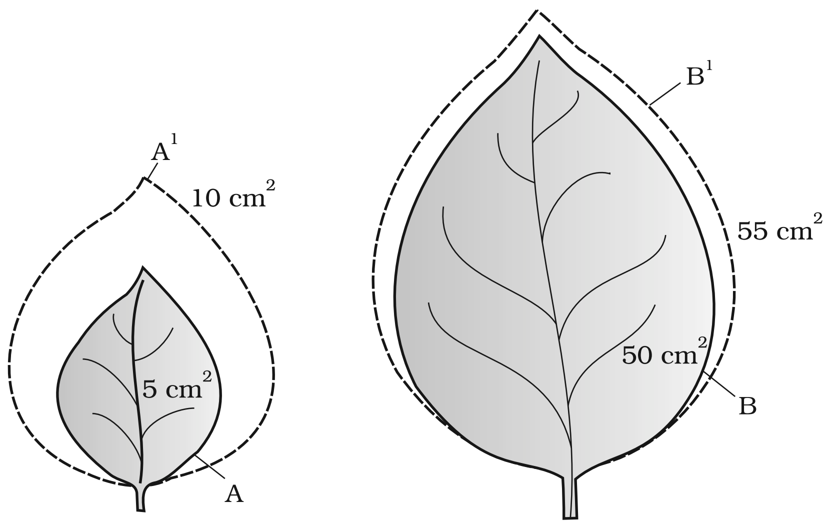


Figure 15.7 Diagrammatic comparison of absolute and relative growth rates. Both leaves A and B have increased their area by 5 cm^2 in a given time to produce A^1, B^1 leaves.

Quantitative comparisons between the growth of living system can also be made in two ways : (i) measurement and the comparison of total growth per unit time is called the absolute growth rate. (ii) The growth of the given system per unit time expressed on a common basis, e.g., per unit initial parameter is called the relative growth rate. In Figure 15.7 two leaves, A and B, are drawn that are of different sizes but shows absolute increase in area in the given time to give leaves, A^1 and B^1. However, one of them shows much higher relative growth rate. Which one and why?

15.1.5 Conditions for Growth

Why do you not try to write down what you think are necessary conditions for growth? This list may have water, oxygen and nutrients as very essential elements for growth. The plant cells grow in size by cell enlargement which in turn requires water. Turgidity of cells helps in extension growth. Thus, plant growth and further development is intimately linked to the water status of the plant. Water also provides the medium for enzymatic activities needed for growth. Oxygen helps in releasing metabolic energy essential for growth activities. Nutrients (macro and micro essential elements) are required by plants for the synthesis of protoplasm and act as source of energy.

In addition, every plant organism has an optimum temperature range best suited for its growth. Any deviation from this range could be detrimental to its survival. Environmental signals such as light and gravity also affect certain phases/stages of growth.

15.2 DIFFERENTIATION, DEDIFFERENTIATION AND REDIFFERENTIATION

The cells derived from root apical and shoot-apical meristems and cambium differentiate and mature to perform specific functions. This act leading to maturation is termed as **differentiation**. During differentiation, cells undergo few to major structural changes both in their cell walls and protoplasm. For example, to form a tracheary element, the cells would lose their protoplasm. They also develops a very strong, elastic, lignocellulosic secondary cell walls, to carry water to long distances even under extreme tension. Try to correlate the various anatomical features you encounter in plants to the functions they perform.

Plants show another interesting phenomenon. The living differentiated cells, that by now have lost the capacity to divide can regain the capacity of division under certain conditions. This phenomenon is termed as **dedifferentiation**. For example, formation of meristems – interfascicular cambium and cork cambium from fully differentiated parenchyma cells. While doing so, such meristems/tissues are able to divide and produce cells that once again lose the capacity to divide but mature to perform specific functions, i.e., get **redifferentiated**. List some of the tissues in a woody dicotyledenous plant that are the products of redifferentiation. How would you describe a tumour? What would you call the parenchyma cells that are made to divide under controlled laboratory conditions during plant tissue culture?

Recall, in Section 15.1.1, we have mentioned that the growth in plants is open, i.e., it can be indeterminate or determinate. Now, we may say that even differentiation in plants is open, because cells/tissues arising out of the same meristem have different structures at maturity. The final structure at maturity of a cell/tissue is also determined by the location of the cell within. For example, cells positioned away from root apical meristems differentiate as root-cap cells, while those pushed to the periphery mature as epidermis. Can you add a few more examples of open differentiation correlating the position of a cell to its position in an organ?

15.3 DEVELOPMENT

Development is a term that includes all changes that an organism goes through during its life cycle from germination of the seed to senescence. Diagrammatic representation of the sequence of processes which constitute the development of a cell of a higher plant is given in Figure 15.8. It is also applicable to tissues/organs.

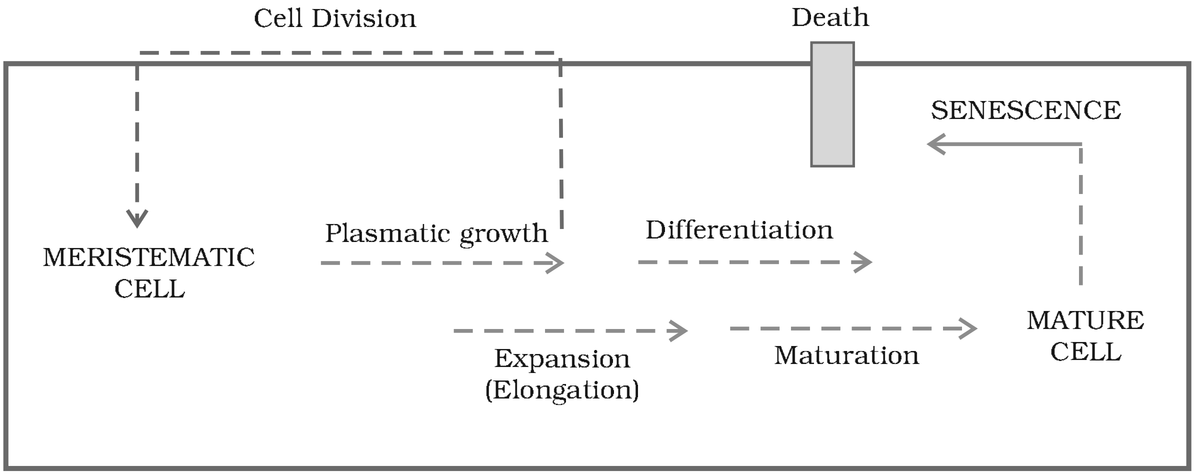


Figure 15.8 Sequence of the developmental process in a plant cell

Plants follow different pathways in response to environment or phases of life to form different kinds of structures. This ability is called **plasticity**, e.g., heterophylly in cotton, coriander and larkspur. In such plants, the leaves of the juvenile plant are different in shape from those in mature plants. On the other hand, difference in shapes of leaves produced in air and those produced in water in buttercup also represent the heterophyllous development due to environment (Figure 15.9). This phenomenon of heterophylly is an example of plasticity.

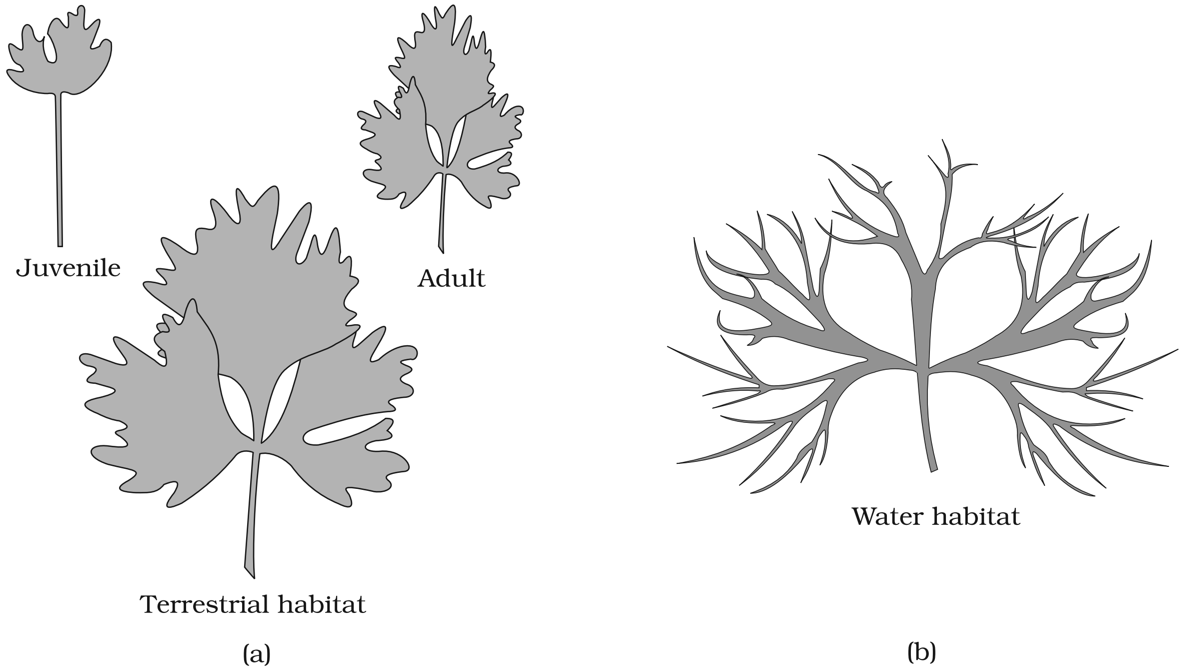


Figure 15.9 Heterophylly in (a) larkspur and (b) buttercup

Thus, growth, differentiation and development are very closely related events in the life of a plant. Broadly, development is considered as the sum of growth and differentiation. Development in plants (i.e., both growth and differentiation) is under the control of intrinsic and extrinsic factors. The former includes both intracellular (genetic) or intercellular factors (chemicals such as plant growth regulators) while the latter includes light, temperature, water, oxygen, nutrition, etc.

15.4 PLANT GROWTH REGULATORS

15.4.1 Characteristics

The plant growth regulators (PGRs) are small, simple molecules of diverse chemical composition. They could be indole compounds (indole-3-acetic acid, IAA); adenine derivatives (N^6-furfurylamino purine, kinetin), derivatives of carotenoids (abscisic acid, ABA); terpenes (gibberellic acid, GA_3) or gases (ethylene, C_2H_4). Plant growth regulators are variously described as plant growth substances, plant hormones or phytohormones in literature.

The PGRs can be broadly divided into two groups based on their functions in a living plant body. One group of PGRs are involved in growth promoting activities, such as cell division, cell enlargement, pattern formation, tropic growth, flowering, fruiting and seed formation. These are also called plant growth promoters, e.g., auxins, gibberellins and cytokinins. The PGRs of the other group play an important role in plant responses to wounds and stresses of biotic and abiotic origin. They are also involved in various growth inhibiting activities such as dormancy and abscission. The PGR abscisic acid belongs to this group. The gaseous PGR, ethylene, could fit either of the groups, but it is largely an inhibitor of growth activities.

15.4.2 The Discovery of Plant Growth Regulators

Interestingly, the discovery of each of the five major groups of PGRs have been accidental. All this started with the observation of Charles Darwin and his son Francis Darwin when they observed that the coleoptiles of canary grass responded to unilateral illumination by growing towards the light source (phototropism). After a series of experiments, it was concluded that the tip of coleoptile was the site of transmittable influence that caused the bending of the entire coleoptile (Figure 15.10). Auxin was isolated by F.W. Went from tips of coleoptiles of oat seedlings.

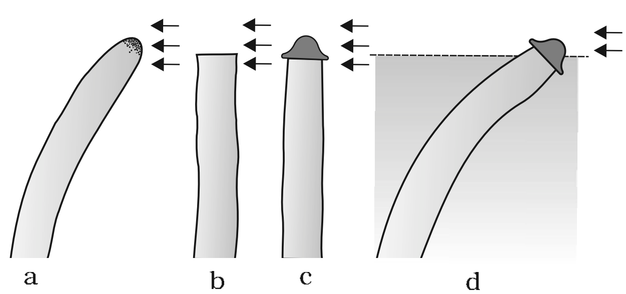


Figure 15.10 Experiment used to demonstrate that tip of the coleoptile is the source of auxin. Arrows indicate direction of light

The 'bakane' (foolish seedling) a disease of rice seedlings, was caused by a fungal pathogen *Gibberalla fujikuroi*. E. Kurosawa reported the appearance of symptoms of the disease in uninfected rice seedlings when they were treated with sterile filtrates of the fungus. The active substances were later identified as gibberellic acid.

F. Skoog and his co-workers observed that from the internodal segments of tobacco stems the callus (a mass of undifferentiated cells) proliferated only if, in addition to auxins the nutrients medium was supplemented with one of the following: extracts of vascular tissues, yeast extract, coconut milk or DNA. Skoog and Miller, later identified and crystallised the cytokinesis promoting active substance that they termed kinetin.

During mid-1960s, three independent researches reported the purification and chemical characterisation of three different kinds of inhibitors: inhibitor-B, abscission II and dormin. Later all the three were proved to be chemically identical. It was named abscisic acid (ABA).

Cousins confirmed the release of a volatile substance from ripened oranges that hastened the ripening of stored unripened bananas. Later this volatile substance was identified as ethylene, a gaseous PGR.

Let us study some of the physiological effects of these five categories of PGRs in the next section.

15.4.3 Physiological Effects of Plant Growth Regulators

15.4.3.1 Auxins

Auxins (from Greek 'auxein' : to grow) was first isolated from human urine. The term 'auxin' is applied to the indole-3-acetic acid (IAA), and to other natural and synthetic compounds having certain growth regulating properties. They are generally produced by the growing apices of the stems and roots, from where they migrate to the regions of their action. Auxins like IAA and indole butyric acid (IBA) have been isolated from plants. NAA (naphthalene acetic acid) and 2, 4-D (2, 4-dichlorophenoxyacetic) are synthetic auxins. All these auxins have been used extensively in agricultural and horticultural practices.

They help to initiate rooting in stem cuttings, an application widely used for plant propagation. Auxins promote flowering e.g. in pineapples. They help to prevent fruit and leaf drop at early stages but promote the abscission of older mature leaves and fruits.

In most higher plants, the growing apical bud inhibits the growth of the lateral (axillary) buds, a phenomenon called **apical dominance**. Removal of shoot tips (decapitation) usually results in the growth of lateral buds (Figure 15.11). It is widely applied in tea plantations, hedge-making. Can you explain why?

Auxins also induce parthenocarpy, e.g., in tomatoes. They are widely used as herbicides. 2, 4-D, widely used to kill dicotyledonous weeds, does not affect mature monocotyledonous plants. It is used to prepare weed-free lawns by gardeners. Auxin also controls xylem differentiation and helps in cell division.

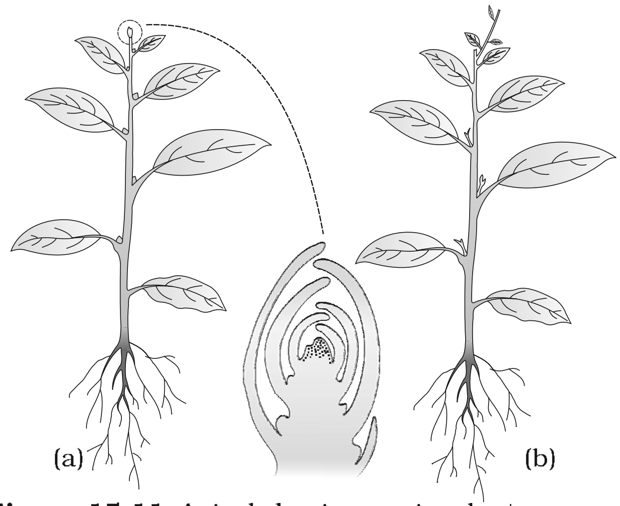


Figure 15.11 Apical dominance in plants : (a) A plant with apical bud intact (b) A plant with apical bud removed Note the growth of lateral buds into branches after decapitation.

15.4.3.2 Gibberellins

Gibberellins are another kind of promotery PGR. There are more than 100 gibberellins reported from widely different organisms such as fungi and higher plants. They are denoted as GA_1, GA_2, GA_3 and so on. However, Gibberellic acid (GA_3) was one of the first gibberellins to be discovered and remains the most intensively studied form. All GAs are acidic. They produce a wide range of physiological responses in the plants. Their ability to cause an increase in length of axis is used to increase the length of grapes stalks. Gibberellins, cause fruits like apple to elongate and improve its shape. They also delay senescence. Thus, the fruits can be left on the tree longer so as to extend the market period. GA_3 is used to speed up the malting process in brewing industry.

Sugarcane stores carbohydrate as sugar in their stems. Spraying sugarcane crop with gibberellins increases the length of the stem, thus increasing the yield by as much as 20 tonnes per acre.

Spraying juvenile conifers with GAs hastens the maturity period, thus leading to early seed production. Gibberellins also promotes bolting (internode elongation just prior to flowering) in beet, cabbages and many plants with rosette habit.

15.4.3.3 Cytokinins

Cytokinins have specific effects on cytokinesis, and were discovered as kinetin (a modified form of adenine, a purine) from the autoclaved herring sperm DNA. Kinetin does not occur naturally in plants. Search for natural substances with cytokinin-like activities led to the isolation of zeatin from corn-kernels and coconut milk. Since the discovery of zeatin, several naturally occurring cytokinins, and some synthetic compounds with cell division promoting activity, have been identified. Natural cytokinins are synthesised in regions where rapid cell division occurs, for example, root apices, developing shoot buds, young fruits etc. It helps to produce new leaves, chloroplasts in leaves, lateral shoot growth and adventitious shoot formation. Cytokinins help overcome the apical dominance. They promote nutrient mobilisation which helps in the delay of leaf senescence.

15.4.3.4 Ethylene

Ethylene is a simple gaseous PGR. It is synthesised in large amounts by tissues undergoing senescence and ripening fruits. Influences of ethylene on plants include horizontal growth of seedlings, swelling of the axis and apical hook formation in dicot seedlings. Ethylene promotes senescence and abscission of plant organs especially of leaves and flowers. Ethylene is highly effective in fruit ripening. It enhances the respiration rate during ripening of the fruits. This rise in rate of respiration is called respiratory climactic.

Ethylene breaks seed and bud dormancy, initiates germination in peanut seeds, sprouting of potato tubers. Ethylene promotes rapid internode/petiole elongation in deep water rice plants. It helps leaves/ upper parts of the shoot to remain above water. Ethylene also promotes root growth and root hair formation, thus helping the plants to increase their absorption surface.

Ethylene is used to initiate flowering and for synchronising fruit-set in pineapples. It also induces flowering in mango. Since ethylene regulates so many physiological processes, it is one of the most widely used PGR in agriculture. The most widely used compound as source of ethylene is ethephon. Ethephon in an aqueous solution is readily absorbed and transported within the plant and releases ethylene slowly. Ethephon hastens fruit ripening in tomatoes and apples and accelerates abscission in flowers and fruits (thinning of cotton, cherry, walnut). It promotes female flowers in cucumbers thereby increasing the yield.

15.4.3.5 Abscisic acid

As mentioned earlier, abscisic acid **(ABA)** was discovered for its role in regulating abscission and dormancy. But like other PGRs, it also has other wide ranging effects on plant growth and development. It acts as a general plant growth inhibitor and an inhibitor of plant metabolism. ABA inhibits seed germination. ABA stimulates the closure of stomata in the epidermis and increases the tolerance of plants to various kinds of stresses. Therefore, it is also called the stress hormone. ABA plays an important role in seed development, maturation and dormancy. By inducing dormancy, ABA helps seeds to withstand desiccation and other factors unfavourable for growth. In most situations, ABA acts as an antagonist to GAs.

We may summarise that for any and every phase of growth, differentiation and development of plants, one or the other PGR has some role to play. Such roles could be complimentary or antagonistic. These could be individualistic or synergistic.

Similarly, there are a number of events in the life of a plant where more than one PGR interact to affect that event, e.g., dormancy in seeds/ buds, abscission, senescence, apical dominance, etc.

Remember, the role of PGR is of only one kind of intrinsic control. Along with genomic control and extrinsic factors, they play an important role in plant growth and development. Many of the extrinsic factors such as temperature and light, control plant growth and development via PGR. Some of such events could be: vernalisation, flowering, dormancy, seed germination, plant movements, etc.

We shall discuss briefly the role of light and temperature (both of them, the extrinsic factors) on initiation of flowering.

15.5 PHOTOPERIODISM

It has been observed that some plants require a periodic exposure to light to induce flowering. It is also seen that such plants are able to measure the duration of exposure to light. For example, some plants require the exposure to light for a period exceding a well defined critical duration, while others must be exposed to light for a period less than this critical duration before the flowering is initiated in them. The former group of plants are called **long day plants** while the latter ones are termed **short day plants**. The critical duration is different for different plants. There are many plants, however, where there is no such correlation between exposure to light duration and inducation of flowering response; such plants are called **day-neutral plants** (Figure 15.12). It is now also

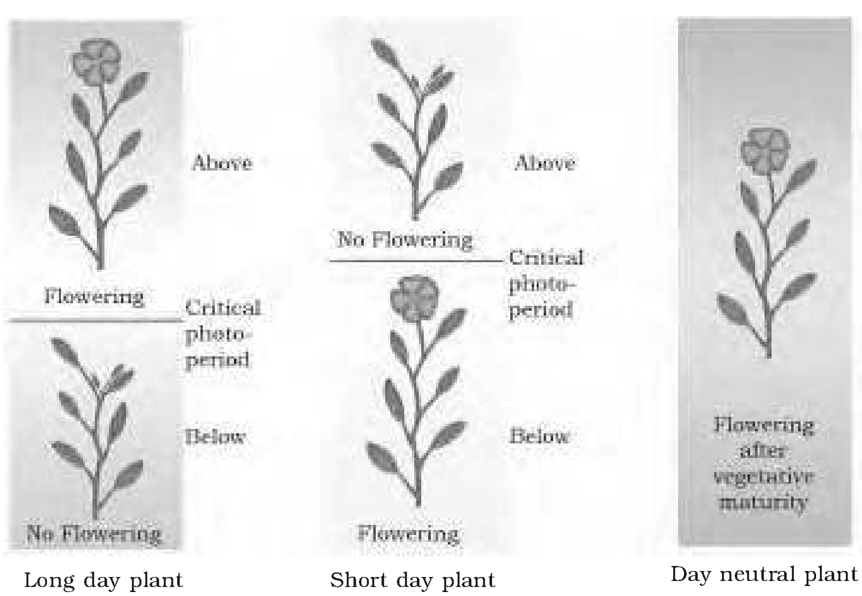


Figure 15.12 Photoperiodism : Long day, short day and day neutral plants

known that not only the duration of light period but that the duration of dark period is also of equal importance. Hence, it can be said that flowering in certain plants depends not only on a combination of light and dark exposures but also their relative durations. This response of plants to periods of day/night is termed **photoperiodism**. It is also interesting to note that while shoot apices modify themselves into flowering apices prior to flowering, they (i.e., shoot apices of plants) by themselves cannot percieve photoperiods. The site of perception of light/dark duration are the leaves. It has been hypothesised that there is a hormonal substance(s) that is responsible for flowering. This hormonal substance migrates from leaves to shoot apices for inducing flowering only when the plants are exposed to the necessary inductive photoperiod.

15.6 Vernalisation

There are plants for which flowering is either quantitatively or qualitatively dependent on exposure to low temperature. This phenomenon is termed **vernalisation**. It prevents precocious reproductive development late in the growing season, and enables the plant to have sufficient time to reach maturity. Vernalisation refers specially to the promotion of flowering by a period of low temperature. Some important food plants, wheat, barley, rye have two kinds of varieties: winter and spring varieties. The 'spring' variety are normally planted in the spring and come to flower and produce grain before the end of the growing season. Winter varieties, however, if planted in spring would normally fail to flower or produce mature grain within a span of a flowering season. Hence, they are planted in autumn. They germinate, and over winter come out as small seedlings, resume growth in the spring, and are harvested usually around mid-summer.

Another example of vernalisation is seen in biennial plants. Biennials are monocarpic plants that normally flower and die in the second season. Sugerbeet, cabbages, carrots are some of the common biennials. Subjecting the growing of a biennial plant to a cold treatment stimulates a subsequent photoperiodic flowering response.

Summary

Growth is one of the most conspicuous events in any living organism. It is an irreversible increase expressed in parameters such as size, area, length, height, volume, cell number etc. It conspicuously involves increased protoplasmic material. In plants, meristems are the sites of growth. Root and shoot apical meristems sometimes alongwith intercalary meristem, contribute to the elongation growth of

plant axes. Growth is indeterminate in higher plants. Following cell division in root and shoot apical meristem cells, the growth could be arithmetic or geometrical. Growth may not be and generally is not sustained at a high rate throughout the life of cell/tissue/organ/organism. One can define three principle phases of growth – the lag, the log and the senescent phase. When a cell loses the capacity to divide, it leads to differentiation. Differentiation results in development of structures that is commensurate with the function the cells finally has to perform. General principles for differentiation for cell, tissues and organs are similar. A differentiated cell may dedifferentiate and then redifferentiate. Since differentiation in plants is open, the development could also be flexible, i.e., the development is the sum of growth and differentiation. Plant exhibit plasticity in development.

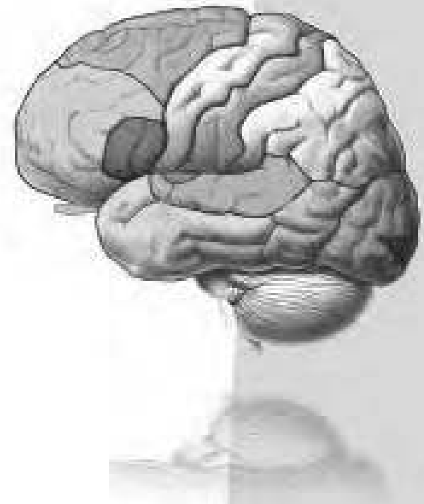
Plant growth and development are under the control of both intrinsic and extrinsic factors. Intercellular intrinsic factors are the chemical substances, called plant growth regulators (PGR). There are diverse groups of PGRs in plants, principally belonging to five groups: auxins, gibberellins, cytokinins, abscisic acid and ethylene. These PGRs are synthesised in various parts of the plant; they control different differentiation and developmental events. Any PGR has diverse physiological effects on plants. Diverse PGRs also manifest similar effects. PGRs may act synergistically or antagonistically. Plant growth and development is also affected by light, temperature, nutrition, oxygen status, gravity and such external factors.

Flowering in some plants is induced only when exposed to certain duration of photoperiod. Depending on the nature of photoperiod requirements, the plants are called short day plants, long day plants and day-neutral plants. Certain plants also need to be exposed to low temperature so as to hasten flowering later in life. This treatement is known as vernalisation.

EXERCISES

1. Define growth, differentiation, development, dedifferentiation, redifferentiation, determinate growth, meristem and growth rate.
2. Why is not any one parameter good enough to demonstrate growth throughout the life of a flowering plant?
3. Describe briefly:
   (a) Arithmetic growth
   (b) Geometric growth
   (c) Sigmoid growth curve
   (d) Absolute and relative growth rates
4. List five main groups of natural plant growth regulators. Write a note on discovery, physiological functions and agricultural/horticultural applications of any one of them.

5. What do you understand by photoperiodism and vernalisation? Describe their significance.
6. Why is abscisic acid also known as stress hormone?
7. 'Both growth and differentiation in higher plants are *open*'. Comment.
8. 'Both a short day plant and a long day plant can produce can flower simultaneously in a given place'. Explain.
9. Which one of the plant growth regulators would you use if you are asked to:
   (a) induce rooting in a twig
   (b) quickly ripen a fruit
   (c) delay leaf senescence
   (d) induce growth in axillary buds
   (e) 'bolt' a rosette plant
   (f) induce immediate stomatal closure in leaves.
10. Would a defoliated plant respond to photoperiodic cycle? Why?
11. What would be expected to happen if:
    (a) GA_3 is applied to rice seedlings
    (b) dividing cells stop differentiating
    (c) a rotten fruit gets mixed with unripe fruits
    (d) you forget to add cytokinin to the culture medium.



UNIT 5

HUMAN PHYSIOLOGY

The reductionist approach to study of life forms resulted in increasing use of physico-chemical concepts and techniques. Majority of these studies employed either surviving tissue model or straightaway cell-free systems. An explosion of knowledge resulted in molecular biology. Molecular physiology became almost synonymous with biochemistry and biophysics. However, it is now being increasingly realised that neither a purely organismic approach nor a purely reductionistic molecular approach would reveal the truth about biological processes or living phenomena. Systems biology makes us believe that all living phenomena are emergent properties due to interaction among components of the system under study. Regulatory network of molecules, supra molecular assemblies, cells, tissues, organisms and indeed, populations and communities, each create emergent properties. In the chapters under this unit, major human physiological processes like digestion, exchage of gases, blood circulation, locomotion and movement are described in cellular and molecular terms. The last two chapters point to the coordination and regulation of body events at the organismic level.

Alfonso Corti
(1822 – 1888)

ALFONSO CORTI, Italian anatomist, was born in 1822. Corti began his scientific career studying the cardiovascular systems of reptiles. Later, he turned his attention to the mammalian auditory system. In 1851, he published a paper describing a structure located on the basilar membrane of the cochlea containing hair cells that convert sound vibrations into nerve impulses, the organ of Corti. He died in the year 1888.

Chapter 16

Digestion and Absorption

Food is one of the basic requirements of all living organisms. The major components of our food are carbohydrates, proteins and fats. Vitamins and minerals are also required in small quantities. Food provides energy and organic materials for growth and repair of tissues. The water we take in, plays an important role in metabolic processes and also prevents dehydration of the body. Biomacromolecules in food cannot be utilised by our body in their original form. They have to be broken down and converted into simple substances in the digestive system. This process of conversion of complex food substances to simple absorbable forms is called **digestion** and is carried out by our digestive system by mechanical and biochemical methods. General organisation of the human digestive system is shown in Figure 16.1.

16.1 Digestive System

The human digestive system consists of the alimentary canal and the associated glands.

16.1.1 Alimentary Canal

The alimentary canal begins with an anterior opening – the mouth, and it opens out posteriorly through the anus. The mouth leads to the buccal cavity or oral cavity. The oral cavity has a number of teeth and a muscular tongue. Each tooth is embedded in a socket of jaw bone (Figure16.2). This type of attachment is called **thecodont**. Majority of mammals including human being forms two sets of teeth during their life, a set of

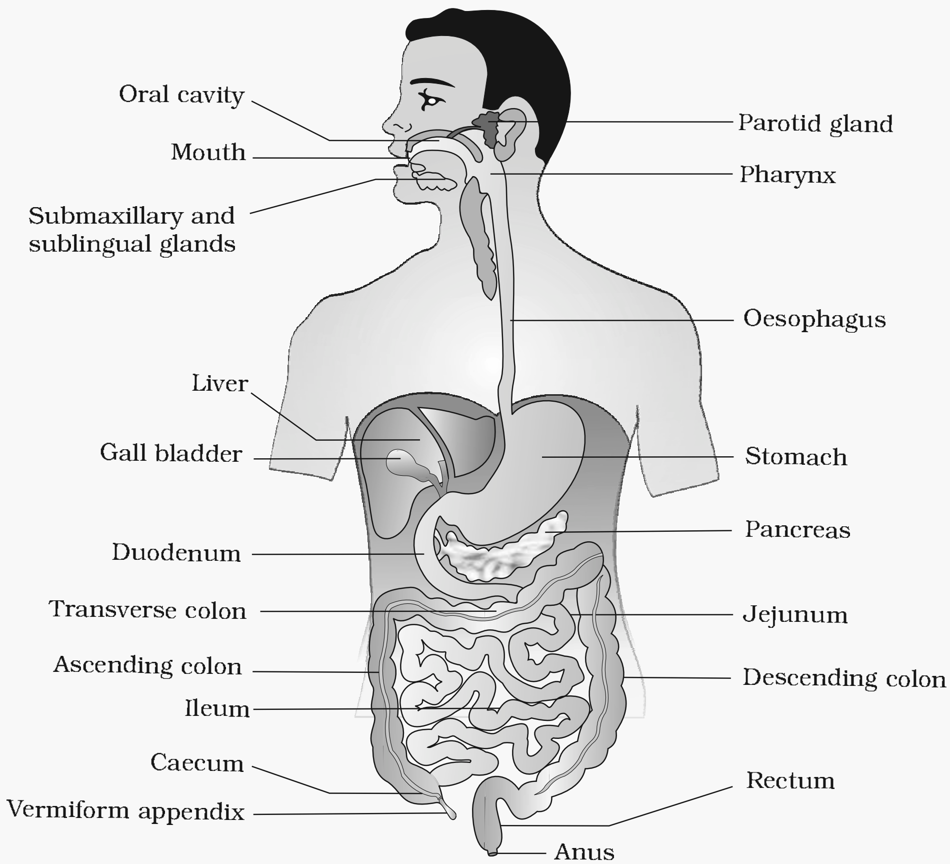


Figure 16.1 The human digestive system

temporary milk or deciduous teeth replaced by a set of permanent or adult teeth. This type of dentition is called **diphyodont**. An adult human has 32 permanent teeth which are of four different types (Heterodont dentition), namely, incisors (I), canine (C), premolars (PM) and molars (M). Arrangement of teeth in each half of the upper and lower jaw in the order I, C, PM, M is represented by a dental formula which in human is $\frac{2123}{2123}$. The hard chewing surface of the teeth, made up of enamel, helps in the mastication of food. The tongue is a freely movable muscular organ attached to the floor of the oral cavity by the frenulum. The upper surface of the tongue has small projections called papillae, some of which bear taste buds.

The oral cavity leads into a short pharynx which serves as a common passage for food and air. The oesophagus and the trachea (wind pipe) open into the pharynx. A cartilaginous flap called epiglottis prevents the entry of food into the glottis – opening of the wind pipe – during swallowing. The oesophagus is a thin, long tube which extends posteriorly passing through the neck, thorax and diaphragm and leads to a 'J' shaped bag like structure called stomach. A muscular sphincter (gastro-oesophageal) regulates the opening of oesophagus into the stomach. The stomach, located in the upper left portion of the abdominal cavity, has three major parts – a **cardiac** portion into which the oesophagus opens, a **fundic** region and a **pyloric** portion which opens into the first part of small intestine (Figure 16.3). Small intestine is distinguishable into three regions, a 'U' shaped duodenum, a long coiled middle portion jejunum and a highly coiled ileum. The opening of the stomach into the duodenum is guarded by the pyloric sphincter. Ileum opens into the large intestine. It consists of caecum, colon and rectum. Caecum is a small blind sac which hosts some symbiotic micro-organisms. A narrow finger-like tubular projection, the vermiform appendix which is a vestigial organ, arises from the caecum. The caecum opens into the colon. The colon is divided into three parts – an ascending, a transverse and a descending part. The descending part opens into the rectum which opens out through the anus.

The wall of alimentary canal from oesophagus to rectum possesses four layers (Figure 16.4) namely serosa, muscularis, sub-mucosa and mucosa. Serosa is the outermost layer and is made up of a thin mesothelium (epithelium of visceral organs) with some connective tissues. Muscularis is formed by smooth muscles usually arranged into an inner circular and an outer longitudinal layer. An oblique muscle layer may be present in some regions. The sub-mucosal layer is formed of loose connective

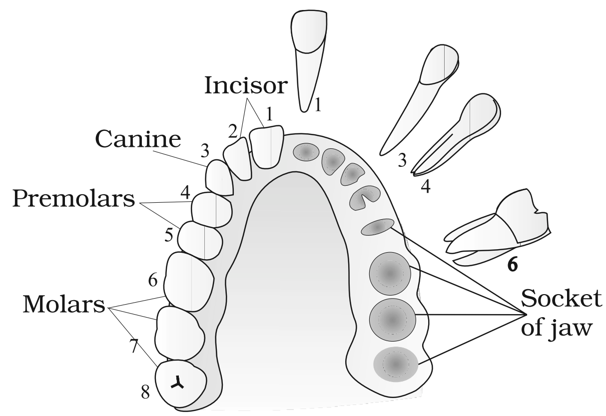


Figure 16.2 Arrangement of different types of teeth in the jaws on one side and the sockets on the other side

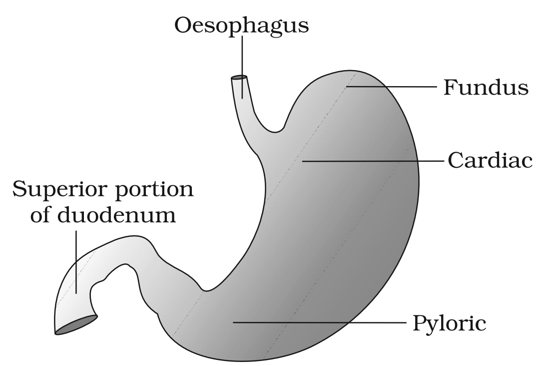


Figure 16.3 Anatomical regions of human stomach

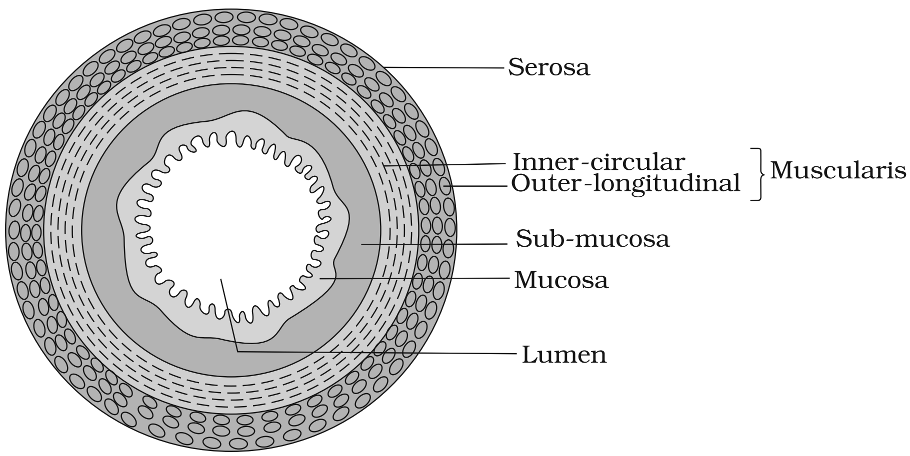


Figure 16.4 Diagrammatic representation of transverse section of gut

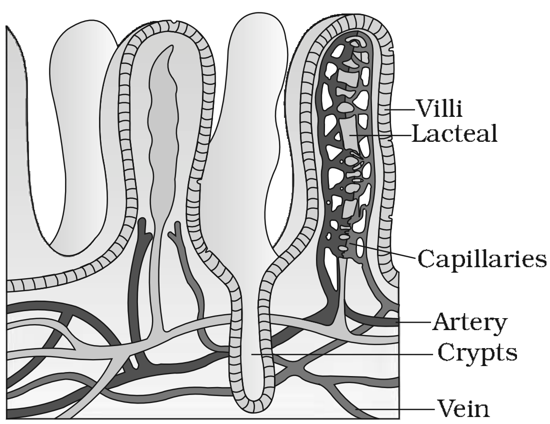


Figure 16.5 A section of small intestinal mucosa showing villi

tissues containing nerves, blood and lymph vessels. In duodenum, glands are also present in sub-mucosa. The innermost layer lining the lumen of the alimentary canal is the mucosa. This layer forms irregular folds (rugae) in the stomach and small finger-like foldings called **villi** in the small intestine (Figure 16.5). The cells lining the villi produce numerous microscopic projections called microvilli giving a brush border appearance. These modifications increase the surface area enormously. Villi are supplied with a network of capillaries and a large lymph vessel called the lacteal. Mucosal epithelium has goblet cells which secrete mucus that help in lubrication. Mucosa also forms glands in the stomach (gastric glands) and crypts in between the bases of villi in the intestine (crypts of Lieberkuhn). All the four layers show modifications in different parts of the alimentary canal.

16.1.2 Digestive Glands

The digestive glands associated with the alimentary canal include the salivary glands, the liver and the pancreas.

Saliva is mainly produced by three pairs of salivary glands, the parotids (cheek), the sub-maxillary/sub-mandibular (lower jaw) and the sub-linguals (below the tongue). These glands situated just outside the buccal cavity secrete salivary juice into the buccal cavity.

Liver is the largest gland of the body weighing about 1.2 to 1.5 kg in an adult human. It is situated in the abdominal cavity, just below the diaphragm and has two lobes. The hepatic lobules are the structural and functional units of liver containing hepatic cells arranged in the form of cords. Each lobule is covered by a thin connective tissue sheath called the Glisson's capsule. The bile secreted by the hepatic cells passes through the hepatic ducts and is stored and concentrated in a thin muscular sac called the gall bladder. The duct of gall bladder (cystic duct) along with the hepatic duct from the liver forms the common bile duct (Figure 16.6).

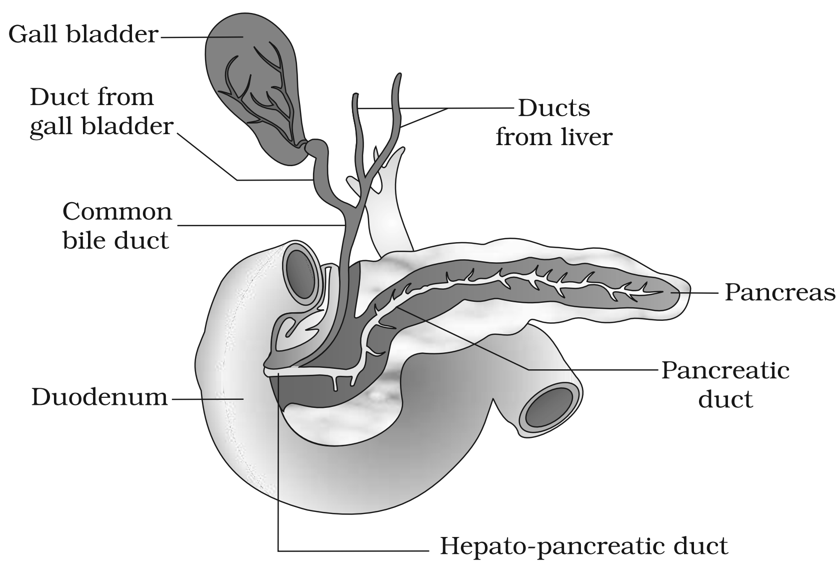


Figure 16.6 The duct systems of liver, gall bladder and pancreas

The bile duct and the pancreatic duct open together into the duodenum as the common hepato-pancreatic duct which is guarded by a sphincter called the sphincter of Oddi.

The pancreas is a compound (both exocrine and endocrine) elongated organ situated between the limbs of the 'U' shaped duodenum. The exocrine portion secretes an alkaline pancreatic juice containing enzymes and the endocrine portion secretes hormones, insulin and glucagon.

16.2 DIGESTION OF FOOD

The process of digestion is accomplished by mechanical and chemical processes.

The buccal cavity performs two major functions, mastication of food and facilitation of swallowing. The teeth and the tongue with the help of saliva masticate and mix up the food thoroughly. Mucus in saliva helps in lubricating and adhering the masticated food particles into a **bolus**. The bolus is then conveyed into the pharynx and then into the oesophagus by swallowing or **deglutition**. The bolus further passes down through the oesophagus by successive waves of muscular contractions called peristalsis. The gastro-oesophageal sphincter controls the passage of food into the stomach. The saliva secreted into the oral cavity contains electrolytes (Na^+, K^+, Cl^-, HCO^-) and enzymes, salivary amylase and lysozyme. The chemical process of digestion is initiated in the oral cavity by the hydrolytic action of the carbohydrate splitting enzyme, the salivary amylase. About 30 per cent of starch is hydrolysed here by this enzyme (optimum pH 6.8) into a disaccharide – maltose. Lysozyme present in saliva acts as an antibacterial agent that prevents infections.

$$\text{Starch} \xrightarrow[\text{pH 6.8}]{\text{Salivary Amylase}} \text{Maltose}$$

The mucosa of stomach has gastric glands. Gastric glands have three major types of cells namely -

(i) mucus neck cells which secrete mucus;
(ii) peptic or chief cells which secrete the proenzyme pepsinogen; and
(iii) parietal or oxyntic cells which secrete HCl and intrinsic factor (factor essential for absorption of vitamin B_{12}).

The stomach stores the food for 4-5 hours. The food mixes thoroughly with the acidic gastric juice of the stomach by the churning movements of its muscular wall and is called the **chyme**. The proenzyme pepsinogen, on exposure to hydrochloric acid gets converted into the active enzyme pepsin, the proteolytic enzyme of the stomach. Pepsin converts proteins into proteoses and peptones (peptides). The mucus and bicarbonates present in the gastric juice play an important role in lubrication and protection of the mucosal epithelium from excoriation by the highly concentrated hydrochloric acid. HCl provides the acidic pH (pH 1.8) optimal for pepsins. Rennin is a proteolytic enzyme found in gastric juice of infants which helps in the digestion of milk proteins. Small amounts of lipases are also secreted by gastric glands.

Various types of movements are generated by the muscularis layer of the small intestine. These movements help in a thorough mixing up of the food with various secretions in the intestine and thereby facilitate digestion. The bile, pancreatic juice and the intestinal juice are the secretions released into the small intestine. Pancreatic juice and bile are released through the hepato-pancreatic duct. The pancreatic juice contains inactive enzymes – trypsinogen, chymotrypsinogen, procarboxypeptidases, amylases, lipases and nucleases. Trypsinogen is activated by an enzyme, enterokinase, secreted by the intestinal mucosa into active trypsin, which in turn activates the other enzymes in the pancreatic juice. The bile released into the duodenum contains bile pigments (bilirubin and bili-verdin), bile salts, cholesterol and phospholipids but no enzymes. Bile helps in emulsification of fats, i.e., breaking down of the fats into very small micelles. Bile also activates lipases.

The intestinal mucosal epithelium has **goblet cells** which secrete mucus. The secretions of the brush border cells of the mucosa alongwith the secretions of the goblet cells constitute the intestinal juice or **succus entericus**. This juice contains a variety of enzymes like disaccharidases (e.g., maltase), dipeptidases, lipases, nucleosidases, etc. The mucus alongwith the bicarbonates from the pancreas protects the intestinal mucosa from acid as well as provide an alkaline medium (pH 7.8) for enzymatic activities. Sub-mucosal glands (Brunner's glands) also help in this.

Proteins, proteoses and peptones (partially hydrolysed proteins) in the chyme reaching the intestine are acted upon by the proteolytic enzymes of pancreatic juice as given below:

$$\left.\begin{array}{l}\text{Proteins}\\\text{Peptones}\\\text{Proteoses}\end{array}\right\}\xrightarrow[\text{Carboxypeptidase}]{\text{Trypsin/Chymotrypsin}}\text{Dipeptides}$$

Carbohydrates in the chyme are hydrolysed by pancreatic amylase into disaccharides.

$$\text{Polysaccharides (starch)}\xrightarrow{\text{Amylase}}\text{Disaccharides}$$

Fats are broken down by lipases with the help of bile into di-and monoglycerides.

$$\text{Fats}\xrightarrow{\text{Lipases}}\text{Diglycerides}\longrightarrow\text{Monoglycerides}$$

Nucleases in the pancreatic juice acts on nucleic acids to form nucleotides and nucleosides

$$\text{Nucleic acids}\xrightarrow{\text{Nucleases}}\text{Nucleotides}\longrightarrow\text{Nucleosides}$$

The enzymes in the succus entericus act on the end products of the above reactions to form the respective simple absorbable forms. These final steps in digestion occur very close to the mucosal epithelial cells of the intestine.

$$\text{Dipeptides} \xrightarrow{\text{Dipeptidases}} \text{Amino acids}$$

$$\text{Maltose} \xrightarrow{\text{Maltase}} \text{Glucose + Glucose}$$

$$\text{Lactose} \xrightarrow{\text{Lactase}} \text{Glucose + Galactose}$$

$$\text{Sucrose} \xrightarrow{\text{Sucrase}} \text{Glucose + Fructose}$$

$$\text{Nucleotides} \xrightarrow{\text{Nucleotidases}} \text{Nucleosides} \xrightarrow{\text{Nucleosidases}} \text{Sugars + Bases}$$

$$\text{Di and Monoglycerides} \xrightarrow{\text{Lipases}} \text{Fatty acids + Glycerol}$$

The breakdown of biomacromolecules mentioned above occurs in the duodenum region of the small intestine. The simple substances thus formed are absorbed in the jejunum and ileum regions of the small intestine. The undigested and unabsorbed substances are passed on to the large intestine.

No significant digestive activity occurs in the large intestine. The functions of large intestine are:

(i) absorption of some water, minerals and certain drugs;
(ii) secretion of mucus which helps in adhering the waste (undigested) particles together and lubricating it for an easy passage.

The undigested, unabsorbed substances called faeces enters into the caecum of the large intestine through ileo-caecal valve, which prevents the back flow of the faecal matter. It is temporarily stored in the rectum till defaecation.

The activities of the gastro-intestinal tract are under neural and hormonal control for proper coordination of different parts. The sight, smell and/or the presence of food in the oral cavity can stimulate the secretion of saliva. Gastric and intestinal secretions are also, similarly, stimulated by neural signals. The muscular activities of different parts of the alimentary canal can also be moderated by neural mechanisms, both local and through CNS. Hormonal control of the secretion of digestive juices is carried out by the local hormones produced by the gastric and intestinal mucosa.

16.3 Absorption of Digested Products

Absorption is the process by which the end products of digestion pass through the intestinal mucosa into the blood or lymph. It is carried out by passive, active or facilitated transport mechanisms. Small amounts of monosacharides like glucose, amino acids and some of electrolytes like chloride ions are generally absorbed by simple diffusion. The passage of these substances into the blood depends upon the concentration gradients. However, some of the substances like fructose and some amino acids are absorbed with the help of the carrier ions like Na^+. This mechanism is called the facilitated transport.

Transport of water depends upon the osmotic gradient. Active transport occurs against the concentration gradient and hence requires energy. Various nutrients like amino acids, monosacharides like glucose, electrolytes like Na^+ are absorbed into the blood by this mechanism.

Fatty acids and glycerol being insoluble, cannot be absorbed into the blood. They are first incorporated into small droplets called micelles which move into the intestinal mucosa. They are re-formed into very small protein coated fat globules called the chylomicrons which are transported into the lymph vessels (lacteals) in the villi. These lymph vessels ultimately release the absorbed substances into the blood stream.

Absorption of substances takes place in different parts of the alimentary canal, like mouth, stomach, small intestine and large intestine. However, maximum absorption occurs in the small intestine. A summary of absorption (sites of absorption and substances absorbed) is given in Table 16.1.

TABLE 16.1 The Summary of Absorption in Different Parts of Digestive System

Mouth	Stomach	Small Intestine	Large Intestine
Certain drugs coming in contact with the mucosa of mouth and lower side of the tongue are absorbed into the blood capillaries lining them.	Absorption of water, simple sugars, and alcohol etc. takes place.	Principal organ for absorption of nutrients. The digestion is completed here and the final products of digestion such as glucose, fructose, fatty acids, glycerol and amino acids are absorbed through the mucosa into the blood stream and lymph.	Absorption of water, some minerals and drugs takes place.

The absorbed substances finally reach the tissues which utilise them for their activities. This process is called assimilation.

The digestive wastes, solidified into coherent faeces in the rectum initiate a neural reflex causing an urge or desire for its removal. The egestion of faeces to the outside through the anal opening (defaecation) is a voluntary process and is carried out by a mass peristaltic movement.

16.4 DISORDERS OF DIGESTIVE SYSTEM

The inflammation of the intestinal tract is the most common ailment due to bacterial or viral infections. The infections are also caused by the parasites of the intestine like tape worm, round worm, thread worm, hook worm, pin worm, etc.

Jaundice: The liver is affected, skin and eyes turn yellow due to the deposit of bile pigments.

Vomiting: It is the ejection of stomach contents through the mouth. This reflex action is controlled by the vomit centre in the medulla. A feeling of nausea precedes vomiting.

Diarrhoea: The abnormal frequency of bowel movement and increased liquidity of the faecal discharge is known as diarrhoea. It reduces the absorption of food.

Constipation: In constipation, the faeces are retained within the rectum as the bowel movements occur irregularly.

Indigestion: In this condition, the food is not properly digested leading to a feeling of fullness. The causes of indigestion are inadequate enzyme secretion, anxiety, food poisoning, over eating, and spicy food.

SUMMARY

The digestive system of humans consists of an alimentary canal and associated digestive glands. The alimentary canal consists of the mouth, buccal cavity, pharynx, oesophagus, stomach, small intestine, large intestine, rectum and the anus. The accessory digestive glands include the salivary glands, the liver (with gall bladder) and the pancreas. Inside the mouth the teeth masticates the food, the tongue tastes the food and manipulates it for proper mastication by mixing with the saliva. Saliva contains a starch digestive enzyme, salivary amylase that digests the starch and converts it into maltose (disaccharide). The food then passes into the pharynx and enters the oesophagus in the form of bolus, which is further carried down through the oesophagus by peristalsis into the stomach. In stomach mainly protein digestion takes place. Absorption of simple sugars, alcohol and medicines also takes place in the stomach.

The chyme (food) enters into the duodenum portion of the small intestine and is acted on by the pancreatic juice, bile and finally by the enzymes in the succus entericus, so that the digestion of carbohydrates, proteins and fats is completed. The food then enters into the jejunum and ileum portions of the small intestine. Carbohydrates are digested and converted into monosaccharides like glucose. Proteins are finally broken down into amino acids. The fats are converted to fatty acids and glycerol. The digested end products are absorbed into the body through the epithelial lining of the intestinal villi. The undigested food (faeces) enters into the caecum of the large intestine through ileo-caecal valve, which prevents the back flow of the faecal matter. Most of the water is absorbed in the large intestine. The undigested food becomes semi-solid in nature and then enters into the rectum, anal canal and is finally egested out through the anus.

EXERCISES

1. Choose the correct answer among the following :
   (a) Gastric juice contains
      (i) pepsin, lipase and rennin
      (ii) trypsin, lipase and rennin
      (iii) trypsin, pepsin and lipase
      (iv) trypsin, pepsin and renin
   (b) Succus entericus is the name given to
      (i) a junction between ileum and large intestine
      (ii) intestinal juice
      (iii) swelling in the gut
      (iv) appendix
2. Match column I with column II

Column I	**Column II**
(a) Bilirubin and biliverdin	(i) Parotid
(b) Hydrolysis of starch	(ii) Bile
(c) Digestion of fat	(iii) Lipases
(d) Salivary gland	(iv) Amylases

3. Answer briefly:
   (a) Why are villi present in the intestine and not in the stomach?
   (b) How does pepsinogen change into its active form?
   (c) What are the basic layers of the wall of alimentary canal?
   (d) How does bile help in the digestion of fats?
4. State the role of pancreatic juice in digestion of proteins.
5. Describe the process of digestion of protein in stomach.
6. Give the dental formula of human beings.
7. Bile juice contains no digestive enzymes, yet it is important for digestion. Why?
8. Describe the digestive role of chymotrypsin. Which two other digestive enzymes of the same category are secreted by its source gland?
9. How are polysaccharides and disaccharides digested?
10. What would happen if HCl were not secreted in the stomach?
11. How does butter in your food get digested and absorbed in the body?
12. Discuss the main steps in the digestion of proteins as the food passes through different parts of the alimentary canal.
13. Explain the term thecodont and diphyodont.
14. Name different types of teeth and their number in an adult human.
15. What are the functions of liver?

Chapter 17

Breathing and Exchange of Gases

As you have read earlier, oxygen (O_2) is utilised by the organisms to indirectly break down nutrient molecules like glucose and to derive energy for performing various activities. Carbon dioxide (CO_2) which is harmful is also released during the above catabolic reactions. It is, therefore, evident that O_2 has to be continuously provided to the cells and CO_2 produced by the cells have to be released out. This process of exchange of O_2 from the atmosphere with CO_2 produced by the cells is called **breathing,** commonly known as **respiration**. Place your hands on your chest; you can feel the chest moving up and down. You know that it is due to breathing. How do we breathe? The respiratory organs and the mechanism of breathing are described in the following sections of this chapter.

17.1 Respiratory Organs

Mechanisms of breathing vary among different groups of animals depending mainly on their habitats and levels of organisation. Lower invertebrates like sponges, coelenterates, flatworms, etc., exchange O_2 with CO_2 by simple diffusion over their entire body surface. Earthworms use their moist cuticle and insects have a network of tubes (tracheal tubes) to transport atmospheric air within the body. Special vascularised structures called **gills** are used by most of the aquatic arthropods and molluscs whereas vascularised bags called **lungs** are used by the terrestrial forms for the exchange of gases. Among vertebrates, fishes use gills whereas reptiles, birds and mammals respire through lungs. Amphibians like frogs can respire through their moist skin also. Mammals have a well developed respiratory system.

17.1.1 Human Respiratory System

We have a pair of external nostrils opening out above the upper lips. It leads to a nasal chamber through the nasal passage. The nasal chamber opens into **nasopharynx**, which is a portion of pharynx, the common passage for food and air. Nasopharynx opens through glottis of the larynx region into the **trachea**. Larynx is a cartilaginous box which helps in sound production and hence called the **sound box**. During swallowing glottis can be covered by a thin elastic cartilaginous flap called epiglottis to prevent the entry of food into the larynx. Trachea is a straight tube extending up to the mid-thoracic cavity, which divides at the level of 5th thoracic vertebra into a right and left primary **bronchi**. Each bronchi undergoes repeated divisions to form the secondary and tertiary bronchi and bronchioles ending up in very thin terminal **bronchioles**. The tracheae, primary, secondary and tertiary bronchi, and initial bronchioles are supported by incomplete cartilaginous rings. Each terminal bronchiole gives rise to a number of very thin, irregular-walled and vascularised bag-like structures called **alveoli**. The branching network of bronchi, bronchioles and alveoli comprise the lungs (Figure 17.1). We have two lungs which are covered by a double layered pleura, with pleural fluid between them. It reduces friction on the lung-surface. The outer pleural membrane is in close contact with the thoracic

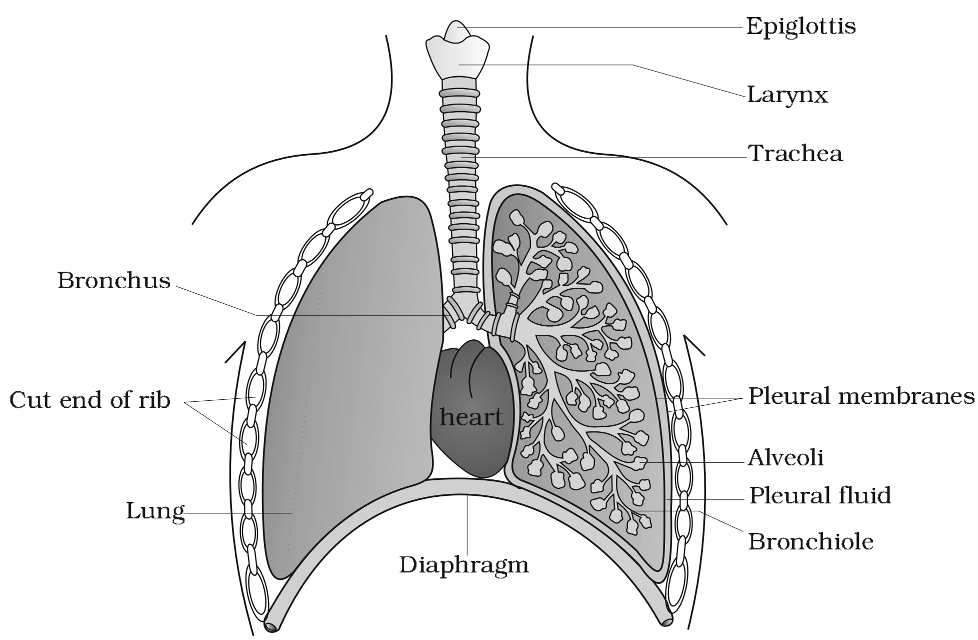


Figure 17.1 Diagrammatic view of human respiratory system (Sectional view of the left lung is also shown)

lining whereas the inner pleural membrane is in contact with the lung surface. The part starting with the external nostrils up to the terminal bronchioles constitute the conducting part whereas the alveoli and their ducts form the respiratory or exchange part of the respiratory system. The conducting part transports the atmospheric air to the alveoli, clears it from foreign particles, humidifies and also brings the air to body temperature. Exchange part is the site of actual diffusion of O_2 and CO_2 between blood and atmospheric air.

The lungs are situated in the thoracic chamber which is anatomically an air-tight chamber. The thoracic chamber is formed dorsally by the vertebral column, ventrally by the sternum, laterally by the ribs and on the lower side by the dome-shaped diaphragm. The anatomical setup of lungs in thorax is such that any change in the volume of the thoracic cavity will be reflected in the lung (pulmonary) cavity. Such an arrangement is essential for breathing, as we cannot directly alter the pulmonary volume.

Respiration involves the following steps:

(i) Breathing or pulmonary ventilation by which atmospheric air is drawn in and CO_2 rich alveolar air is released out.

(ii) Diffusion of gases (O_2 and CO_2) across alveolar membrane.

(iii) Transport of gases by the blood.

(iv) Diffusion of O_2 and CO_2 between blood and tissues.

(v) Utilisation of O_2 by the cells for catabolic reactions and resultant release of CO_2 (cellular respiration as dealt in the Chapter 14 – Respiration).

17.2 Mechanism of Breathing

Breathing involves two stages : **inspiration** during which atmospheric air is drawn in and **expiration** by which the alveolar air is released out. The movement of air into and out of the lungs is carried out by creating a pressure gradient between the lungs and the atmosphere. Inspiration can occur if the pressure within the lungs (intra-pulmonary pressure) is less than the atmospheric pressure, i.e., there is a negative pressure in the lungs with respect to atmospheric pressure. Similarly, expiration takes place when the intra-pulmonary pressure is higher than the atmospheric pressure. The diaphragm and a specialised set of muscles – external and internal intercostals between the ribs, help in generation of such gradients. Inspiration is initiated by the contraction of diaphragm which increases the volume of thoracic chamber in the antero-posterior axis. The contraction of external inter-costal muscles lifts up the ribs and the sternum causing an increase in the volume of the thoracic chamber in the dorso-ventral axis. The overall increase in the thoracic volume causes a similar increase in pulmonary volume. An increase in pulmonary volume decreases the intra-pulmonary pressure to less than the atmospheric pressure which forces the air from outside to move into the lungs, i.e., inspiration (Figure 17.2a). Relaxation of the diaphragm and the inter-costal muscles returns the diaphragm and sternum to their normal positions and reduce the thoracic volume and thereby the pulmonary volume. This leads to an increase in intra-pulmonary pressure to slightly above the atmospheric pressure causing the expulsion of air from the lungs, i.e., expiration (Figure 17.2b). We have the ability to increase the strength of inspiration and expiration with the help of additional muscles in the abdomen. On an average, a healthy human breathes 12-16 times/minute. The volume of air involved in breathing movements can be estimated by using a spirometer which helps in clinical assessment of pulmonary functions.

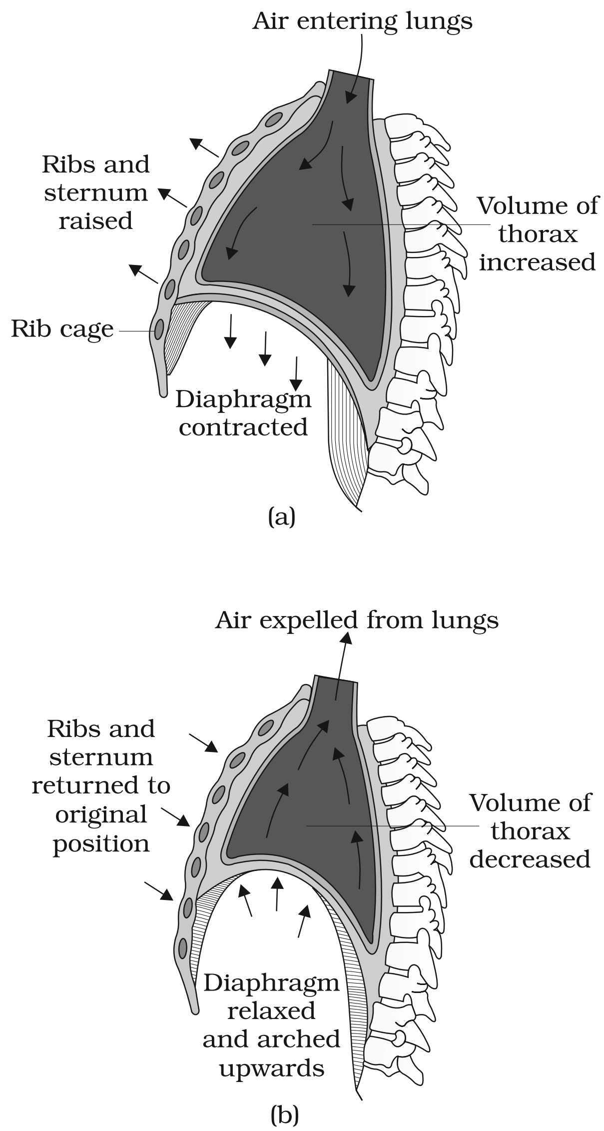


Figure 17.2 Mechanism of breathing showing : (a) inspiration (b) expiration

17.2.1 Respiratory Volumes and Capacities

Tidal Volume (TV): Volume of air inspired or expired during a normal respiration. It is approx. 500 mL., i.e., a healthy man can inspire or expire approximately 6000 to 8000 mL of air per minute.

Inspiratory Reserve Volume (IRV): Additional volume of air, a person can inspire by a forcible inspiration. This averages 2500 mL to 3000 mL.

Expiratory Reserve Volume (ERV): Additional volume of air, a person can expire by a forcible expiration. This averages 1000 mL to 1100 mL.

Residual Volume (RV): Volume of air remaining in the lungs even after a forcible expiration. This averages 1100 mL to 1200 mL.

By adding up a few respiratory volumes described above, one can derive various pulmonary capacities, which can be used in clinical diagnosis.

Inspiratory Capacity (IC): Total volume of air a person can inspire after a normal expiration. This includes tidal volume and inspiratory reserve volume (TV+IRV).

Expiratory Capacity (EC): Total volume of air a person can expire after a normal inspiration. This includes tidal volume and expiratory reserve volume (TV+ERV).

Functional Residual Capacity (FRC): Volume of air that will remain in the lungs after a normal expiration. This includes ERV+RV.

Vital Capacity (VC): The maximum volume of air a person can breathe in after a forced expiration. This includes ERV, TV and IRV or the maximum volume of air a person can breathe out after a forced inspiration.

Total Lung Capacity: Total volume of air accommodated in the lungs at the end of a forced inspiration. This includes RV, ERV, TV and IRV or vital capacity + residual volume.

17.3 Exchange of Gases

Alveoli are the primary sites of exchange of gases. Exchange of gases also occur between blood and tissues. O_2 and CO_2 are exchanged in these sites by simple diffusion mainly based on pressure/concentration gradient. Solubility of the gases as well as the thickness of the membranes involved in diffusion are also some important factors that can affect the rate of diffusion.

Pressure contributed by an individual gas in a mixture of gases is called partial pressure and is represented as pO_2 for oxygen and pCO_2 for carbon dioxide. Partial pressures of these two gases in the atmospheric air and the two sites of diffusion are given in Table 17.1 and in Figure 17.3. The data given in the table clearly indicates a concentration gradient for oxygen from alveoli to blood and blood to tissues. Similarly,

Table 17.1 Partial Pressures (in mm Hg) of Oxygen and Carbon dioxide at Different Parts Involved in Diffusion in Comparison to those in Atmosphere

Respiratory Gas	Atmospheric Air	Alveoli	Blood (Deoxygenated)	Blood (Oxygenated)	Tissues
O_2	159	104	40	95	40
CO_2	0.3	40	45	40	45

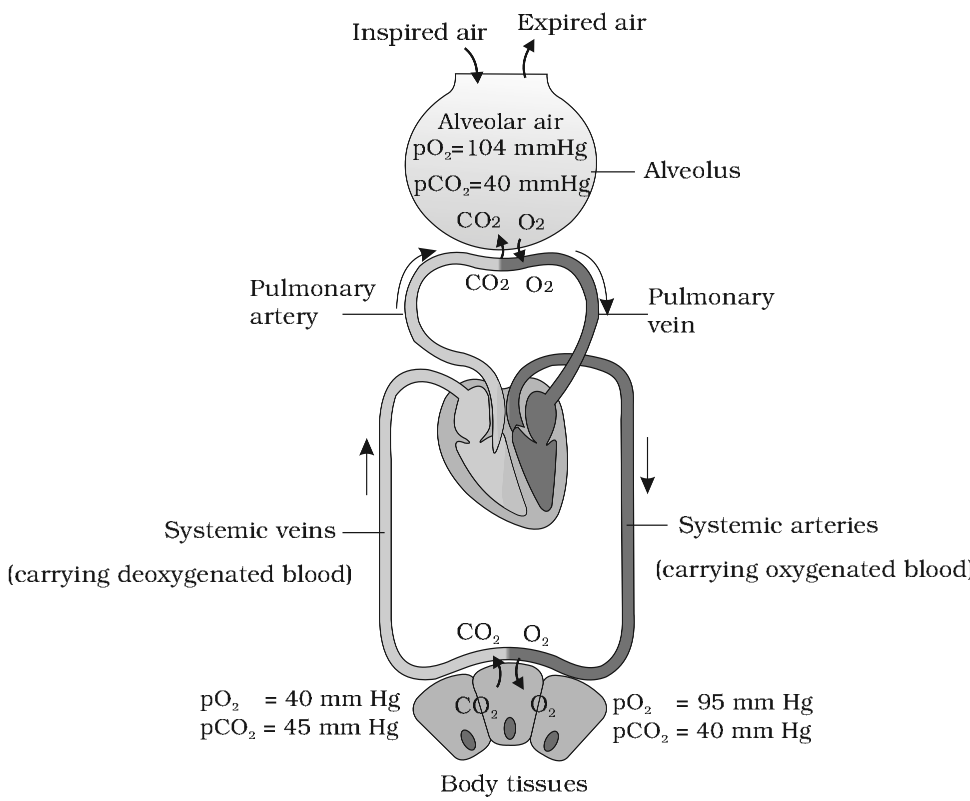


Figure 17.3 Diagrammatic representation of exchange of gases at the alveolus and the body tissues with blood and transport of oxygen and carbon dioxide

a gradient is present for CO_2 in the opposite direction, i.e., from tissues to blood and blood to alveoli. As the solubility of CO_2 is 20-25 times higher than that of O_2, the amount of CO_2 that can diffuse through the diffusion membrane per unit difference in partial pressure is much higher compared to that of O_2. The diffusion membrane is made up of three major layers (Figure 17.4) namely, the thin squamous epithelium of alveoli, the endothelium of alveolar capillaries and the basement substance in between them. However, its total thickness is much less than a millimetre. Therefore, all the factors in our body are favourable for diffusion of O_2 from alveoli to tissues and that of CO_2 from tissues to alveoli.

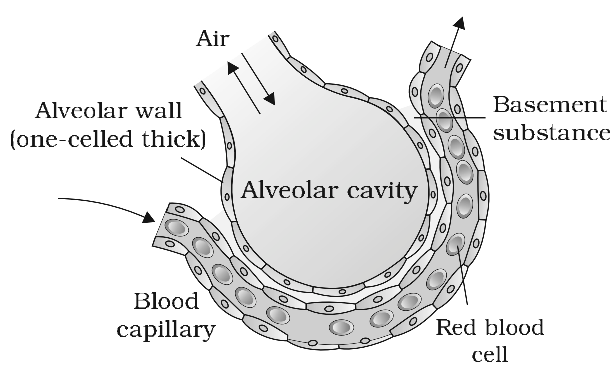


Figure 17.4 A Diagram of a section of an alveolus with a pulmonary capillary.

17.4 TRANSPORT OF GASES

Blood is the medium of transport for O_2 and CO_2. About 97 per cent of O_2 is transported by RBCs in the blood. The remaining 3 per cent of O_2 is carried in a dissolved state through the plasma. Nearly 20-25 per cent of CO_2 is transported by RBCs whereas 70 per cent of it is carried as bicarbonate. About 7 per cent of CO_2 is carried in a dissolved state through plasma.

17.4.1 Transport of Oxygen

Haemoglobin is a red coloured iron containing pigment present in the RBCs. O_2 can bind with haemoglobin in a reversible manner to form **oxyhaemoglobin**. Each haemoglobin molecule can carry a maximum of four molecules of O_2. Binding of oxygen with haemoglobin is primarily related to partial pressure of O_2. Partial pressure of CO_2, hydrogen ion concentration and temperature are the other factors which can interfere with this binding. A sigmoid curve is obtained when percentage saturation of haemoglobin with O_2 is plotted against the pO_2. This curve is called the Oxygen dissociation curve (Figure 17.5) and is highly useful in studying the effect of factors like pCO_2, H^+ concentration, etc., on binding of O_2 with haemoglobin. In the alveoli, where there is high pO_2, low pCO_2, lesser H^+ concentration and lower temperature, the factors are all favourable for the formation of oxyhaemoglobin, whereas in the tissues, where low pO_2, high pCO_2, high H^+ concentration and higher temperature exist, the conditions are favourable for dissociation of oxygen from the oxyhaemoglobin. This clearly indicates that O_2 gets bound to haemoglobin in the lung surface and gets dissociated at the tissues. Every 100 ml of oxygenated blood can deliver around 5 ml of O_2 to the tissues under normal physiological conditions.

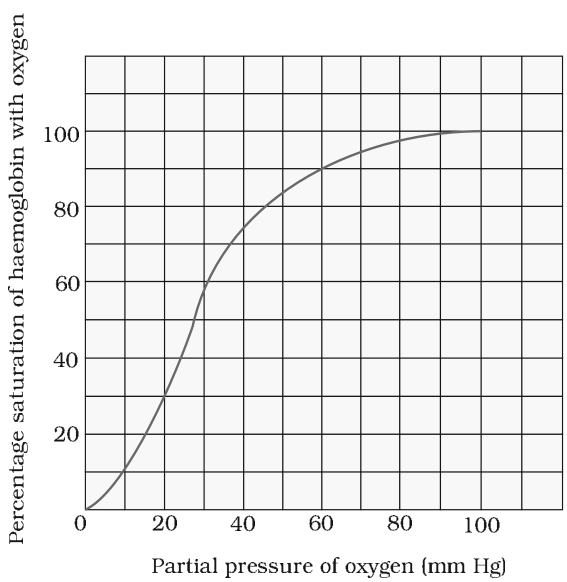


Figure 17.5 Oxygen dissociation curve

17.4.2 Transport of Carbon dioxide

CO_2 is carried by haemoglobin as **carbamino-haemoglobin** (about 20-25 per cent). This binding is related to the partial pressure of CO_2. pO_2 is a major factor which could affect this binding. When pCO_2 is high and pO_2 is low as in the tissues, more binding of carbon dioxide occurs whereas, when the pCO_2 is low and pO_2 is high as in the alveoli, dissociation of CO_2 from carbamino-haemoglobin takes place, i.e., CO_2 which is bound to haemoglobin from the tissues is delivered at the alveoli. RBCs contain a very high concentration of the enzyme, carbonic anhydrase and minute quantities of the same is present in the plasma too. This enzyme facilitates the following reaction in both directions.

$$CO_2 + H_2O \xrightleftharpoons[]{\text{Carbonic anhydrase}} H_2CO_3 \xrightleftharpoons[]{\text{Carbonic anhydrase}} HCO_3^- + H^+$$

At the tissue site where partial pressure of CO_2 is high due to catabolism, CO_2 diffuses into blood (RBCs and plasma) and forms HCO_3^- and H^+. At the alveolar site where pCO_2 is low, the reaction proceeds in the opposite direction leading to the formation of CO_2 and H_2O. Thus, CO_2 trapped as bicarbonate at the tissue level and transported to the alveoli is released out as CO_2 (Figure 17.4). Every 100 ml of deoxygenated blood delivers approximately 4 ml of CO_2 to the alveoli.

17.5 REGULATION OF RESPIRATION

Human beings have a significant ability to maintain and moderate the respiratory rhythm to suit the demands of the body tissues. This is done by the neural system. A specialised centre present in the medulla region of the brain called respiratory rhythm centre is primarily responsible for this regulation. Another centre present in the pons region of the brain called pneumotaxic centre can moderate the functions of the respiratory rhythm centre. Neural signal from this centre can reduce the duration of inspiration and thereby alter the respiratory rate. A chemosensitive area is situated adjacent to the rhythm centre which is highly sensitive to CO_2 and hydrogen ions. Increase in these substances can activate this centre, which in turn can signal the rhythm centre to make necessary adjustments in the respiratory process by which these substances can be eliminated. Receptors associated with aortic arch and carotid artery also can recognise changes in CO_2 and H^+ concentration and send necessary signals to the rhythm centre for remedial actions. The role of oxygen in the regulation of respiratory rhythm is quite insignificant.

17.6 DISORDERS OF RESPIRATORY SYSTEM

Asthma is a difficulty in breathing causing wheezing due to inflammation of bronchi and bronchioles.

Emphysema is a chronic disorder in which alveolar walls are damaged due to which respiratory surface is decreased. One of the major causes of this is cigarette smoking.

Occupational Respiratory Disorders: In certain industries, especially those involving grinding or stone-breaking, so much dust is produced that the defense mechanism of the body cannot fully cope with the situation. Long exposure can give rise to inflammation leading to fibrosis (proliferation of fibrous tissues) and thus causing serious lung damage. Workers in such industries should wear protective masks.

SUMMARY

Cells utilise oxygen for metabolism and produce energy along with substances like carbon dioxide which is harmful. Animals have evolved different mechanisms for the transport of oxygen to the cells and for the removal of carbon dioxide from there. We have a well developed respiratory system comprising two lungs and associated air passages to perform this function.

The first step in respiration is breathing by which atmospheric air is taken in (inspiration) and the alveolar air is released out (expiration). Exchange of O_2 and CO_2 between deoxygenated blood and alveoli, transport of these gases throughout the body by blood, exchange of O_2 and CO_2 between the oxygenated blood and tissues and utilisation of O_2 by the cells (cellular respiration) are the other steps involved.

Inspiration and expiration are carried out by creating pressure gradients between the atmosphere and the alveoli with the help of specialised muscles – intercostals and diaphragm. Volumes of air involved in these activities can be estimated with the help of spirometer and are of clinical significance.

Exchange of O_2 and CO_2 at the alveoli and tissues occur by diffusion. Rate of diffusion is dependent on the partial pressure gradients of O_2 (pO_2) and CO_2 (pCO_2), their solubility as well as the thickness of the diffusion surface. These factors in our body facilitate diffusion of O_2 from the alveoli to the deoxygenated blood as well as from the oxygenated blood to the tissues. The factors are favourable for the diffusion of CO_2 in the opposite direction, i.e., from tissues to alveoli.

Oxygen is transported mainly as oxyhaemoglobin. In the alveoli where pO_2 is higher, O_2 gets bound to haemoglobin which is easily dissociated at the tissues where pO_2 is low and pCO_2 and H^+ concentration are high. Nearly 70 per cent of carbon dioxide is transported as bicarbonate (HCO_3^-) with the help of the enzyme carbonic anhydrase. 20-25 per cent of carbon dioxide is carried by haemoglobin as carbamino-haemoglobin. In the tissues where pCO_2 is high, it gets bound to blood whereas in the alveoli where pCO_2 is low and pO_2 is high, it gets removed from the blood.

Respiratory rhythm is maintained by the respiratory centre in the medulla region of brain. A pneumotaxic centre in the pons region of the brain and a chemosensitive area in the medulla can alter respiratory mechanism.

EXERCISES

1. Define vital capacity. What is its significance?
2. State the volume of air remaining in the lungs after a normal breathing.
3. Diffusion of gases occurs in the alveolar region only and not in the other parts of respiratory system. Why?
4. What are the major transport mechanisms for CO_2? Explain.
5. What will be the pO_2 and pCO_2 in the atmospheric air compared to those in the alveolar air ?
   (i) pO_2 lesser, pCO_2 higher
   (ii) pO_2 higher, pCO_2 lesser
   (iii) pO_2 higher, pCO_2 higher
   (iv) pO_2 lesser, pCO_2 lesser
6. Explain the process of inspiration under normal conditions.
7. How is respiration regulated?
8. What is the effect of pCO_2 on oxygen transport?
9. What happens to the respiratory process in a man going up a hill?
10. What is the site of gaseous exchange in an insect?
11. Define oxygen dissociation curve. Can you suggest any reason for its sigmoidal pattern?
12. Have you heard about hypoxia? Try to gather information about it, and discuss with your friends.
13. Distinguish between
    (a) IRV and ERV
    (b) Inspiratory capacity and Expiratory capacity.
    (c) Vital capacity and Total lung capacity.
14. What is Tidal volume? Find out the Tidal volume (approximate value) for a healthy human in an hour.

Chapter 18

Body Fluids and Circulation

You have learnt that all living cells have to be provided with nutrients, O_2 and other essential substances. Also, the waste or harmful substances produced, have to be removed continuously for healthy functioning of tissues. It is therefore, essential to have efficient mechanisms for the movement of these substances to the cells and from the cells. Different groups of animals have evolved different methods for this transport. Simple organisms like sponges and coelenterates circulate water from their surroundings through their body cavities to facilitate the cells to exchange these substances. More complex organisms use special fluids within their bodies to transport such materials. **Blood** is the most commonly used body fluid by most of the higher organisms including humans for this purpose. Another body fluid, **lymph,** also helps in the transport of certain substances. In this chapter, you will learn about the composition and properties of blood and lymph (tissue fluid) and the mechanism of circulation of blood is also explained herein.

18.1 Blood

Blood is a special connective tissue consisting of a fluid matrix, plasma, and formed elements.

18.1.1 Plasma

Plasma is a straw coloured, viscous fluid constituting nearly 55 per cent of the blood. 90-92 per cent of plasma is water and proteins contribute 6-8 per cent of it. Fibrinogen, globulins and albumins are the major proteins.

Fibrinogens are needed for clotting or coagulation of blood. Globulins primarly are involved in defense mechanisms of the body and the albumins help in osmotic balance. Plasma also contains small amounts of minerals like Na^+, Ca^{++}, Mg^{++}, HCO_3^-, Cl^-, etc. Glucose, amino acids, lipids, etc., are also present in the plasma as they are always in transit in the body. Factors for coagulation or clotting of blood are also present in the plasma in an inactive form. Plasma without the clotting factors is called serum.

18.1.2 Formed Elements

Erythrocytes, leucocytes and platelets are collectively called formed elements (Figure 18.1) and they constitute nearly 45 per cent of the blood.

Erythrocytes or red blood cells (RBC) are the most abundant of all the cells in blood. A healthy adult man has, on an average, 5 millions to 5.5 millions of RBCs mm^{-3} of blood. RBCs are formed in the red bone marrow in the adults. RBCs are devoid of nucleus in most of the mammals and are biconcave in shape. They have a red coloured, iron containing complex protein called haemoglobin, hence the colour and name of these cells. A healthy individual has 12-16 gms of haemoglobin in every 100 ml of blood. These molecules play a significant role in transport of respiratory gases. RBCs have an average life span of 120 days after which they are destroyed in the spleen (graveyard of RBCs).

Leucocytes are also known as white blood cells (WBC) as they are colourless due to the lack of haemoglobin. They are nucleated and are relatively lesser in number which averages 6000-8000 mm^{-3} of blood. Leucocytes are generally short lived. We have two main categories of WBCs – granulocytes and agranulocytes. Neutrophils, eosinophils and basophils are different types of granulocytes, while lymphocytes and monocytes are the agranulocytes. Neutrophils are the most abundant cells (60-65 per cent) of the total WBCs and basophils are the least (0.5-1 per cent) among them. Neutrophils and monocytes (6-8 per cent) are phagocytic cells which destroy foreign organisms entering the body. Basophils secrete histamine, serotonin, heparin, etc., and are involved in inflammatory reactions. Eosinophils (2-3 per cent) resist infections and are also

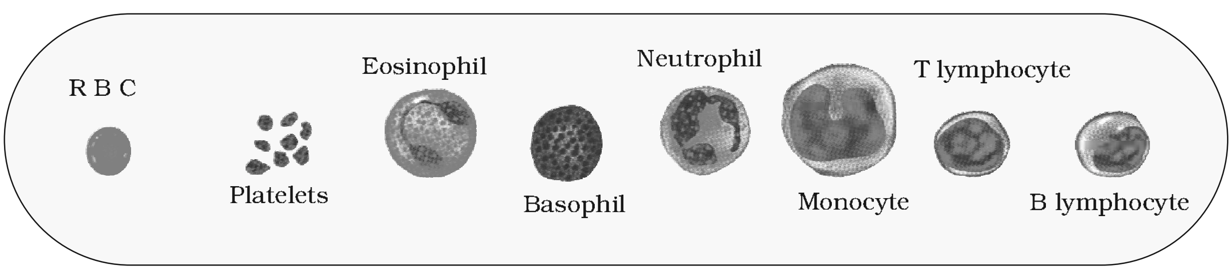


Figure 18.1 Diagrammatic representation of formed elements in blood

associated with allergic reactions. Lymphocytes (20-25 per cent) are of two major types – 'B' and 'T' forms. Both B and T lymphocytes are responsible for immune responses of the body.

Platelets also called **thrombocytes**, are cell fragments produced from megakaryocytes (special cells in the bone marrow). Blood normally contains 1,500,00-3,500,00 platelets mm^{-3}. Platelets can release a variety of substances most of which are involved in the coagulation or clotting of blood. A reduction in their number can lead to clotting disorders which will lead to excessive loss of blood from the body.

18.1.3 Blood Groups

As you know, blood of human beings differ in certain aspects though it appears to be similar. Various types of grouping of blood has been done. Two such groupings – the ABO and Rh – are widely used all over the world.

18.1.3.1 ABO grouping

ABO grouping is based on the presence or absence of two surface antigens (chemicals that can induce immune response) on the RBCs namely A and B. Similarly, the plasma of different individuals contain two natural antibodies (proteins produced in response to antigens). The distribution of antigens and antibodies in the four groups of blood, **A, B, AB** and **O** are given in Table 18.1. You probably know that during blood transfusion, any blood cannot be used; the blood of a donor has to be carefully matched with the blood of a recipient before any blood transfusion to avoid severe problems of clumping (destruction of RBC). The donor's compatibility is also shown in the Table 18.1.

TABLE 18.1 Blood Groups and Donor Compatibility

Blood Group	Antigens on RBCs	Antibodies in Plasma	Donor's Group
A	A	anti-B	A, O
B	B	anti-A	B, O
AB	A, B	nil	AB, A, B, O
O	nil	anti-A, B	O

From the above mentioned table it is evident that group 'O' blood can be donated to persons with any other blood group and hence 'O' group individuals are called 'universal donors'. Persons with 'AB' group can accept blood from persons with AB as well as the other groups of blood. Therefore, such persons are called 'universal recipients'.

18.1.3.2 Rh grouping

Another antigen, the Rh antigen similar to one present in Rhesus monkeys (hence Rh), is also observed on the surface of RBCs of majority (nearly 80 per cent) of humans. Such individuals are called **Rh positive** (Rh+ve) and those in whom this antigen is absent are called **Rh negative** (Rh-ve). An Rh-ve person, if exposed to Rh+ve blood, will form specific antibodies against the Rh antigens. Therefore, Rh group should also be matched before transfusions. A special case of Rh incompatibility (mismatching) has been observed between the Rh-ve blood of a pregnant mother with Rh+ve blood of the foetus. Rh antigens of the foetus do not get exposed to the Rh-ve blood of the mother in the first pregnancy as the two bloods are well separated by the placenta. However, during the delivery of the first child, there is a possibility of exposure of the maternal blood to small amounts of the Rh+ve blood from the foetus. In such cases, the mother starts preparing antibodies against Rh in her blood. In case of her subsequent pregnancies, the Rh antibodies from the mother (Rh-ve) can leak into the blood of the foetus (Rh+ve) and destroy the foetal RBCs. This could be fatal to the foetus or could cause severe anaemia and jaundice to the baby. This condition is called *erythroblastosis foetalis.* This can be avoided by administering anti-Rh antibodies to the mother immediately after the delivery of the first child.

18.1.4 Coagulation of Blood

You know that when you cut your finger or hurt yourself, your wound does not continue to bleed for a long time; usually the blood stops flowing after sometime. *Do you know why?* Blood exhibits coagulation or clotting in response to an injury or trauma. This is a mechanism to prevent excessive loss of blood from the body. You would have observed a dark reddish brown scum formed at the site of a cut or an injury over a period of time. It is a clot or coagulam formed mainly of a network of threads called fibrins in which dead and damaged formed elements of blood are trapped. Fibrins are formed by the conversion of inactive fibrinogens in the plasma by the enzyme thrombin. Thrombins, in turn are formed from another inactive substance present in the plasma called prothrombin. An enzyme complex, thrombokinase, is required for the above reaction. This complex is formed by a series of linked enzymic reactions (cascade process) involving a number of factors present in the plasma in an inactive state. An injury or a trauma stimulates the platelets in the blood to release certain factors which activate the mechanism of coagulation. Certain factors released by the tissues at the site of injury also can initiate coagulation. Calcium ions play a very important role in clotting.

18.2 LYMPH (TISSUE FLUID)

As the blood passes through the capillaries in tissues, some water along with many small water soluble substances move out into the spaces between the cells of tissues leaving the larger proteins and most of the formed elements in the blood vessels. This fluid released out is called the interstitial fluid or tissue fluid. It has the same mineral distribution as that in plasma. Exchange of nutrients, gases, etc., between the blood and the cells always occur through this fluid. An elaborate network of vessels called the lymphatic system collects this fluid and drains it back to the major veins. The fluid present in the lymphatic system is called the lymph. Lymph is a colourless fluid containing specialised lymphocytes which are responsible for the immune responses of the body. Lymph is also an important carrier for nutrients, hormones, etc. Fats are absorbed through lymph in the lacteals present in the intestinal villi.

18.3 CIRCULATORY PATHWAYS

The circulatory patterns are of two types – open or closed. **Open circulatory system** is present in arthropods and molluscs in which blood pumped by the heart passes through large vessels into open spaces or body cavities called sinuses. Annelids and chordates have a **closed circulatory system** in which the blood pumped by the heart is always circulated through a closed network of blood vessels. This pattern is considered to be more advantageous as the flow of fluid can be more precisely regulated.

All vertebrates possess a muscular chambered heart. Fishes have a 2-chambered heart with an atrium and a ventricle. Amphibians and the reptiles (except crocodiles) have a 3-chambered heart with two atria and a single ventricle, whereas crocodiles, birds and mammals possess a 4-chambered heart with two atria and two ventricles. In fishes the heart pumps out deoxygenated blood which is oxygenated by the gills and supplied to the body parts from where deoxygenated blood is returned to the heart (single circulation). In amphibians and reptiles, the left atrium receives oxygenated blood from the gills/lungs/skin and the right atrium gets the deoxygenated blood from other body parts. However, they get mixed up in the single ventricle which pumps out mixed blood (incomplete double circulation). In birds and mammals, oxygenated and deoxygenated blood received by the left and right atria respectively passes on to the ventricles of the same sides. The ventricles pump it out without any mixing up, i.e., two separate circulatory pathways are present in these organisms, hence, these animals have double circulation. Let us study the human circulatory system.

18.3.1 Human Circulatory System

Human circulatory system, also called the blood vascular system consists of a muscular chambered heart, a network of closed branching blood vessels and blood, the fluid which is circulated.

Heart, the mesodermally derived organ, is situated in the thoracic cavity, in between the two lungs, slightly tilted to the left. It has the size of a clenched fist. It is protected by a double walled membranous bag, **pericardium,** enclosing the pericardial fluid. Our heart has four chambers, two relatively small upper chambers called **atria** and two larger lower chambers called **ventricles**. A thin, muscular wall called the inter-atrial septum separates the right and the left atria, whereas a thick-walled, the inter-ventricular septum, separates the left and the right ventricles (Figure 18.2). The atrium and the ventricle of the same side are also separated by a thick fibrous tissue called the atrio-ventricular septum. However, each of these septa are provided with an opening through which the two chambers of the same side are connected. The opening between the right atrium and the right ventricle is guarded by a valve formed of three muscular flaps or cusps, the tricuspid valve, whereas a bicuspid or mitral valve guards the opening between the left atrium and the left ventricle. The openings of the right and the left ventricles into the

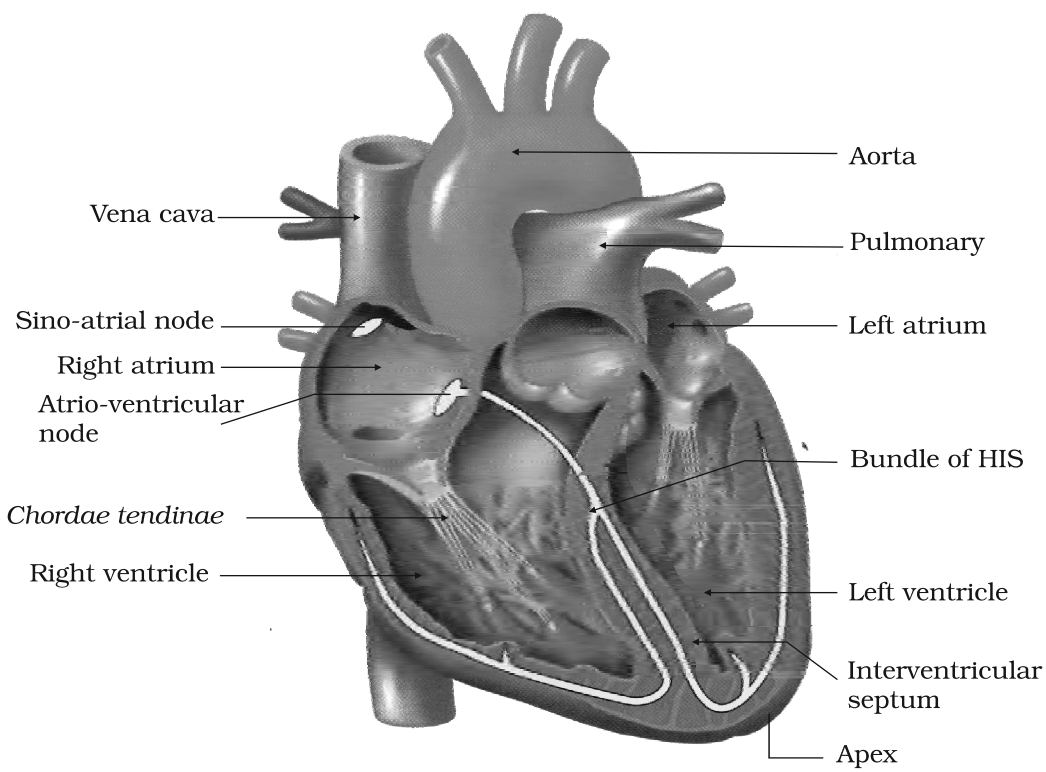


Figure 18.2 Section of a human heart

pulmonary artery and the aorta respectively are provided with the semilunar valves. The valves in the heart allows the flow of blood only in one direction, i.e., from the atria to the ventricles and from the ventricles to the pulmonary artery or aorta. These valves prevent any backward flow.

The entire heart is made of cardiac muscles. The walls of ventricles are much thicker than that of the atria. A specialised cardiac musculature called the nodal tissue is also distributed in the heart (Figure 18.2). A patch of this tissue is present in the right upper corner of the right atrium called the **sino-atrial node** (SAN). Another mass of this tissue is seen in the lower left corner of the right atrium close to the atrio-ventricular septum called the **atrio-ventricular node** (AVN). A bundle of nodal fibres, atrio-ventricular bundle (AV bundle) continues from the AVN which passes through the atrio-ventricular septa to emerge on the top of the inter-ventricular septum and immediately divides into a right and left bundle. These branches give rise to minute fibres throughout the ventricular musculature of the respective sides and are called purkinje fibres. These fibres alongwith right and left bundles are known as bundle of HIS. The nodal musculature has the ability to generate action potentials without any external stimuli, i.e., it is autoexcitable. However, the number of action potentials that could be generated in a minute vary at different parts of the nodal system. The SAN can generate the maximum number of action potentials, i.e., 70-75 min^{-1}, and is responsible for initiating and maintaining the rhythmic contractile activity of the heart. Therefore, it is called the pacemaker. Our heart normally beats 70-75 times in a minute (average 72 beats min^{-1}).

18.3.2 Cardiac Cycle

How does the heart function? Let us take a look. To begin with, all the four chambers of heart are in a relaxed state, i.e., they are in joint diastole. As the tricuspid and bicuspid valves are open, blood from the pulmonary veins and vena cava flows into the left and the right ventricle respectively through the left and right atria. The semilunar valves are closed at this stage. The SAN now generates an action potential which stimulates both the atria to undergo a simultaneous contraction – the atrial systole. This increases the flow of blood into the ventricles by about 30 per cent. The action potential is conducted to the ventricular side by the AVN and AV bundle from where the bundle of HIS transmits it through the entire ventricular musculature. This causes the ventricular muscles to contract, (ventricular systole), the atria undergoes relaxation (diastole), coinciding with the ventricular systole. Ventricular systole increases the ventricular pressure causing the closure of tricuspid and bicuspid valves due to attempted backflow of blood into the atria. As the ventricular pressure increases further, the semilunar valves guarding the pulmonary artery (right side) and the aorta (left side) are forced open, allowing the blood in the ventricles to flow through these vessels into the circulatory pathways. The ventricles now relax (ventricular diastole) and the ventricular pressure falls causing the closure of semilunar valves which prevents the backflow of blood into the ventricles. As the ventricular pressure declines further, the tricuspid and bicuspid valves are pushed open by the pressure in the atria exerted by the blood which was being emptied into them by the veins. The blood now once again moves freely to the ventricles. The ventricles and atria are now again in a relaxed (joint diastole) state, as earlier. Soon the SAN generates a new action potential and the events described above are repeated in that sequence and the process continues.

This sequential event in the heart which is cyclically repeated is called the cardiac cycle and it consists of systole and diastole of both the atria and ventricles. As mentioned earlier, the heart beats 72 times per minute, i.e., that many cardiac cycles are performed per minute. From this it could be deduced that the duration of a cardiac cycle is 0.8 seconds. During a cardiac cycle, each ventricle pumps out approximately 70 mL of blood which is called the stroke volume. The stroke volume multiplied by the heart rate (no. of beats per min.) gives the cardiac output. Therefore, the cardiac output can be defined as the volume of blood pumped out by each ventricle per minute and averages 5000 mL or 5 litres in a healthy individual. The body has the ability to alter the stroke volume as well as the heart rate and thereby the cardiac output. For example, the cardiac output of an athlete will be much higher than that of an ordinary man.

During each cardiac cycle two prominent sounds are produced which can be easily heard through a stethoscope. The first heart sound (lub) is associated with the closure of the tricuspid and bicuspid valves whereas the second heart sound (dub) is associated with the closure of the semilunar valves. These sounds are of clinical diagnostic significance.

18.3.3 Electrocardiograph (ECG)

You are probably familiar with this scene from a typical hospital television show: A patient is hooked up to a monitoring machine that shows voltage traces on a screen and makes the sound "... pip... pip... pip..... peeeeeeeeeeeeeeeeeeeeeee" as the patient goes into cardiac arrest. This type of machine (electro-cardiograph) is used to obtain an electrocardiogram (ECG). ECG is a graphical representation of the electrical activity of the heart during a cardiac cycle. To obtain a standard ECG (as shown in the

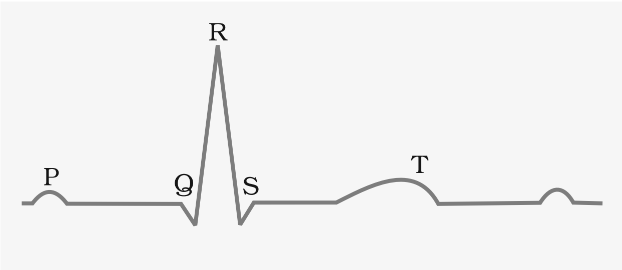


Figure 18.3 Diagrammatic presentation of a standard ECG

Figure 18.3), a patient is connected to the machine with three electrical leads (one to each wrist and to the left ankle) that continuously monitor the heart activity. For a detailed evaluation of the heart's function, multiple leads are attached to the chest region. Here, we will talk only about a standard ECG.

Each peak in the ECG is identified with a letter from P to T that corresponds to a specific electrical activity of the heart.

The P-wave represents the electrical **excitation (or depolarisation) of the atria**, which leads to the contraction of both the atria.

The QRS complex represents the **depolarisation of the ventricles**, which initiates the ventricular contraction. The contraction starts shortly after Q and marks the beginning of the systole.

The T-wave represents the return of the ventricles from excited to normal state (**repolarisation**). The end of the T-wave marks the end of systole.

Obviously, by counting the number of QRS complexes that occur in a given time period, one can determine the heart beat rate of an individual. Since the ECGs obtained from different individuals have roughly the same shape for a given lead configuration, any deviation from this shape indicates a possible abnormality or disease. Hence, it is of a great clinical significance.

18.4 Double Circulation

As mentioned earlier, the blood pumped by the right ventricle enters the pulmonary artery, whereas the left ventricle pumps blood into the aorta. The deoxygenated blood pumped into the pulmonary artery is passed on to the lungs from where the oxygenated blood is carried by the pulmonary veins into the left atrium. This pathway constitutes the pulmonary circulation. The oxygenated blood entering the aorta is carried by a network of arteries, arterioles and capillaries to the tissues from where the deoxygenated blood is collected by a system of venules, veins and vena cava and emptied into the right atrium. This is the systemic circulation (Figure 18.4). The systemic circulation provides nutrients, O_2 and other essential substances to the tissues and takes CO_2 and other harmful substances away for elimination. A unique vascular connection exists between the digestive tract and liver called hepatic portal system. The hepatic portal vein carries blood from intestine to the liver before it is delivered to the systemic circulation. A special coronary system of blood vessels is present in our body exclusively for the circulation of blood to and from the cardiac musculature.

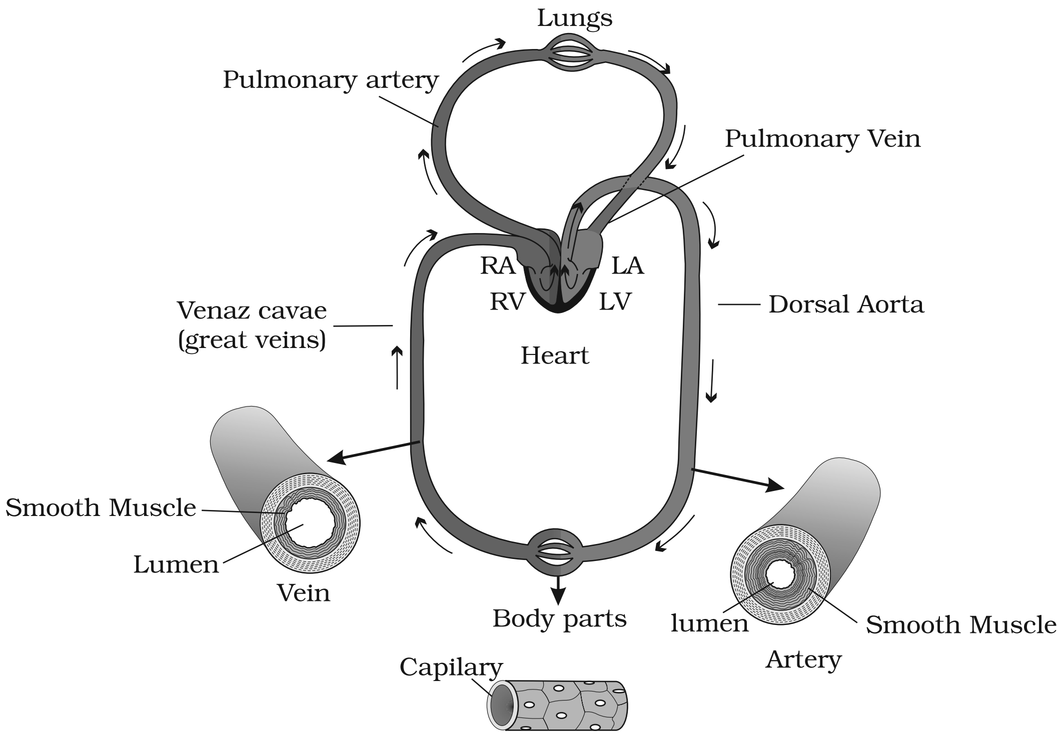


Figure 18.4 Schematic plan of blood circulation in human

18.5 REGULATION OF CARDIAC ACTIVITY

Normal activities of the heart are regulated intrinsically, i.e., auto regulated by specialised muscles (nodal tissue), hence the heart is called myogenic. A special neural centre in the medulla oblangata can moderate the cardiac function through autonomic nervous system (ANS). Neural signals through the sympathetic nerves (part of ANS) can increase the rate of heart beat, the strength of ventricular contraction and thereby the cardiac output. On the other hand, parasympathetic neural signals (another component of ANS) decrease the rate of heart beat, speed of conduction of action potential and thereby the cardiac output. Adrenal medullary hormones can also increase the cardiac output.

18.6 DISORDERS OF CIRCULATORY SYSTEM

High Blood Pressure (Hypertension): Hypertension is the term for blood pressure that is higher than normal (120/80). In this measurement 120 mm Hg (millimetres of mercury pressure) is the systolic, or pumping, pressure and 80 mm Hg is the diastolic, or resting, pressure. If repeated checks of blood pressure of an individual is 140/90 (140 over 90) or higher, it shows hypertension. High blood pressure leads to heart diseases and also affects vital organs like brain and kidney.

Coronary Artery Disease (CAD): Coronary Artery Disease, often referred to as **atherosclerosis**, affects the vessels that supply blood to the heart muscle. It is caused by deposits of calcium, fat, cholesterol and fibrous tissues, which makes the lumen of arteries narrower.

Angina: It is also called 'angina pectoris'. A symptom of acute chest pain appears when no enough oxygen is reaching the heart muscle. Angina can occur in men and women of any age but it is more common among the middle-aged and elderly. It occurs due to conditions that affect the blood flow.

Heart Failure: Heart failure means the state of heart when it is not pumping blood effectively enough to meet the needs of the body. It is sometimes called congestive heart failure because congestion of the lungs is one of the main symptoms of this disease. Heart failure is not the same as cardiac arrest (when the heart stops beating) or a heart attack (when the heart muscle is suddenly damaged by an inadequate blood supply).

SUMMARY

Vertebrates circulate blood, a fluid connective tissue, in their body, to transport essential substances to the cells and to carry waste substances from there. Another fluid, lymph (tissue fluid) is also used for the transport of certain substances.

Blood comprises of a fluid matrix, plasma and formed elements. Red blood cells (RBCs, erythrocytes), white blood cells (WBCs, leucocytes) and platelets (thrombocytes) constitute the formed elements. Blood of humans are grouped into A, B, AB and O systems based on the presence or absence of two surface antigens, A, B on the RBCs. Another blood grouping is also done based on the presence or absence of another antigen called Rhesus factor (Rh) on the surface of RBCs. The spaces between cells in the tissues contain a fluid derived from blood called tissue fluid. This fluid called lymph is almost similar to blood except for the protein content and the formed elements.

All vertebrates and a few invertebrates have a closed circulatory system. Our circulatory system consists of a muscular pumping organ, heart, a network of vessels and a fluid, blood. Heart has two atria and two ventricles. Cardiac musculature is auto-excitable. Sino-atrial node (SAN) generates the maximum number of action protentials per minute (70-75/min) and therefore, it sets the pace of the activities of the heart. Hence it is called the Pacemaker. The action potential causes the atria and then the ventricles to undergo contraction (systole) followed by their relaxation (diastole). The systole forces the blood to move from the atria to the ventricles and to the pulmonary artery and the aorta. The cardiac cycle is formed by sequential events in the heart which is cyclically repeated and is called the cardiac cycle. A healthy person shows 72 such cycles per minute. About 70 mL of blood is pumped out by each ventricle during a cardiac cycle and it is called the stroke or beat volume. Volume of blood pumped out by each ventricle of

heart per minute is called the cardiac output and it is equal to the product of stroke volume and heart rate (approx 5 litres). The electrical activity of the heart can be recorded from the body surface by using electrocardiograph and the recording is called electrocardiogram (ECG) which is of clinical importance.

We have a complete double circulation, i.e., two circulatory pathways, namely, pulmonary and systemic are present. The pulmonary circulation starts by the pumping of deoxygenated blood by the right ventricle which is carried to the lungs where it is oxygenated and returned to the left atrium. The systemic circulation starts with the pumping of oxygenated blood by the left ventricle to the aorta which is carried to all the body tissues and the deoxygenated blood from there is collected by the veins and returned to the right atrium. Though the heart is autoexcitable, its functions can be moderated by neural and hormonal mechanisms.

EXERCISES

1. Name the components of the formed elements in the blood and mention one major function of each of them.
2. What is the importance of plasma proteins?
3. Match Column I with Column II :

Column I	**Column II**
(a) Eosinophils	(i) Coagulation
(b) RBC	(ii) Universal Recipient
(c) AB Group	(iii) Resist Infections
(d) Platelets	(iv) Contraction of Heart
(e) Systole	(v) Gas transport

4. Why do we consider blood as a connective tissue?
5. What is the difference between lymph and blood?
6. What is meant by double circulation? What is its significance?
7. Write the differences between :
   (a) Blood and Lymph
   (b) Open and Closed system of circulation
   (c) Systole and Diastole
   (d) P-wave and T-wave
8. Describe the evolutionary change in the pattern of heart among the vertebrates.
9. Why do we call our heart myogenic?
10. Sino-atrial node is called the pacemaker of our heart. Why?
11. What is the significance of atrio-ventricular node and atrio-ventricular bundle in the functioning of heart?
12. Define a cardiac cycle and the cardiac output.
13. Explain heart sounds.
14. Draw a standard ECG and explain the different segments in it.

Chapter 19

Excretory Products and their Elimination

Animals accumulate ammonia, urea, uric acid, carbon dioxide, water and ions like Na^+, K^+, Cl^-, phosphate, sulphate, etc., either by metabolic activities or by other means like excess ingestion. These substances have to be removed totally or partially. In this chapter, you will learn the mechanisms of elimination of these substances with special emphasis on common nitrogenous wastes. Ammonia, urea and uric acid are the major forms of nitrogenous wastes excreted by the animals. Ammonia is the most toxic form and requires large amount of water for its elimination, whereas uric acid, being the least toxic, can be removed with a minimum loss of water.

The process of excreting ammonia is *Ammonotelism*. Many bony fishes, aquatic amphibians and aquatic insects are ***ammonotelic*** in nature. Ammonia, as it is readily soluble, is generally excreted by diffusion across body surfaces or through gill surfaces (in fish) as ammonium ions. Kidneys do not play any significant role in its removal. Terrestrial adaptation necessitated the production of lesser toxic nitrogenous wastes like urea and uric acid for conservation of water. Mammals, many terrestrial amphibians and marine fishes mainly excrete urea and are called ***ureotelic*** animals. Ammonia produced by metabolism is converted into urea in the liver of these animals and released into the blood which is filtered and excreted out by the kidneys. Some amount of urea may be retained in the kidney matrix of some of these animals to maintain a desired osmolarity. Reptiles, birds, land snails and insects excrete nitrogenous wastes as uric acid in the form of pellet or paste with a minimum loss of water and are called ***uricotelic*** animals.

A survey of animal kingdom presents a variety of excretory structures. In most of the invertebrates, these structures are simple tubular forms whereas vertebrates have complex tubular organs called kidneys. Some of these structures are mentioned here. Protonephridia or flame cells are the excretory structures in Platyhelminthes (Flatworms, e.g., *Planaria*), rotifers, some annelids and the cephalochordate – *Amphioxus*. Protonephridia are primarily concerned with ionic and fluid volume regulation, i.e., osmoregulation. Nephridia are the tubular excretory structures of earthworms and other annelids. Nephridia help to remove nitrogenous wastes and maintain a fluid and ionic balance. Malpighian tubules are the excretory structures of most of the insects including cockroaches. Malpighian tubules help in the removal of nitrogenous wastes and osmoregulation. Antennal glands or green glands perform the excretory function in crustaceans like prawns.

19.1 HUMAN EXCRETORY SYSTEM

In humans, the excretory system consists of a pair of kidneys, one pair of ureters, a urinary bladder and a urethra (Figure 19.1). Kidneys are reddish brown, bean shaped structures situated between the levels of last thoracic and third lumbar vertebra close to the dorsal inner wall of the abdominal cavity. Each kidney of an adult human measures 10-12 cm in length, 5-7 cm in width, 2-3 cm in thickness with an average weight of 120-170 g. Towards the centre of the inner concave surface of the kidney is a notch called hilum through which ureter, blood vessels and nerves enter. Inner to the hilum is a broad funnel shaped space called the renal pelvis with projections called calyces. The outer layer of kidney is a tough capsule. Inside the kidney, there are two zones, an outer *cortex* and an inner *medulla*. The medulla is divided into a few conical masses (medullary pyramids) projecting into the calyces (sing.: calyx). The cortex extends in between the

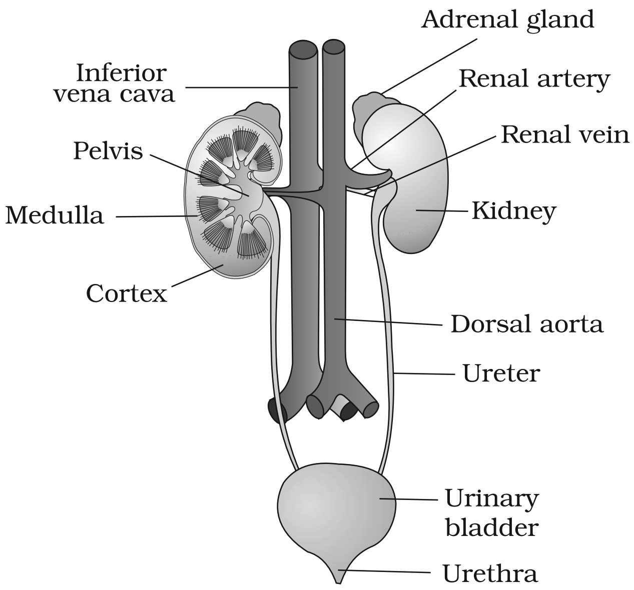


Figure 19.1 Human Urinary system

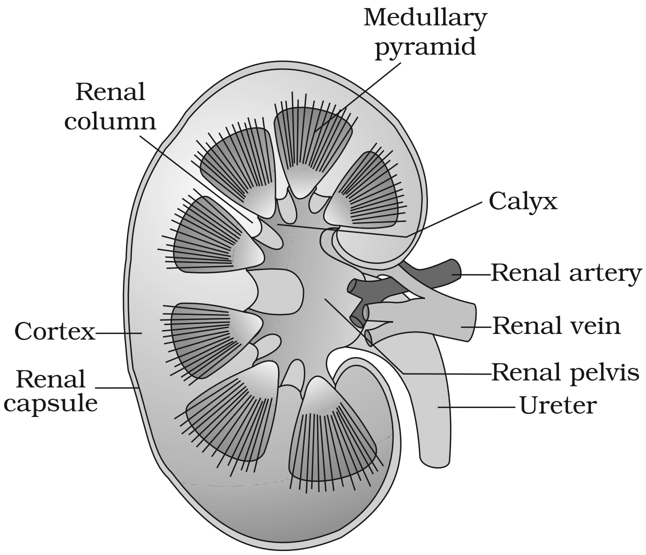


Figure 19.2 Longitudinal section (Diagrammatic) of Kidney

medullary pyramids as renal columns called **Columns of Bertini** (Figure 19.2).

Each kidney has nearly one million complex tubular structures called **nephrons** (Figure 19.3), which are the functional units. Each nephron has two parts – the glomerulus and the renal tubule. Glomerulus is a tuft of capillaries formed by the afferent arteriole – a fine branch of renal artery. Blood from the glomerulus is carried away by an efferent arteriole.

The renal tubule begins with a double walled cup-like structure called **Bowman's capsule**, which encloses the glomerulus. Glomerulus alongwith Bowman's capsule, is called the *malpighian body* or *renal corpuscle* (Figure 19.4). The tubule continues further to form a highly coiled network – **proximal convoluted tubule**

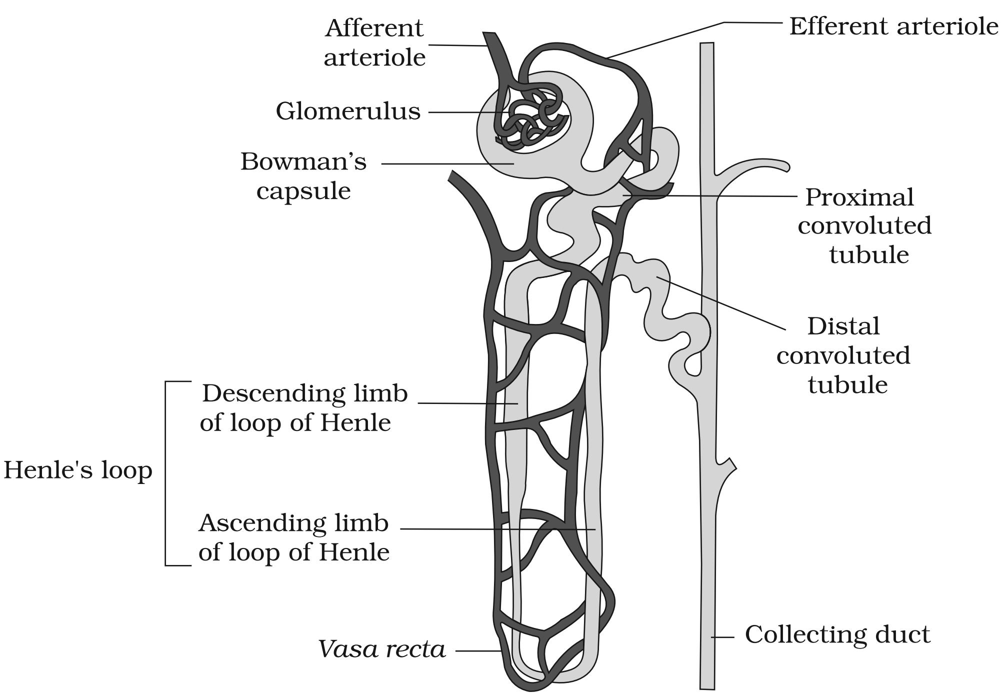


Figure 19.3 A diagrammatic representation of a nephron showing blood vessels, duct and tubule

(PCT). A hairpin shaped **Henle's loop** is the next part of the tubule which has a descending and an ascending limb. The ascending limb continues as another highly coiled tubular region called **distal convoluted tubule** (DCT). The DCTs of many nephrons open into a straight tube called *collecting duct*, many of which converge and open into the renal pelvis through medullary pyramids in the calyces.

The Malpighian corpuscle, PCT and DCT of the nephron are situated in the cortical region of the kidney whereas the loop of Henle dips into the medulla. In majority of nephrons, the loop of Henle is too short and extends only very little into the medulla. Such nephrons are called cortical nephrons. In some of the nephrons, the loop of Henle is very long and runs deep into the medulla. These nephrons are called juxta medullary nephrons.

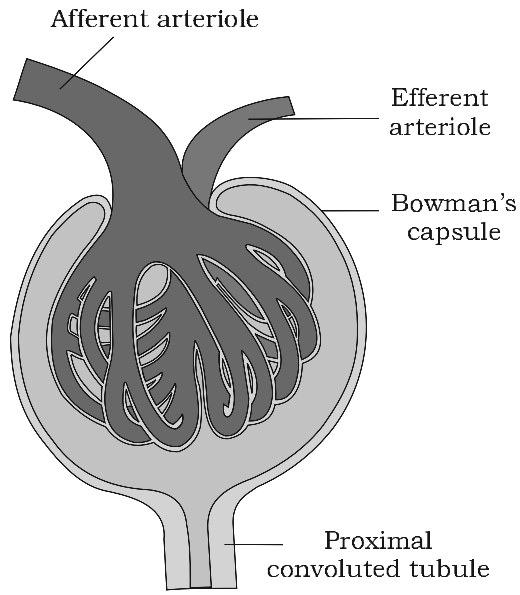


Figure 19.4 Malpighian body (renal corpuscle)

The efferent arteriole emerging from the glomerulus forms a fine capillary network around the renal tubule called the peritubular capillaries. A minute vessel of this network runs parallel to the Henle's loop forming a 'U' shaped *vasa recta*. *Vasa recta* is absent or highly reduced in cortical nephrons.

19.2 URINE FORMATION

Urine formation involves three main processes namely, glomerular filtration, reabsorption and secretion, that takes place in different parts of the nephron.

The first step in urine formation is the filtration of blood, which is carried out by the glomerulus and is called **glomerular filtration**. On an average, 1100-1200 ml of blood is filtered by the kidneys per minute which constitute roughly $1/5^{th}$ of the blood pumped out by each ventricle of the heart in a minute. The glomerular capillary blood pressure causes filtration of blood through 3 layers, i.e., the endothelium of glomerular blood vessels, the epithelium of Bowman's capsule and a basement membrane between these two layers. The epithelial cells of Bowman's capsule called podocytes are arranged in an intricate manner so as to leave some minute spaces called filtration slits or slit pores. Blood is filtered so finely through these membranes, that almost all the constituents of the plasma except the proteins pass onto the lumen of the Bowman's capsule. Therefore, it is considered as a process of **ultra filtration.**

The amount of the filtrate formed by the kidneys per minute is called **glomerular filtration rate** (GFR). GFR in a healthy individual is approximately 125 ml/minute, i.e., 180 litres per day !

The kidneys have built-in mechanisms for the regulation of glomerular filtration rate. One such efficient mechanism is carried out by juxta glomerular apparatus (JGA). JGA is a special sensitive region formed by cellular modifications in the distal convoluted tubule and the afferent arteriole at the location of their contact. A fall in GFR can activate the JG cells to release renin which can stimulate the glomerular blood flow and thereby the GFR back to normal.

A comparison of the volume of the filtrate formed per day (180 litres per day) with that of the urine released (1.5 litres), suggest that nearly 99 per cent of the filtrate has to be reabsorbed by the renal tubules. This process is called **reabsorption**. The tubular epithelial cells in different segments of nephron perform this either by active or passive mechanisms. For example, substances like glucose, amino acids, Na^+, etc., in the filtrate are reabsorbed actively whereas the nitrogenous wastes are absorbed by passive transport. Reabsorption of water also occurs passively in the initial segments of the nephron (Figure 19.5).

During urine formation, the tubular cells secrete substances like H^+, K^+ and ammonia into the filtrate. Tubular secretion is also an important step in urine formation as it helps in the maintenance of ionic and acid base balance of body fluids.

19.3 Function of the Tubules

Proximal Convoluted Tubule (PCT): PCT is lined by simple cuboidal brush border epithelium which increases the surface area for reabsorption. Nearly all of the essential nutrients, and 70-80 per cent of electrolytes and water are reabsorbed by this segment. PCT also helps to maintain the pH and ionic balance of the body fluids by selective secretion of hydrogen ions, ammonia and potassium ions into the filtrate and by absorption of HCO_3^- from it.

Henle's Loop: Reabsorption in this segment is minimum. However, this region plays a significant role in the maintenance of high osmolarity of medullary interstitial fluid. The descending limb of loop of Henle is permeable to water but almost impermeable to electrolytes. This concentrates the filtrate as it moves down. The ascending limb is impermeable to water but allows transport of electrolytes actively or passively. Therefore, as the concentrated filtrate pass upward, it gets diluted due to the passage of electrolytes to the medullary fluid.

Distal Convoluted Tubule (DCT): Conditional reabsorption of Na^+ and water takes place in this segment. DCT is also capable of reabsorption of HCO_3^- and selective secretion of hydrogen and potassium ions and NH_3 to maintain the pH and sodium-potassium balance in blood.

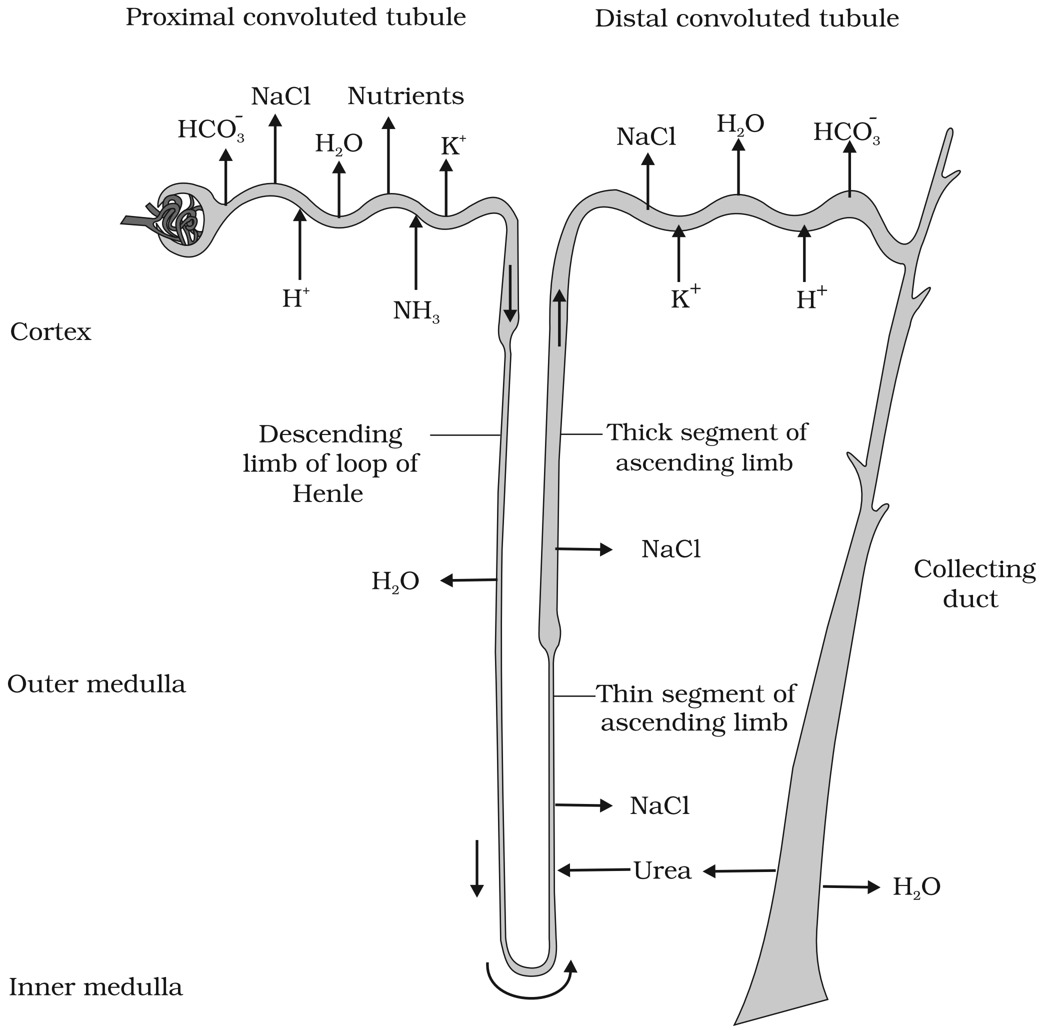


Figure 19.5 Reabsorption and secretion of major substances at different parts of the nephron (Arrows indicate direction of movement of materials.)

Collecting Duct: This long duct extends from the cortex of the kidney to the inner parts of the medulla. Large amounts of water could be reabsorbed from this region to produce a concentrated urine. This segment allows passage of small amounts of urea into the medullary interstitium to keep up the osmolarity. It also plays a role in the maintenance of pH and ionic balance of blood by the selective secretion of H^+ and K^+ ions (Figure 19.5).

19.4 MECHANISM OF CONCENTRATION OF THE FILTRATE

Mammals have the ability to produce a concentrated urine. The Henle's loop and *vasa recta* play a significant role in this. The flow of filtrate in the two limbs of Henle's loop is in opposite directions and thus forms a counter current. The flow of blood through the two limbs of *vasa recta* is also in a counter current pattern. The proximity between the Henle's loop and *vasa recta*, as well as the counter current in them help in maintaining an increasing osmolarity towards the inner medullary interstitium, i.e., from 300 $mOsmolL^{-1}$ in the cortex to about 1200 $mOsmolL^{-1}$ in the inner medulla. This gradient is mainly caused by NaCl and urea. NaCl is transported by the ascending limb of Henle's loop which is exchanged with the descending limb of *vasa recta*. NaCl is returned to the interstitium by the ascending portion of *vasa recta*. Similarly, small amounts of urea enter the thin segment of the ascending limb of Henle's loop which is transported back to the interstitium by the collecting tubule. The above described transport of substances facilitated by the special arrangement of Henle's loop and *vasa recta* is called the **counter current mechanism** (Figure. 19.6). This mechanism helps to maintain a concentration gradient

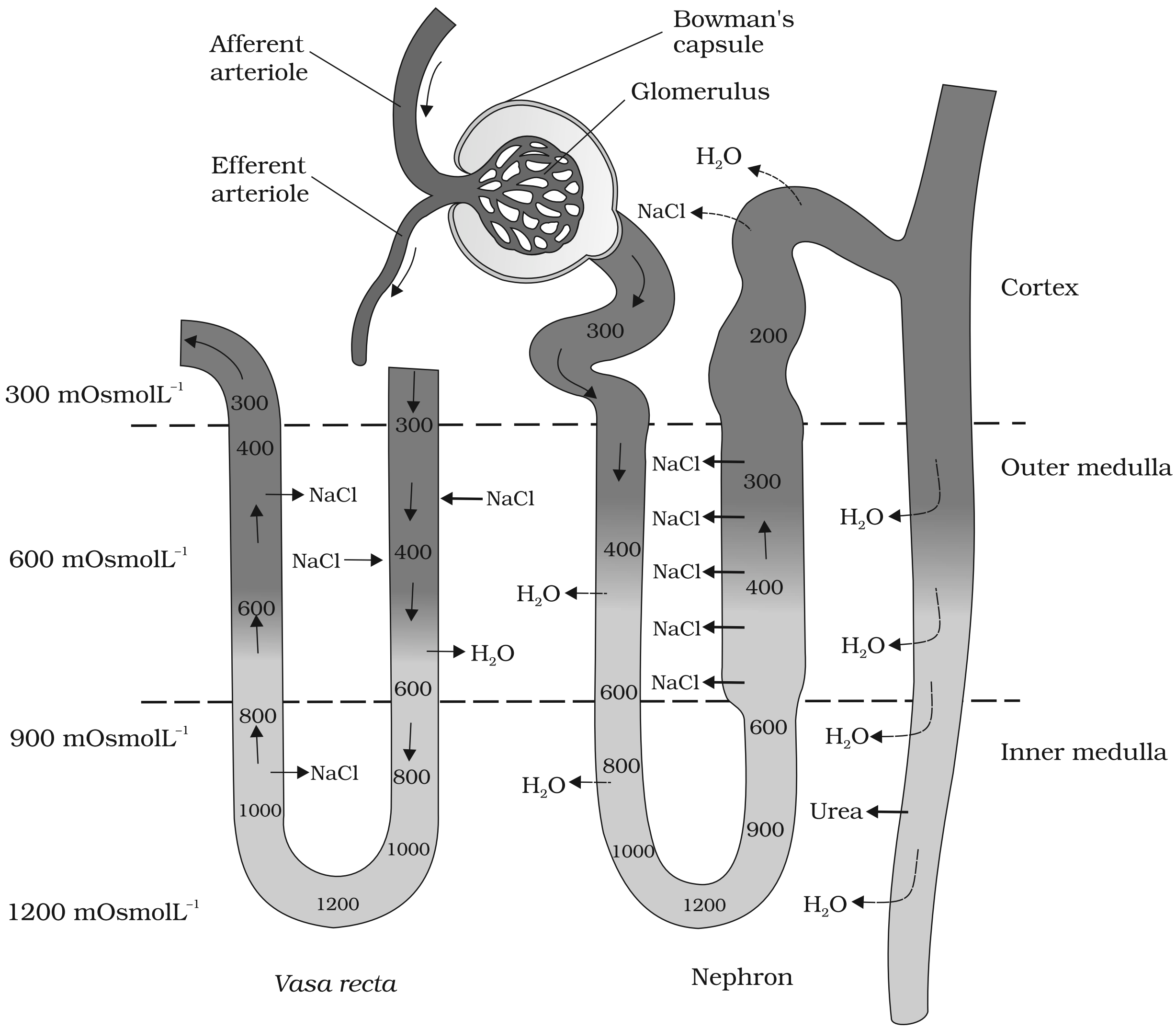


Figure 19.6 Diagrammatic representation of a nephron and *vasa recta* showing counter current mechanisms

in the medullary interstitium. Presence of such interstitial gradient helps in an easy passage of water from the collecting tubule thereby concentrating the filtrate (urine). Human kidneys can produce urine nearly four times concentrated than the initial filtrate formed.

19.5 REGULATION OF KIDNEY FUNCTION

The functioning of the kidneys is efficiently monitored and regulated by hormonal feedback mechanisms involving the hypothalamus, JGA and to a certain extent, the heart.

Osmoreceptors in the body are activated by changes in blood volume, body fluid volume and ionic concentration. An excessive loss of fluid from the body can activate these receptors which stimulate the hypothalamus to release antidiuretic hormone (ADH) or vasopressin from the neurohypophysis. ADH facilitates water reabsorption from latter parts of the tubule, thereby preventing diuresis. An increase in body fluid volume can switch off the osmoreceptors and suppress the ADH release to complete the feedback. ADH can also affect the kidney function by its constrictory effects on blood vessels. This causes an increase in blood pressure. An increase in blood pressure can increase the glomerular blood flow and thereby the GFR.

The JGA plays a complex regulatory role. A fall in glomerular blood flow/glomerular blood pressure/GFR can activate the JG cells to release **renin** which converts angiotensinogen in blood to angiotensin I and further to angiotensin II. Angiotensin II, being a powerful vasoconstrictor, increases the glomerular blood pressure and thereby GFR. Angiotensin II also activates the adrenal cortex to release Aldosterone. Aldosterone causes reabsorption of Na^+ and water from the distal parts of the tubule. This also leads to an increase in blood pressure and GFR. This complex mechanism is generally known as the **Renin-Angiotensin** mechanism.

An increase in blood flow to the atria of the heart can cause the release of **Atrial Natriuretic Factor** (ANF). ANF can cause vasodilation (dilation of blood vessels) and thereby decrease the blood pressure. ANF mechanism, therefore, acts as a check on the renin-angiotensin mechanism.

19.6 MICTURITION

Urine formed by the nephrons is ultimately carried to the urinary bladder where it is stored till a voluntary signal is given by the central nervous system (CNS). This signal is initiated by the stretching of the urinary bladder as it gets filled with urine. In response, the stretch receptors on the walls of the bladder send signals to the CNS. The CNS passes on motor messages to initiate the contraction of smooth muscles of the bladder and simultaneous relaxation of the urethral sphincter causing the release of urine. The process of release of urine is called micturition and the neural mechanisms causing it is called the micturition reflex. An adult human excretes, on an average, 1 to 1.5 litres of urine per day. The urine formed is a light yellow coloured watery fluid which is slightly acidic (pH-6.0) and has a characterestic odour. On an average, 25-30 gm of urea is excreted out per day. Various conditions can affect the characteristics of urine. Analysis of urine helps in clinical diagnosis of many metabolic discorders as well as malfunctioning of the kidney. For example, presence of glucose (Glycosuria) and ketone bodies (Ketonuria) in urine are indicative of diabetes mellitus.

19.7 Role of other Organs in Excretion

Other than the kidneys, lungs, liver and skin also help in the elimination of excretory wastes.

Our lungs remove large amounts of CO_2 (18 litres/day) and also significant quantities of water every day. Liver, the largest gland in our body, secretes bile-containing substances like bilirubin, biliverdin, cholesterol, degraded steroid hormones, vitamins and drugs. Most of these substances ultimately pass out alongwith digestive wastes.

The sweat and sebaceous glands in the skin can eliminate certain substances through their secretions. Sweat produced by the sweat glands is a watery fluid containing NaCl, small amounts of urea, lactic acid, etc. Though the primary function of sweat is to facilitate a cooling effect on the body surface, it also helps in the removal of some of the wastes mentioned above. Sebaceous glands eliminate certain substances like sterols, hydrocarbons and waxes through sebum. This secretion provides a protective oily covering for the skin. Do you know that small amounts of nitrogenous wastes could be eliminated through saliva too?

19.8 Disorders of the Excretory System

Malfunctioning of kidneys can lead to accumulation of urea in blood, a condition called **uremia**, which is highly harmful and may lead to kidney failure. In such patients, urea can be removed by a process called **hemodialysis**. Blood drained from a convenient artery is pumped into a dialysing unit after adding an anticoagulant like heparin. The unit contains a coiled cellophane tube surrounded by a fluid (dialysing fluid) having the same composition as that of plasma except the nitrogenous wastes. The porous cellophane membrance of the tube allows the passage of molecules based on concentration gradient. As nitrogenous wastes are absent in the dialysing fluid, these substances freely move out, thereby clearing the blood. The cleared blood is pumped back to the body through a vein after adding anti-heparin to it. This method is a boon for thousands of uremic patients all over the world.

Kidney transplantation is the ultimate method in the correction of acute **renal failures** (kidney failure). A functioning kidney is used in transplantation from a donor, preferably a close relative, to minimise its chances of rejection by the immune system of the host. Modern clinical procedures have increased the success rate of such a complicated technique.

Renal calculi: Stone or insoluble mass of crystallised salts (oxalates, etc.) formed within the kidney.

Glomerulonephritis: Inflammation of glomeruli of kidney.

SUMMARY

Many nitrogen containing substances, ions, CO_2, water, etc., that accumulate in the body have to be eliminated. Nature of nitrogenous wastes formed and their excretion vary among animals, mainly depending on the habitat (availability of water). Ammonia, urea and uric acid are the major nitrogenous wastes excreted.

Protonephridia, nephridia, malpighian tubules, green glands and the kidneys are the common excretory organs in animals. They not only eliminate nitrogenous wastes but also help in the maintenance of ionic and acid-base balance of body fluids.

In humans, the excretory system consists of one pair of kidneys, a pair of ureters, a urinary bladder and a urethra. Each kidney has over a million tubular structures called nephrons. Nephron is the functional unit of kidney and has two portions – glomerulus and renal tubule. Glomerulus is a tuft of capillaries formed from afferent arterioles, fine branches of renal artery. The renal tubule starts with a double walled Bowman's capsule and is further differentiated into a proximal convoluted tubule (PCT), Henle's loop (HL) and distal convoluted tubule (DCT). The DCTs of many nephrons join to a common collecting duct many of which ultimately open into the renal pelvis through the medullary pyramids. The Bowman's capsule encloses the glomerulus to form Malpighian or renal corpuscle.

Urine formation involves three main processes, i.e., filtration, reabsorption and secretion. Filtration is a non-selective process performed by the glomerulus using the glomerular capillary blood pressure. About 1200 ml of blood is filtered by the

glomerulus per minute to form 125 ml of filtrate in the Bowman's capsule per minute (GFR). JGA, a specialised portion of the nephrons, plays a significant role in the regulation of GFR. Nearly 99 per cent reabsorption of the filtrate takes place through different parts of the nephrons. PCT is the major site of reabsorption and selective secretion. HL primarily helps to maintain osmolar gradient (300 mOsmolL^{-1} -1200 mOsmolL^{-1}) within the kidney interstitium. DCT and collecting duct allow extensive reabsorption of water and certain electrolytes, which help in osmoregulation: H^+, K^+ and NH_3 could be secreted into the filtrate by the tubules to maintain the ionic balance and pH of body fluids.

A counter current mechanism operates between the two limbs of the loop of Henle and those of *vasa recta* (capillary parallel to Henle's loop). The filtrate gets concentrated as it moves down the descending limb but is diluted by the ascending limb. Electrolytes and urea are retained in the interstitium by this arrangement. DCT and collecting duct concentrate the filtrate about four times, i.e., from 300 mOsmolL^{-1} to 1200 mOsmolL^{-1}, an excellent mechanism of conservation of water. Urine is stored in the urinary bladder till a voluntary signal from CNS carries out its release through urethra, i.e., micturition. Skin, lungs and liver also assist in excretion.

EXERCISES

1. Define Glomerular Filtration Rate (GFR)
2. Explain the autoregulatory mechanism of GFR.
3. Indicate whether the following statements are true or false :
   (a) Micturition is carried out by a reflex.
   (b) ADH helps in water elimination, making the urine hypotonic.
   (c) Protein-free fluid is filtered from blood plasma into the Bowman's capsule.
   (d) Henle's loop plays an important role in concentrating the urine.
   (e) Glucose is actively reabsorbed in the proximal convoluted tubule.
4. Give a brief account of the counter current mechanism.
5. Describe the role of liver, lungs and skin in excretion.
6. Explain micturition.
7. Match the items of column I with those of column II :

Column I	Column II
(a) Ammonotelism	(i) Birds
(b) Bowman's capsule	(ii) Water reabsorption
(c) Micturition	(iii) Bony fish
(d) Uricotelism	(iv) Urinary bladder
(d) ADH	(v) Renal tubule

8. What is meant by the term osmoregulation?
9. Terrestrial animals are generally either ureotelic or uricotelic, not ammonotelic, why ?
10. What is the significance of juxta glomerular apparatus (JGA) in kidney function?
11. Name the following:
    (a) A chordate animal having flame cells as excretory structures
    (b) Cortical portions projecting between the medullary pyramids in the human kidney
    (c) A loop of capillary running parallel to the Henle's loop.
12. Fill in the gaps :
    (a) Ascending limb of Henle's loop is _______ to water whereas the descending limb is _______ to it.
    (b) Reabsorption of water from distal parts of the tubules is facilitated by hormone _______.
    (c) Dialysis fluid contain all the constituents as in plasma except _______.
    (d) A healthy adult human excretes (on an average) _______ gm of urea/day.

Chapter 20

Locomotion and Movement

Movement is one of the significant features of living beings. Animals and plants exhibit a wide range of movements. Streaming of protoplasm in the unicellular organisms like *Amoeba* is a simple form of movement. Movement of cilia, flagella and tentacles are shown by many organisms. Human beings can move limbs, jaws, eyelids, tongue, etc. Some of the movements result in a change of place or location. Such voluntary movements are called **locomotion**. Walking, running, climbing, flying, swimming are all some forms of locomotory movements. Locomotory structures need not be different from those affecting other types of movements. For example, in *Paramoecium*, cilia helps in the movement of food through cytopharynx and in locomotion as well. *Hydra* can use its tentacles for capturing its prey and also use them for locomotion. We use limbs for changes in body postures and locomotion as well. The above observations suggest that movements and locomotion cannot be studied separately. The two may be linked by stating that all locomotions are movements but all movements are not locomotions.

Methods of locomotion performed by animals vary with their habitats and the demand of the situation. However, locomotion is generally for search of food, shelter, mate, suitable breeding grounds, favourable climatic conditions or to escape from enemies/predators.

20.1 Types of Movement

Cells of the human body exhibit three main types of movements, namely, amoeboid, ciliary and muscular.

Some specialised cells in our body like macrophages and leucocytes in blood exhibit amoeboid movement. It is effected by pseudopodia formed by the streaming of protoplasm (as in *Amoeba*). Cytoskeletal elements like microfilaments are also involved in amoeboid movement.

Ciliary movement occurs in most of our internal tubular organs which are lined by ciliated epithelium. The coordinated movements of cilia in the trachea help us in removing dust particles and some of the foreign substances inhaled alongwith the atmospheric air. Passage of ova through the female reproductive tract is also facilitated by the ciliary movement.

Movement of our limbs, jaws, tongue, etc, require muscular movement. The contractile property of muscles are effectively used for locomotion and other movements by human beings and majority of multicellular organisms. Locomotion requires a perfect coordinated activity of muscular, skeletal and neural systems. In this chapter, you will learn about the types of muscles, their structure, mechanism of their contraction and important aspects of the skeletal system.

20.2 MUSCLE

Muscle is a specialised tissue of mesodermal origin. About 40-50 per cent of the body weight of a human adult is contributed by muscles. They have special properties like excitability, contractility, extensibility and elasticity. Muscles have been classified using different criteria, namely location, appearance and nature of regulation of their activities. Based on their location, three types of muscles are identified : (i) Skeletal (ii) Visceral and (iii) Cardiac.

Skeletal muscles are closely associated with the skeletal components of the body. They have a striped appearance under the microscope and hence are called **striated muscles**. As their activities are under the voluntary control of the nervous system, they are known as voluntary muscles too. They are primarily involved in locomotory actions and changes of body postures.

Visceral muscles are located in the inner walls of hollow visceral organs of the body like the alimentary canal, reproductive tract, etc. They do not exhibit any striation and are smooth in appearance. Hence, they are called **smooth muscles (nonstriated muscle)**. Their activities are not under the voluntary control of the nervous system and are therefore known as involuntary muscles. They assist, for example, in the transportation of food through the digestive tract and gametes through the genital tract.

As the name suggests, **Cardiac muscles** are the muscles of heart. Many cardiac muscle cells assemble in a branching pattern to form a cardiac muscle. Based on appearance, cardiac muscles are striated. They are involuntary in nature as the nervous system does not control their activities directly.

Let us examine a skeletal muscle in detail to understand the structure and mechanism of contraction. Each organised skeletal muscle in our body is made of a number of **muscle bundles** or **fascicles** held together by a common collagenous connective tissue layer called **fascia**. Each muscle bundle contains a number of muscle fibres (Figure 20.1). Each

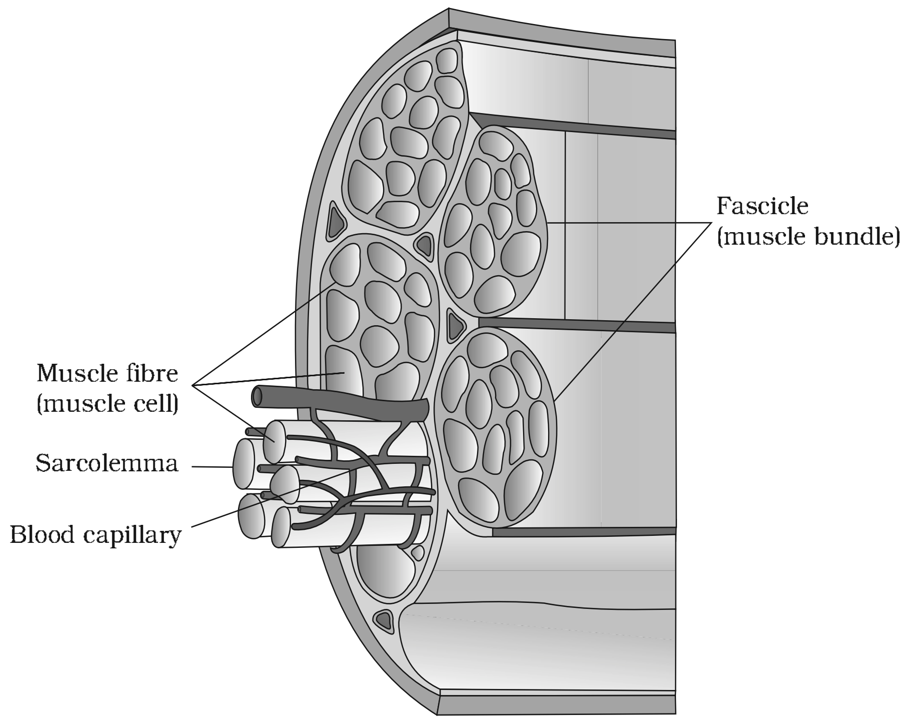


Figure 20.1 Diagrammatic cross sectional view of a muscle showing muscle bundles and muscle fibres

muscle fibre is lined by the plasma membrane called sarcolemma enclosing the sarcoplasm. Muscle fibre is a syncitium as the sarcoplasm contains many nuclei. The endoplasmic reticulum, i.e., sarcoplasmic reticulum of the muscle fibres is the store house of calcium ions. A characteristic feature of the muscle fibre is the presence of a large number of parallelly arranged filaments in the sarcoplasm called myofilaments or **myofibrils**. Each myofibril has alternate dark and light bands on it. A detailed study of the myofibril has established that the striated appearance is due to the distribution pattern of two important proteins – **Actin** and **Myosin**. The light bands contain actin and is called I-band or Isotropic band, whereas the dark band called 'A' or Anisotropic band contains myosin. Both the proteins are arranged as rod-like structures, parallel to each other and also to the longitudinal axis of the myofibrils. Actin filaments are thinner as compared to the myosin filaments, hence are commonly called thin and thick filaments respectively. In the centre of each 'I' band is an elastic fibre called 'Z' line which bisects it. The thin filaments are firmly attached to the 'Z' line. The thick filaments in the 'A' band are also held together in the middle of this band by a thin fibrous membrane called 'M' line. The 'A' and 'I' bands are arranged alternately throughout the length of the myofibrils. The portion of the myofibril between two successive 'Z' lines is considered as the functional unit of contraction and is called a sarcomere (Figure 20.2). In a resting state, the edges of thin filaments on either side of the thick filaments partially overlap the free ends of the thick filaments leaving the central part of the thick filaments. This central part of thick filament, not overlapped by thin filaments is called the 'H' zone.

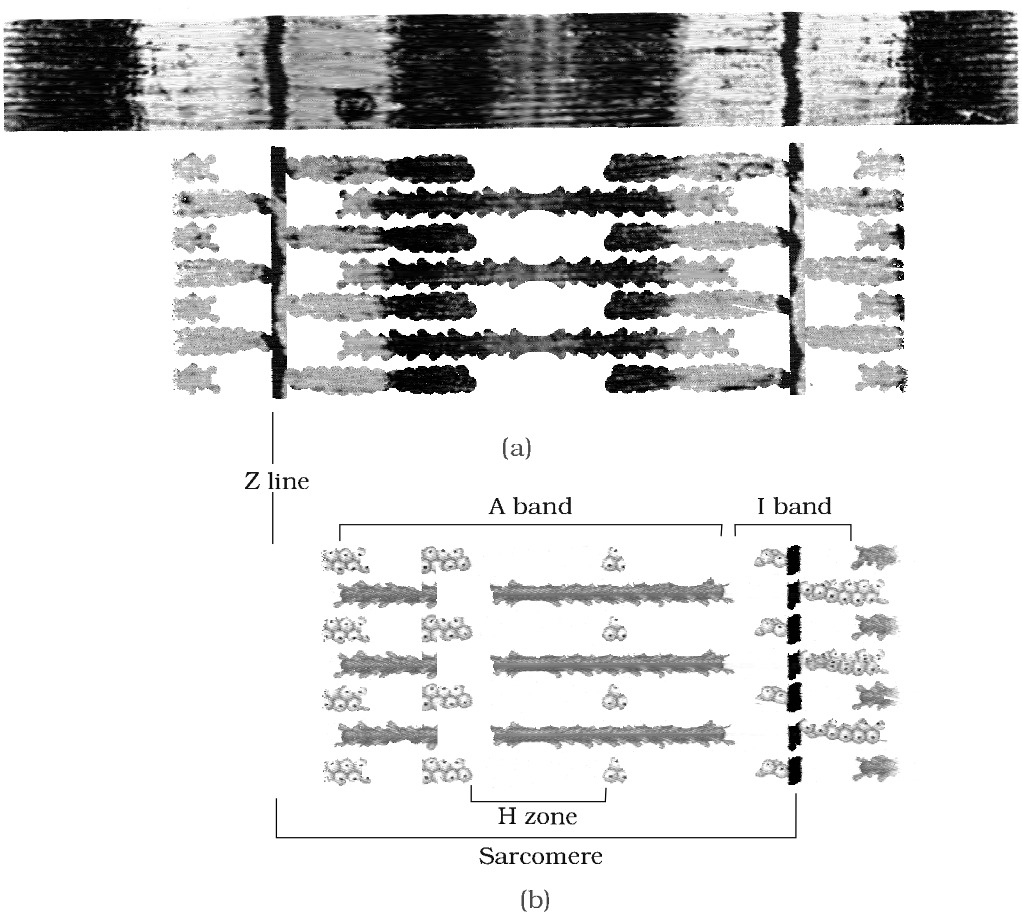
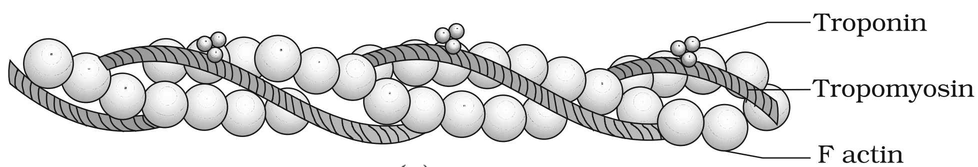


Figure 20.2 Diagrammatic representation of (a) anatomy of a muscle fibre showing a sarcomere (b) a sarcomere

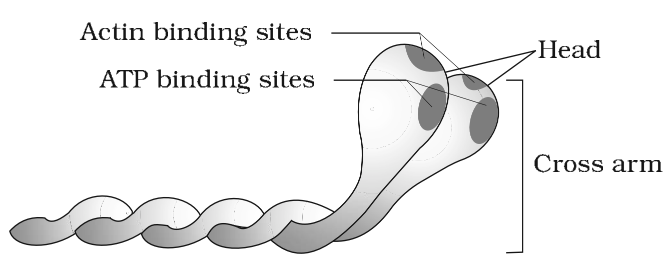
20.2.1 Structure of Contractile Proteins

Each actin (thin) filament is made of two 'F' (filamentous) actins helically wound to each other. Each 'F' actin is a polymer of monomeric 'G' (Globular) actins. Two filaments of another protein, tropomyosin also run close to the 'F' actins throughout its length. A complex protein Troponin is distributed at regular intervals on the tropomyosin. In the resting state a subunit of troponin masks the active binding sites for myosin on the actin filaments (Figure 20.3a).

Each myosin (thick) filament is also a polymerised protein. Many monomeric proteins called Meromyosins (Figure 20.3b) constitute one thick filament. Each meromyosin has two important parts, a globular head with a short arm and a tail, the former being called the heavy meromyosin (HMM) and the latter, the light meromyosin (LMM). The HMM component, i.e.; the head and short arm projects outwards at regular distance and angle from each other from the surface of a polymerised myosin filament and is known as cross arm. The globular head is an active ATPase enzyme and has binding sites for ATP and active sites for actin.



(a)



(b)

Figure 20.3 (a) An actin (thin) filament (b) Myosin monomer (Meromyosin)

20.2.2 Mechanism of Muscle Contraction

Mechanism of muscle contraction is best explained by the sliding filament theory which states that contraction of a muscle fibre takes place by the sliding of the thin filaments over the thick filaments.

Muscle contraction is initiated by a signal sent by the central nervous system (CNS) via a motor neuron. A motor neuron alongwith the muscle fibres connected to it constitute a motor unit. The junction between a motor neuron and the sarcolemma of the muscle fibre is called the neuromuscular junction or motor-end plate. A neural signal reaching this junction releases a neurotransmitter (Acetyl choline) which generates an action potential in the sarcolemma. This spreads through the muscle fibre and causes the release of calcium ions into the sarcoplasm. Increase in Ca^{++} level leads to the binding of calcium with a subunit of troponin on actin filaments and thereby remove the masking of active sites for myosin. Utilising the energy from ATP hydrolysis, the myosin head now binds to the exposed active sites on actin to form a cross bridge (Figure 20.4). This

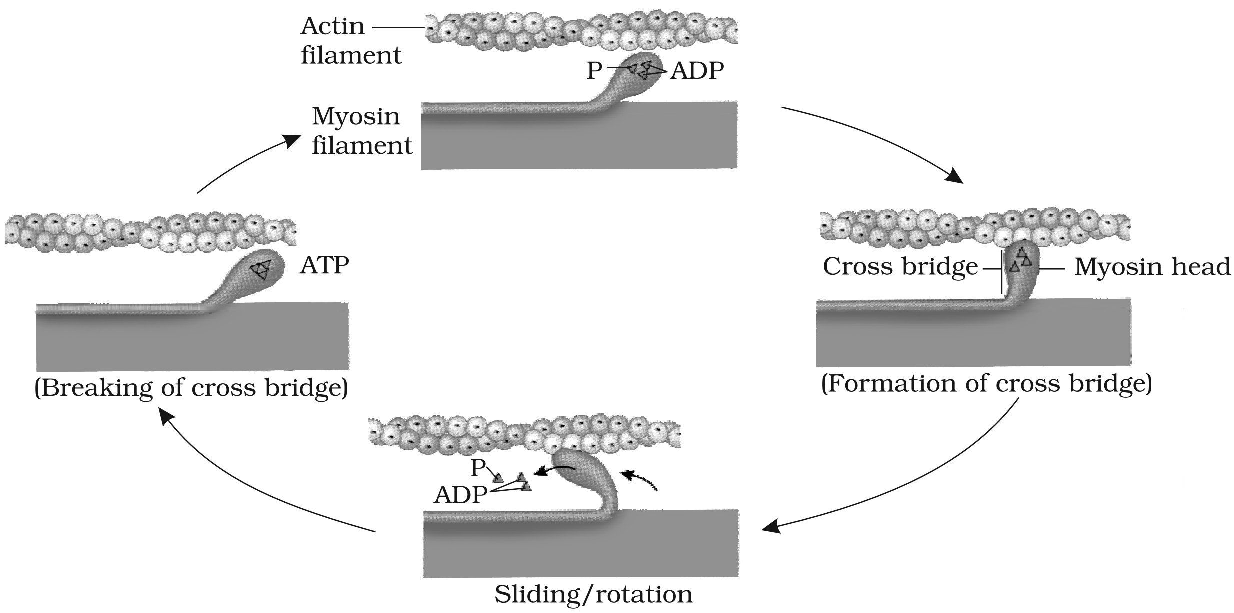


Figure 20.4 Stages in cross bridge formation, rotation of head and breaking of cross bridge

pulls the attached actin filaments towards the centre of 'A' band. The 'Z' line attached to these actins are also pulled inwards thereby causing a shortening of the sarcomere, i.e., contraction. It is clear from the above steps, that during shortening of the muscle, i.e., contraction, the 'I' bands get reduced, whereas the 'A' bands retain the length (Figure 20.5). The myosin, releasing the ADP and P_1 goes back to its relaxed state. A new ATP binds and the cross-bridge is broken (Figure 20.4). The ATP is again hydrolysed by the myosin head and the cycle of cross bridge formation

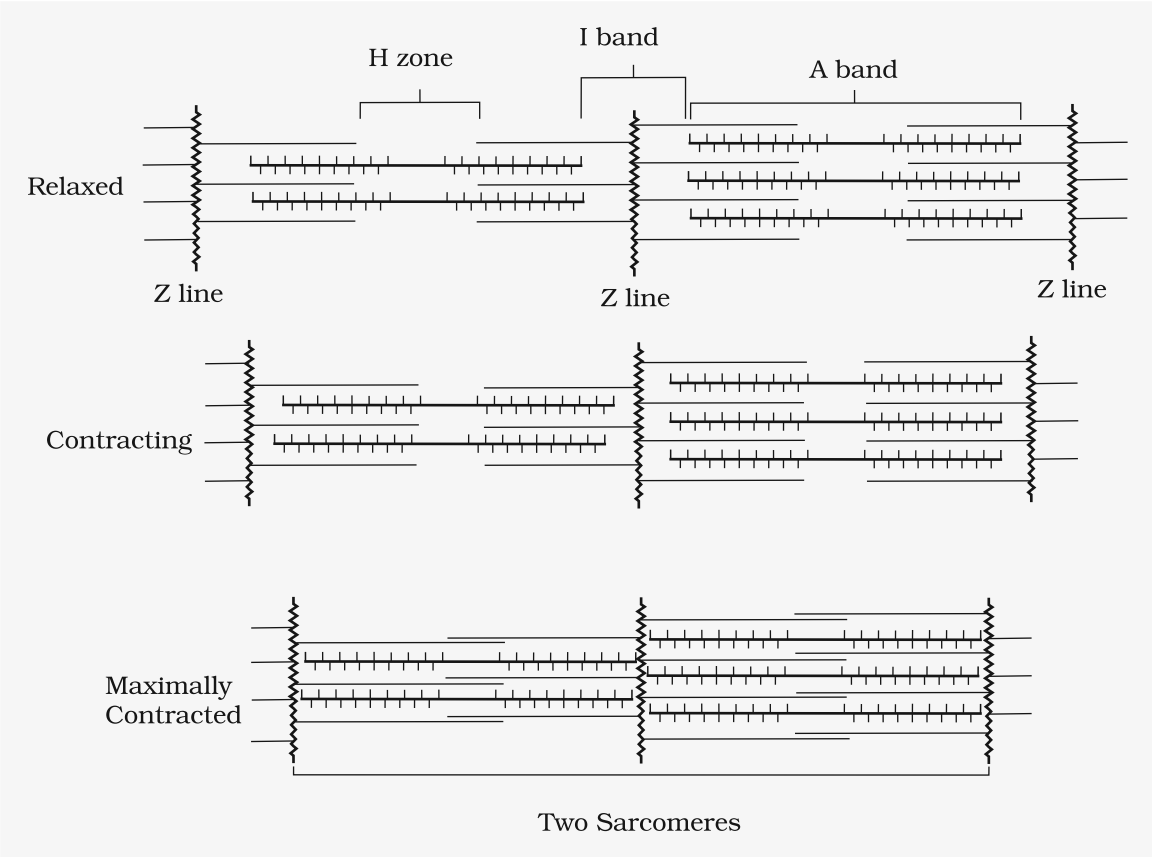


Figure 20.5 Sliding-filament theory of muscle contraction (movement of the thin filaments and the relative size of the I band and H zones)

and breakage is repeated causing further sliding. The process continues till the Ca^{++} ions are pumped back to the sarcoplasmic cisternae resulting in the masking of actin filaments. This causes the return of 'Z' lines back to their original position, i.e., relaxation. The reaction time of the fibres can vary in different muscles. Repeated activation of the muscles can lead to the accumulation of lactic acid due to anaerobic breakdown of glycogen in them, causing fatigue. Muscle contains a red coloured oxygen storing pigment called myoglobin. Myoglobin content is high in some of the muscles which gives a reddish appearance. Such muscles are called the Red fibres. These muscles also contain plenty of mitochondria which can utilise the large amount of oxygen stored in them for ATP production. These muscles, therefore, can also be called aerobic muscles. On the other hand, some of the muscles possess very less quantity of myoglobin and therefore, appear pale or whitish. These are the White fibres. Number of mitochondria are also few in them, but the amount of sarcoplasmic reticulum is high. They depend on anaerobic process for energy.

20.3 SKELETAL SYSTEM

Skeletal system consists of a framework of bones and a few cartilages. This system has a significant role in movement shown by the body. Imagine chewing food without jaw bones and walking around without the limb bones. Bone and cartilage are specialised connective tissues. The former has a very hard matrix due to calcium salts in it and the latter has slightly pliable matrix due to chondroitin salts. In human beings, this system is made up of 206 bones and a few cartilages. It is grouped into two principal divisions – the axial and the appendicular skeleton.

Axial skeleton comprises 80 bones distributed along the main axis of the body. The skull, vertebral column, sternum and ribs constitute axial skeleton. The **skull** (Figure 20.6) is composed of two sets of bones –

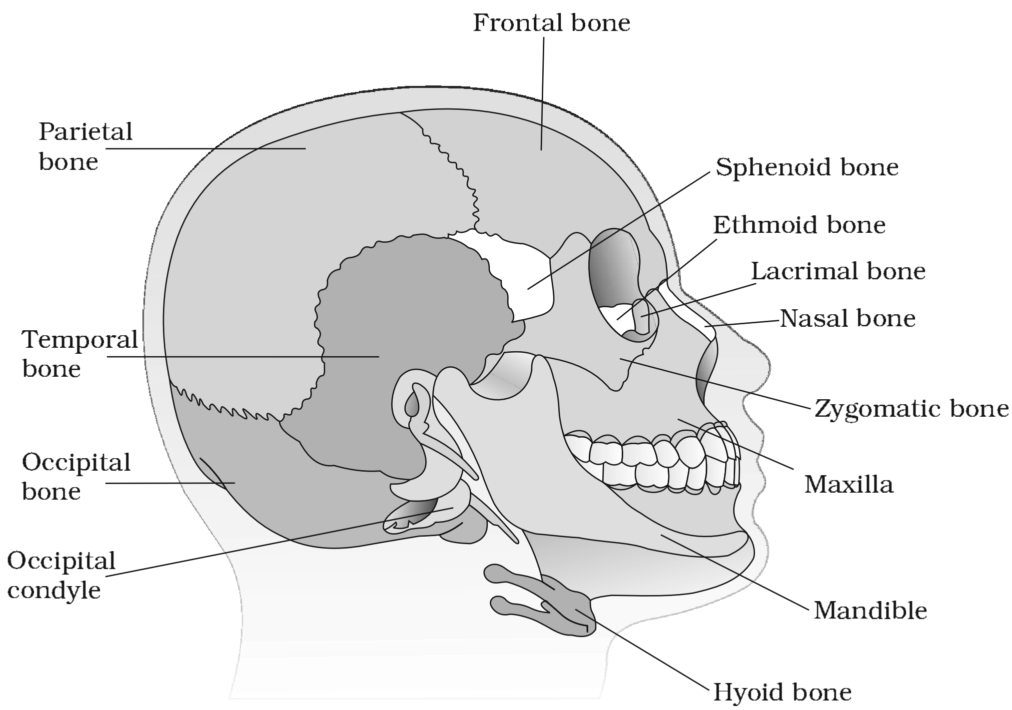


Figure 20.6 Diagrammatic view of human skull

cranial and facial, that totals to 22 bones. Cranial bones are 8 in number. They form the hard protective outer covering, cranium for the brain. The facial region is made up of 14 skeletal elements which form the front part of the skull. A single U-shaped bone called hyoid is present at the base of the buccal cavity and it is also included in the skull. Each middle ear contains three tiny bones – Malleus, Incus and Stapes, collectively called **Ear Ossicles**. The skull region articulates with the superior region of the

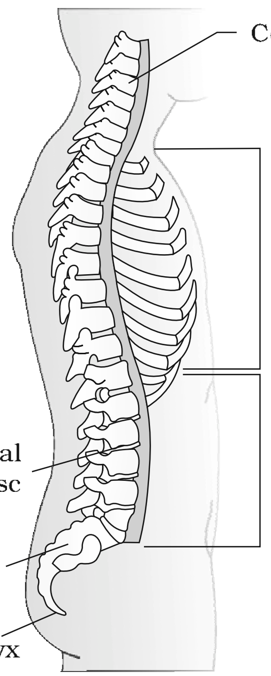


Figure 20.7 Vertebral column (right lateral view)

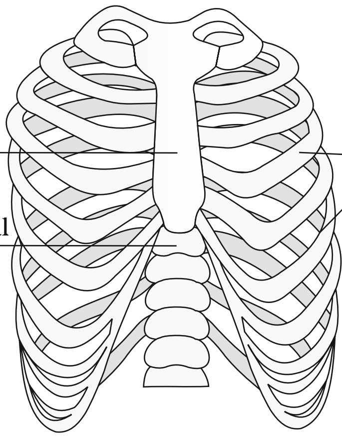


Figure 20.8 Ribs and rib cage

vertebral column with the help of two occipital condyles (dicondylic skull).

Our **vertebral column** (Figure 20.7) is formed by 26 serially arranged units called vertebrae and is dorsally placed. It extends from the base of the skull and constitutes the main framework of the trunk. Each vertebra has a central hollow portion (neural canal) through which the spinal cord passes. First vertebra is the atlas and it articulates with the occipital condyles. The vertebral column is differentiated into cervical (7), thoracic (12), lumbar (5), sacral (1-fused) and coccygeal (1-fused) regions starting from the skull. The number of cervical vertebrae are seven in almost all mammals including human beings. The vertebral column protects the spinal cord, supports the head and serves as the point of attachment for the ribs and musculature of the back. **Sternum** is a flat bone on the ventral midline of thorax.

There are 12 pairs of **ribs.** Each rib is a thin flat bone connected dorsally to the vertebral column and ventrally to the sternum. It has two articulation surfaces on its dorsal end and is hence called bicephalic. First seven pairs of ribs are called true ribs. Dorsally, they are attached to the thoracic vertebrae and ventrally connected to the sternum with the help of hyaline cartilage. The 8^{th}, 9^{th} and 10^{th} pairs of ribs do not articulate directly with the sternum but join the seventh rib with the help of hyaline cartilage. These are called vertebrochondral (false) ribs. Last 2 pairs (11^{th} and 12^{th}) of ribs are not connected ventrally and are therefore, called floating ribs. Thoracic vertebrae, ribs and sternum together form the rib cage (Figure 20.8).

The bones of the limbs alongwith their girdles constitute the **appendicular skeleton.** Each **limb** is made of 30 bones. The bones of the hand (fore limb) are humerus, radius and ulna, carpals (wrist bones – 8 in number), metacarpals (palm bones – 5 in number) and phalanges (digits – 14 in number) (Figure 20.9). Femur (thigh bone – the longest bone), tibia and fibula, tarsals (ankle bones – 7 in number), metatarsals (5 in number) and phalanges (digits – 14 in number) are the bones of the legs (hind limb) (Figure 20.10). A cup shaped bone called patella cover the knee ventrally (knee cap).

Pectoral and **Pelvic girdle** bones help in the articulation of the upper and the lower limbs respectively with the axial skeleton. Each girdle is formed of two halves. Each half of pectoral girdle consists of a clavicle and a scapula (Figure 20.9). Scapula is a large triangular flat bone situated in the dorsal part of the thorax between the second and the seventh ribs. The dorsal, flat, triangular body of scapula has a slightly elevated ridge called the spine which projects as a flat, expanded process called the acromion. The clavicle articulates with this. Below the acromion is a depression called the glenoid cavity which articulates with the head of the humerus to form the shoulder joint. Each clavicle is a long slender bone with two curvatures. This bone is commonly called the collar bone.

Pelvic girdle consists of two coxal bones (Figure 20.10). Each coxal bone is formed by the fusion of three bones – ilium, ischium and pubis. At the point of fusion of the above bones is a cavity called acetabulum to which the thigh bone articulates. The two halves of the pelvic girdle meet ventrally to form the pubic symphysis containing fibrous cartilage.

20.4 JOINTS

Joints are essential for all types of movements involving the bony parts of the body. Locomotory movements are no exception to

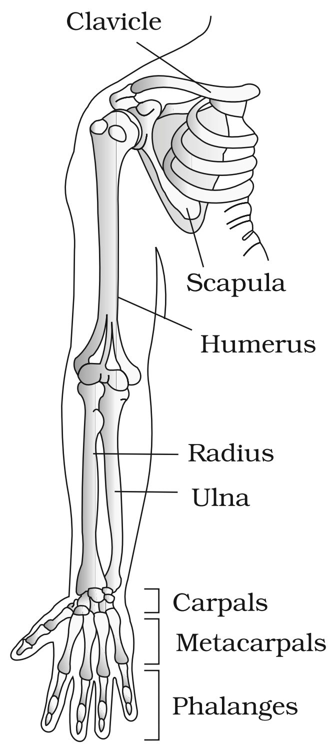


Figure 20.9 Right pectoral girdle and upper arm. (frontal view)

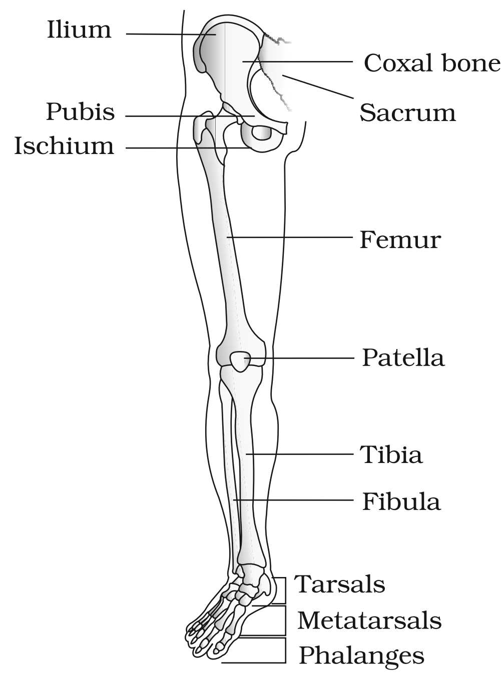


Figure 20.10 Right pelvic girdle and lower limb bones (frontal view)

this. Joints are points of contact between bones, or between bones and cartilages. Force generated by the muscles is used to carry out movement through joints, where the joint acts as a fulcrum. The movability at these joints vary depending on different factors. Joints have been classified into three major structural forms, namely, fibrous, cartilaginous and synovial.

Fibrous joints do not allow any movement. This type of joint is shown by the flat skull bones which fuse end-to-end with the help of dense fibrous connective tissues in the form of sutures, to form the cranium.

In **cartilaginous joints,** the bones involved are joined together with the help of cartilages. The joint between the adjacent vertebrae in the vertebral column is of this pattern and it permits limited movements.

Synovial joints are characterised by the presence of a fluid filled synovial cavity between the articulating surfaces of the two bones. Such an arragement allows considerable movement. These joints help in locomotion and many other movements. Ball and socket joint (between humerus and pectoral girdle), Hinge joint (knee joint), Pivot joint (between atlas and axis), Gliding joint (between the carpals) and Saddle joint (between carpal and metacarpal of thumb) are some examples.

20.5 Disorders of Muscular and Skeletal System

Myasthenia gravis: Auto immune disorder affecting neuromuscular junction leading to fatigue, weakening and paralysis of skeletal muscle.

Muscular dystrophy: Progressive degeneration of skeletal muscle mostly due to genetic disorder.

Tetany: Rapid spasms (wild contractions) in muscle due to low Ca^{++} in body fluid.

Arthritis: Inflammation of joints.

Osteoporosis: Age-related disorder characterised by decreased bone mass and increased chances of fractures. Decreased levels of estrogen is a common cause.

Gout: Inflammation of joints due to accumulation of uric acid crystals.

Summary

Movement is an essential feature of all living beings. Protoplasmic streaming, ciliary movements, movements of fins, limbs, wings, etc., are some forms exhibited by animals. A voluntary movement which causes the animal to change its place, is

called locomotion. Animals move generally in search of food, shelter, mate, breeding ground, better climate or to protect themselves.

The cells of the human body exhibit amoeboid, ciliary and muscular movements. Locomotion and many other movements require coordinated muscular activities. Three types of muscles are present in our body. Skeletal muscles are attached to skeletal elements. They appear striated and are voluntary in nature. Visceral muscles, present in the inner walls of visceral organs are nonstriated and involuntary. Cardiac muscles are the muscles of the heart. They are striated, branched and involuntary. Muscles possess excitability, contractility, extensibility and elasticity.

Muscle fibre is the anatomical unit of muscle. Each muscle fibre has many parallelly arranged myofibrils. Each myofibril contains many serially arranged units called sarcomere which are the functional units. Each sarcomere has a central 'A' band made of thick myosin filaments, and two half 'I' bands made of thin actin filaments on either side of it marked by 'Z' lines. Actin and myosin are polymerised proteins with contractility. The active sites for myosin on resting actin filament are masked by a protein-troponin. Myosin head contains ATPase and has ATP binding sites and active sites for actin. A motor neuron carries signal to the muscle fibre which generates an action potential in it. This causes the release of Ca^{++} from sarcoplasmic reticulum. Ca^{++} activates actin which binds to the myosin head to form a cross bridge. These cross bridges pull the actin filaments causing them to slide over the myosin filaments and thereby causing contraction. Ca^{++} are then returned to sarcoplasmic reticulum which inactivate the actin. Cross bridges are broken and the muscles relax.

Repeated stimulation of muscles leads to fatigue. Muscles are classified as Red and White fibres based primarily on the amount of red coloured myoglobin pigment in them.

Bones and cartilages constitute our skeletal system. The skeletal system is divisible into axial and appendicular. Skull, vertebral column, ribs and sternum constitute the axial skeleton. Limb bones and girdles form the appendicular skeleton. Three types of joints are formed between bones or between bone and cartilage – fibrous, cartilaginous and synovial. Synovial joints allow considerable movements and therefore, play a significant role in locomotion.

EXERCISES

1. Draw the diagram of a sarcomere of skeletal muscle showing different regions.
2. Define sliding filament theory of muscle contraction.
3. Describe the important steps in muscle contraction.

4. Write true or false. If false change the statement so that it is true.
   (a) Actin is present in thin filament
   (b) H-zone of striated muscle fibre represents both thick and thin filaments.
   (c) Human skeleton has 206 bones.
   (d) There are 11 pairs of ribs in man.
   (e) Sternum is present on the ventral side of the body.
5. Write the difference between :
   (a) Actin and Myosin
   (b) Red and White muscles
   (c) Pectoral and Pelvic girdle
6. Match Column I with Column II :

Column I	**Column II**
(a) Smooth muscle	(i) Myoglobin
(b) Tropomyosin	(ii) Thin filament
(c) Red muscle	(iii) Sutures
(d) Skull	(iv) Involuntary

7. What are the different types of movements exhibited by the cells of human body?
8. How do you distinguish between a skeletal muscle and a cardiac muscle?
9. Name the type of joint between the following:-
   (a) atlas/axis
   (b) carpal/metacarpal of thumb
   (c) between phalanges
   (d) femur/acetabulum
   (e) between cranial bones
   (f) between pubic bones in the pelvic girdle
10. Fill in the blank spaces:
   (a) All mammals (except a few) have __________ cervical vertebra.
   (b) The number of phalanges in each limb of human is __________
   (c) Thin filament of myofibril contains 2 'F' actins and two other proteins namely __________ and __________.
   (d) In a muscle fibre Ca^{++} is stored in __________
   (e) __________ and __________ pairs of ribs are called floating ribs.
   (f) The human cranium is made of __________ bones.

CHAPTER 21

NEURAL CONTROL AND COORDINATION

As you know, the functions of the organs/organ systems in our body must be coordinated to maintain homeostasis. **Coordination** is the process through which two or more organs interact and complement the functions of one another. For example, when we do physical exercises, the energy demand is increased for maintaining an increased muscular activity. The supply of oxygen is also increased. The increased supply of oxygen necessitates an increase in the rate of respiration, heart beat and increased blood flow via blood vessels. When physical exercise is stopped, the activities of nerves, lungs, heart and kidney gradually return to their normal conditions. Thus, the functions of muscles, lungs, heart, blood vessels, kidney and other organs are coordinated while performing physical exercises. In our body the neural system and the endocrine system jointly coordinate and integrate all the activities of the organs so that they function in a synchronised fashion.

The neural system provides an organised network of point-to-point connections for a quick coordination. The endocrine system provides chemical integration through hormones. In this chapter, you will learn about the neural system of human, mechanisms of neural coordination like transmission of nerve impulse, impulse conduction across a synapse and the physiology of reflex action.

21.1 Neural System

The neural system of all animals is composed of highly specialised cells called **neurons** which can detect, receive and transmit different kinds of stimuli.

The neural organisation is very simple in lower invertebrates. For example, in *Hydra* it is composed of a network of neurons. The neural system is better organised in insects, where a brain is present along with a number of ganglia and neural tissues. The vertebrates have a more developed neural system.

21.2 Human Neural System

The human neural system is divided into two parts :

(i) the **central neural system** (CNS)
(ii) the **peripheral neural system** (PNS)

The CNS includes the **brain** and the **spinal cord** and is the site of information processing and control. The PNS comprises of all the nerves of the body associated with the CNS (brain and spinal cord). The nerve fibres of the PNS are of two types :

(a) **afferent fibres**
(b) **efferent fibres**

The afferent nerve fibres transmit impulses from tissues/organs to the CNS and the efferent fibres transmit regulatory impulses from the CNS to the concerned peripheral tissues/organs.

The PNS is divided into two divisions called **somatic neural system** and **autonomic neural system**. The somatic neural system relays impulses from the CNS to skeletal muscles while the autonomic neural system transmits impulses from the CNS to the involuntary organs and smooth muscles of the body. The autonomic neural system is further classified into **sympathetic neural system** and **parasympathetic neural system**.

21.3 Neuron as Structural and Functional Unit of Neural System

A neuron is a microscopic structure composed of three major parts, namely, **cell body**, **dendrites** and **axon** (Figure 21.1). The cell body contains cytoplasm with typical cell organelles and certain granular bodies called **Nissl's granules**. Short fibres which branch repeatedly and project out of the cell body also contain Nissl's granules and are called dendrites. These fibres transmit impulses towards the cell body. The axon is a long fibre, the distal end of which is branched. Each branch terminates as a bulb-like structure called **synaptic knob** which possess synaptic vesicles containing chemicals called **neurotransmitters**. The axons transmit nerve impulses away from the cell body to a synapse or to a neuro-muscular junction. Based on the number of axon and dendrites, the neurons are divided into three types, i.e., **multipolar** (with one axon and two or more dendrites; found in the cerebral cortex), **bipolar** (with one axon and one dendrite, found in the retina of eye) and **unipolar** (cell body with one axon only; found usually in the embryonic stage). There are two types of axons, namely, **myelinated** and **non-myelinated**. The myelinated nerve fibres are enveloped with **Schwann cells,** which form a myelin sheath around the axon. The gaps between two adjacent myelin sheaths are called **nodes of Ranvier**. Myelinated nerve fibres are found in spinal and cranial nerves. Unmyelinated nerve fibre is enclosed by a Schwann cell that does not form a myelin sheath around the axon, and is commonly found in autonomous and the somatic neural systems.

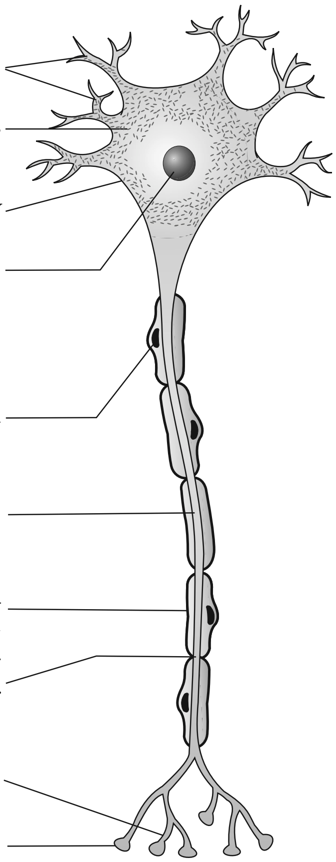


Figure 21.1 Structure of a neuron

21.3.1 Generation and Conduction of Nerve Impulse

Neurons are excitable cells because their membranes are in a polarised state. *Do you know why the membrane of a neuron is polarised?* Different types of ion channels are present on the neural membrane. These ion channels are selectively permeable to different ions. When a neuron is not conducting any impulse, i.e., resting, the axonal membrane is comparatively more permeable to potassium ions (K^+) and nearly impermeable to sodium ions (Na^+). Similarly, the membrane is impermeable to negatively charged proteins present in the axoplasm. Consequently, the axoplasm inside the axon contains high concentration of K^+ and negatively charged proteins and low concentration of Na^+. In contrast, the fluid outside the axon contains a low concentration of K^+, a high concentration of Na^+ and thus form a concentration gradient. These ionic gradients across the resting membrane are maintained by the active transport of ions by the sodium-potassium pump which transports 3 Na^+ outwards for 2 K^+ into the cell. As a result, the outer surface of the axonal membrane possesses a positive charge while its inner surface

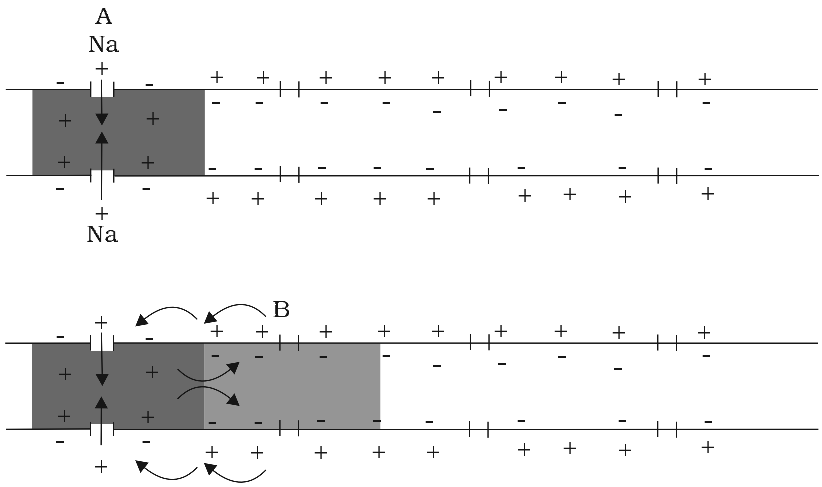


Figure 21.2 Diagrammatic representation of impulse conduction through an axon (at points A and B)

becomes negatively charged and therefore is polarised. The electrical potential difference across the resting plasma membrane is called as the **resting potential**.

You might be curious to know about the mechanisms of generation of nerve impulse and its conduction along an axon. When a stimulus is applied at a site (Figure 21.2 e.g., point A) on the polarised membrane, the membrane at the site A becomes freely permeable to Na^+. This leads to a rapid influx of Na^+ followed by the reversal of the polarity at that site, i.e., the outer surface of the membrane becomes negatively charged and the inner side becomes positively charged. The polarity of the membrane at the site A is thus reversed and hence depolarised. The electrical potential difference across the plasma membrane at the site A is called the **action potential**, which is in fact termed as a **nerve impulse**. At sites immediately ahead, the axon (e.g., site B) membrane has a positive charge on the outer surface and a negative charge on its inner surface. As a result, a current flows on the inner surface from site A to site B. On the outer surface current flows from site B to site A (Figure 21.2) to complete the circuit of current flow. Hence, the polarity at the site is reversed, and an action potential is generated at site B. Thus, the **impulse** (action potential) generated at site A arrives at site B. The sequence is repeated along the length of the axon and consequently the impulse is conducted. The rise in the stimulus-induced permeability to Na^+ is extremely short-lived. It is quickly followed by a rise in permeability to K^+. Within a fraction of a second, K^+ diffuses outside the membrane and restores the resting potential of the membrane at the site of excitation and the fibre becomes once more responsive to further stimulation.

21.3.2 Transmission of Impulses

A nerve impulse is transmitted from one neuron to another through junctions called synapses. A **synapse** is formed by the membranes of a pre-synaptic neuron and a post-synaptic neuron, which may or may not be separated by a gap called **synaptic cleft**. There are two types of synapses, namely, electrical synapses and chemical synapses. At electrical synapses, the membranes of pre- and post-synaptic neurons are in very close proximity. Electrical current can flow directly from one neuron into the other across these synapses. Transmission of an impulse across electrical synapses is very similar to impulse conduction along a single axon. Impulse transmission across an electrical synapse is always faster than that across a chemical synapse. Electrical synapses are rare in our system.

At a chemical synapse, the membranes of the pre- and post-synaptic neurons are separated by a fluid-filled space called synaptic cleft (Figure 21.3). *Do you know how the pre-synaptic neuron transmits an impulse (action potential) across the synaptic cleft to the post-synaptic neuron*? Chemicals called neurotransmitters are involved in the transmission of impulses at these synapses. The axon terminals contain vesicles filled with these neurotransmitters. When an impulse (action potential) arrives at the axon terminal, it stimulates the movement of the synaptic vesicles towards the membrane where they fuse with the plasma

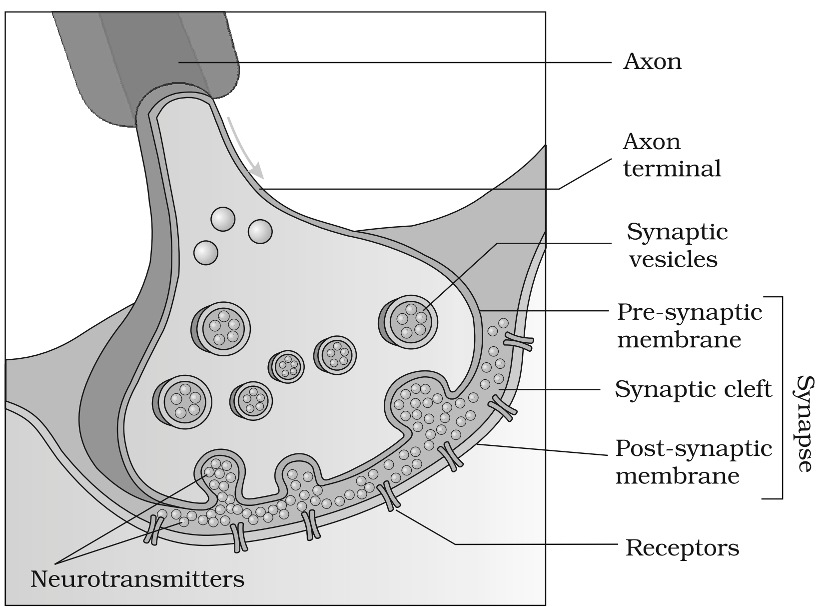


Figure 21.3 Diagram showing axon terminal and synapse

membrane and release their neurotransmitters in the synaptic cleft. The released neurotransmitters bind to their specific **receptors**, present on the post-synaptic membrane. This binding opens ion channels allowing the entry of ions which can generate a new potential in the post-synaptic neuron. The new potential developed may be either excitatory or inhibitory.

21.4 Central Neural System

The brain is the central information processing organ of our body, and acts as the 'command and control system'. It controls the voluntary movements, balance of the body, functioning of vital involuntary organs (e.g., lungs, heart, kidneys, etc.), thermoregulation, hunger and thirst, circadian (24-hour) rhythms of our body, activities of several endocrine glands and human behaviour. It is also the site for processing of vision, hearing, speech, memory, intelligence, emotions and thoughts.

The human brain is well protected by the skull. Inside the skull, the brain is covered by **cranial meninges** consisting of an outer layer called **dura mater**, a very thin middle layer called **arachnoid** and an inner layer (which is in contact with the brain tissue) called **pia mater**. The brain can be divided into three major parts: (i) **forebrain**, (ii) **midbrain**, and (iii) **hindbrain** (Figure 21.4).

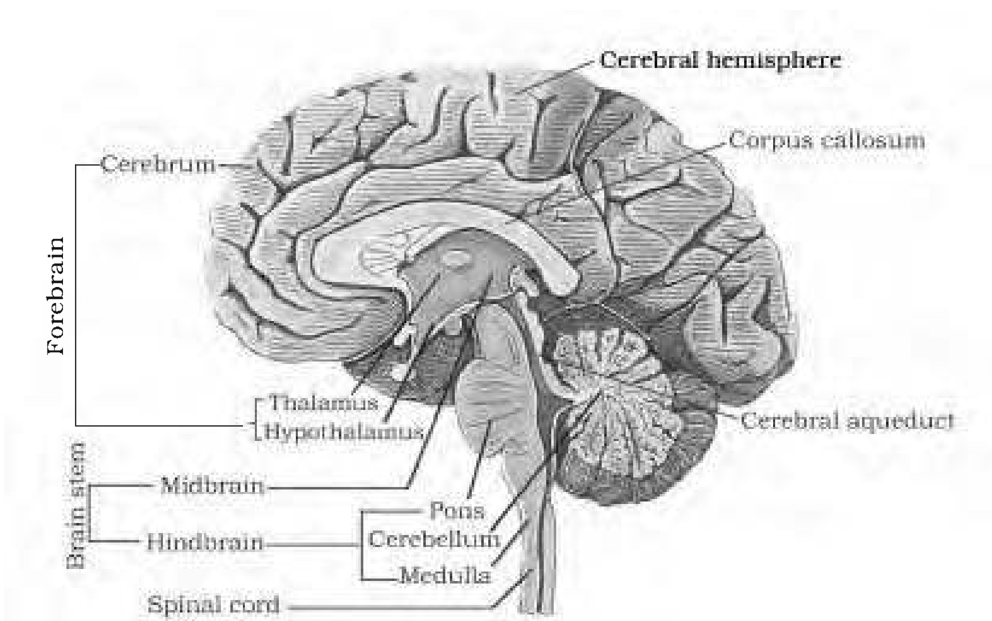


Figure 21.4 Diagram showing sagital section of the human brain

21.4.1 Forebrain

The forebrain consists of **cerebrum**, **thalamus** and **hypothalamus** (Figure 21.4). Cerebrum forms the major part of the human brain. A deep cleft divides the cerebrum longitudinally into two halves, which are termed as the left and right **cerebral hemispheres**. The hemispheres are connected by a tract of nerve fibres called **corpus callosum**. The layer of cells which covers the cerebral hemisphere is called cerebral cortex and is thrown into prominent folds. The cerebral cortex is referred to as the grey matter due to its greyish appearance. The neuron cell bodies are concentrated here giving the colour. The cerebral cortex contains motor areas, sensory areas and large regions that are neither clearly sensory nor motor in function. These regions called as the **association areas** are responsible for complex functions like intersensory associations, memory and communication. Fibres of the tracts are covered with the myelin sheath, which constitute the inner part of cerebral hemisphere. They give an opaque white appearance to the layer and, hence, is called the white matter. The cerebrum wraps around a structure called thalamus, which is a major coordinating centre for sensory and motor signaling. Another very important part of the brain called **hypothalamus** lies at the base of the thalamus. The hypothalamus contains a number of centres which control body temperature, urge for eating and drinking. It also contains several groups of neurosecretory cells, which secrete hormones called hypothalamic hormones. The inner parts of cerebral hemispheres and a group of associated deep structures like amygdala, hippocampus, etc., form a complex structure called the limbic lobe or limbic system. Along with the hypothalamus, it is involved in the regulation of sexual behaviour, expression of emotional reactions (e.g., excitement, pleasure, rage and fear), and motivation.

21.4.2 Midbrain

The midbrain is located between the thalamus/hypothalamus of the forebrain and pons of the hindbrain. A canal called the **cerebral aqueduct** passess through the midbrain. The dorsal portion of the midbrain consists mainly of four round swellings (lobes) called **corpora quadrigemina**. Midbrain and hindbrain form the brain stem.

21.4.3 Hindbrain

The hindbrain comprises **pons**, **cerebellum** and **medulla** (also called the medulla oblongata). Pons consists of fibre tracts that interconnect different regions of the brain. Cerebellum has very convoluted surface in order to provide the additional space for many more neurons. The medulla of the brain is connected to the spinal cord. The medulla contains centres which control respiration, cardiovascular reflexes and gastric secretions.

21.5 Reflex Action and Reflex Arc

You must have experienced a sudden withdrawal of a body part which comes in contact with objects that are extremely hot, cold pointed or animals that are scary or poisonous. The entire process of response to a peripheral nervous stimulation, that occurs involuntarily, i.e., without conscious effort or thought and requires the involvment of a part of the central nervous system is called a **reflex action**. The reflex pathway comprises at least one afferent neuron (receptor) and one efferent (effector or excitor) neuron appropriately arranged in a series (Figure 21.5). The afferent neuron receives signal from a sensory organ and transmits the impulse via a dorsal nerve root into the CNS (at the level of spinal cord). The efferent nueuron then carries signals from CNS to the effector. The stimulus and response thus forms a reflex arc as shown below in the knee jerk reflex. You should carefully study Figure 21.5 to understand the mechanism of a knee jerk reflex.

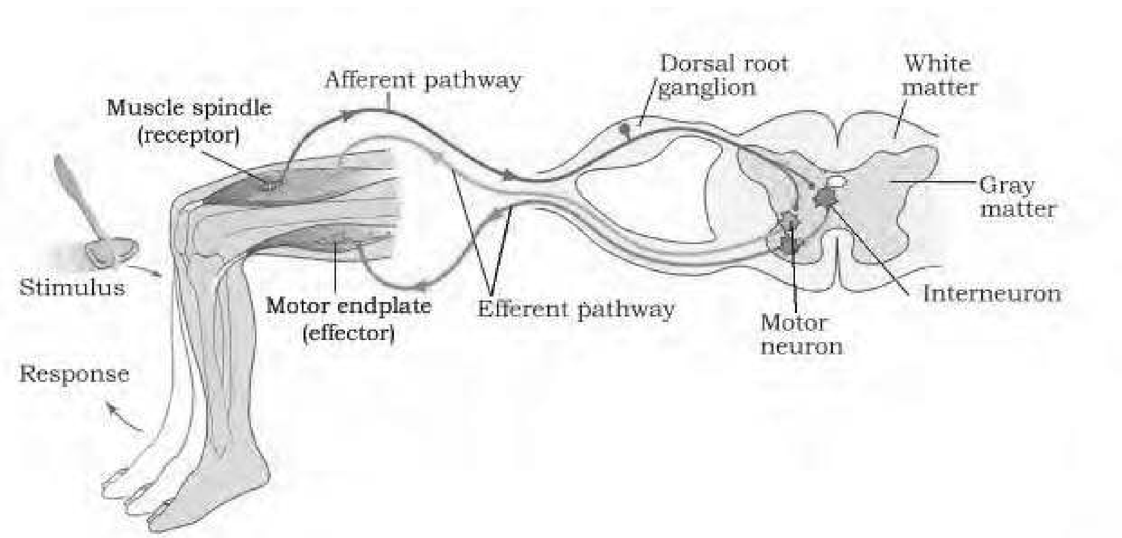


Figure 21.5 Diagrammatic presentation of reflex action (showing knee jerk reflex)

21.6 Sensory Reception and Processing

Have you ever thought how do you feel the climatic changes in the environment? How do you see an object and its colour? How do you hear a sound? The sensory organs detect all types of changes in the environment and send appropriate signals to the CNS, where all the inputs are processed and analysed. Signals are then sent to different parts/ centres of the brain. This is how you can sense changes in the environment.

In the following sections, you will be introduced to the structure and functioning of the eye (sensory organ for vision) and the ear (sensory organ for hearing).

21.6.1 Eye

Our paired eyes are located in sockets of the skull called **orbits**. A brief account of structure and functions of the human eye is given in the following sections.

21.6.1.1 Parts of an eye

The adult human eye ball is nearly a spherical structure. The wall of the eye ball is composed of three layers (Figure 21.6). The external layer is composed of a dense connective tissue and is called the **sclera**. The anterior portion of this layer is called the **cornea**. The middle layer, **choroid**, contains many blood vessels and looks bluish in colour. The choroid layer is thin over the posterior two-thirds of the eye ball, but it becomes thick in the anterior part to form the **ciliary body**. The ciliary body itself continues forward to form a pigmented and opaque structure called the **iris** which is the visible coloured portion of the eye. The eye ball contains a transparent crystalline **lens** which is held in place by ligaments attached to the ciliary body. In front of the lens, the aperture surrounded by the iris is called the **pupil**. The diameter of the pupil is regulated by the muscle fibres of iris.

The inner layer is the **retina** and it contains three layers of cells – from inside to outside – ganglion cells, bipolar cells and photoreceptor cells.

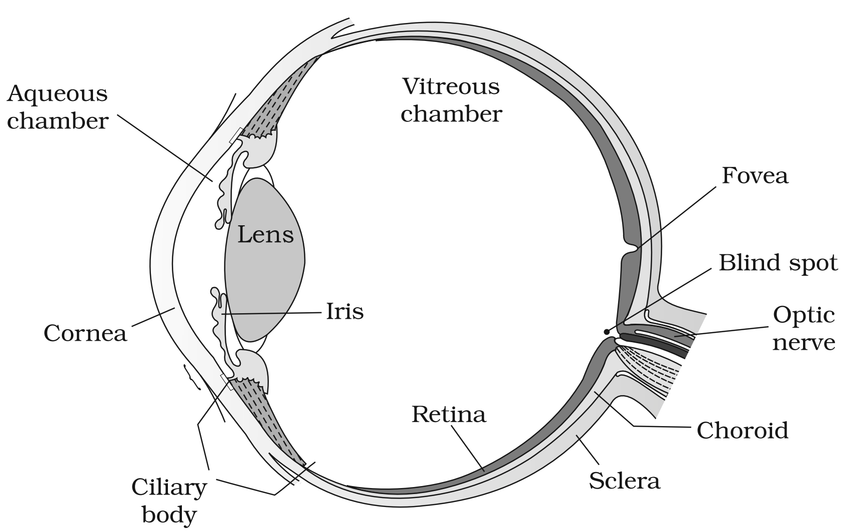


Figure 21.6 Diagram showing parts of an eye

There are two types of photoreceptor cells, namely, **rods** and **cones**. These cells contain the light-sensitive proteins called the photopigments. The daylight (photopic) vision and colour vision are functions of cones and the twilight (scotopic) vision is the function of the rods. The rods contain a purplish-red protein called the rhodopsin or visual purple, which contains a derivative of Vitamin A. In the human eye, there are three types of cones which possess their own characteristic photopigments that respond to red, green and blue lights. The sensations of different colours are produced by various combinations of these cones and their photopigments. When these cones are stimulated equally, a sensation of white light is produced.

The **optic nerves** leave the eye and the retinal blood vessels enter it at a point medial to and slightly above the posterior pole of the eye ball. Photoreceptor cells are not present in that region and hence it is called the **blind spot**. At the posterior pole of the eye lateral to the blind spot, there is a yellowish pigmented spot called macula lutea with a central pit called the **fovea**. The fovea is a thinned-out portion of the retina where only the cones are densely packed. It is the point where the visual acuity (resolution) is the greatest.

The space between the cornea and the lens is called the **aqueous chamber** and contains a thin watery fluid called aqueous humor. The space between the lens and the retina is called the **vitreous chamber** and is filled with a transparent gel called vitreous humor.

21.6.1.2 Mechanism of Vision

The light rays in visible wavelength focussed on the retina through the cornea and lens generate potentials (impulses) in rods and cones. As mentioned earlier, the photosensitive compounds (photopigments) in the human eyes is composed of **opsin** (a protein) and **retinal** (an aldehyde of vitamin A). Light induces dissociation of the retinal from opsin resulting in changes in the structure of the opsin. This causes membrane permeability changes. As a result, potential differences are generated in the photoreceptor cells. This produces a signal that generates action potentials in the ganglion cells through the bipolar cells. These action potentials (impulses) are transmitted by the optic nerves to the **visual cortex** area of the brain, where the neural impulses are analysed and the image formed on the retina is recognised based on earlier memory and experience.

21.6.2 The Ear

The ears perform two sensory functions, hearing and maintenance of body balance. Anatomically, the ear can be divided into three major sections called the **outer ear**, the **middle ear** and the **inner ear** (Figure 21.7). The

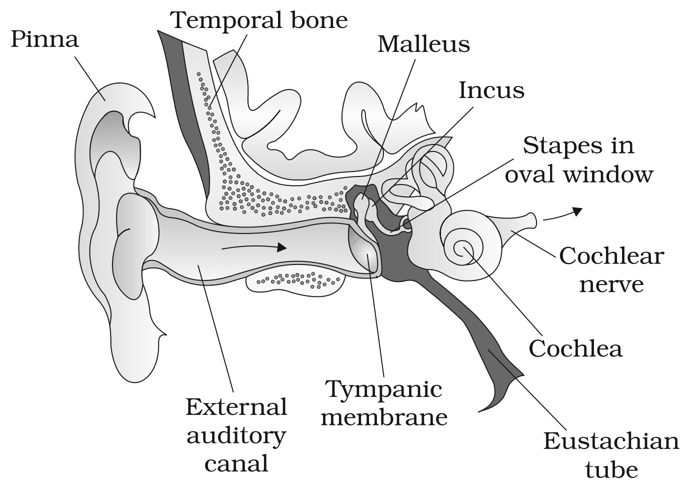


Figure 21.7 Diagrammatic view of ear

outer ear consists of the **pinna** and **external auditory meatus** (canal). The pinna collects the vibrations in the air which produce sound. The external auditory meatus leads inwards and extends up to the **tympanic membrane** (the **ear drum**). There are very fine hairs and wax-secreting sebaceous glands in the skin of the pinna and the meatus. The tympanic membrane is composed of connective tissues covered with skin outside and with mucus membrane inside. The middle ear contains three ossicles called **malleus**, **incus** and **stapes** which are attached to one another in a chain-like fashion. The malleus is attached to the tympanic membrane and the stapes is attached to the **oval window** of the cochlea. The ear ossicles increase the efficiency of transmission of sound waves to the inner ear. An **Eustachian tube** connects the middle ear cavity with the pharynx. The Eustachian tube helps in equalising the pressures on either sides of the ear drum.

The fluid-filled inner ear called **labyrinth** consists of two parts, the bony and the membranous labyrinths. The bony labyrinth is a series of channels. Inside these channels lies the membranous labyrinth, which is surrounded by a fluid called perilymph. The membranous labyrinth is filled with a fluid called endolymph. The coiled portion of the labyrinth is called **cochlea**. The membranes constituting cochlea, the reissner's and basilar, divide the surounding perilymph filled bony labyrinth into an upper scala vestibuli and a lower scala tympani (Figure 21.8). The space within cochlea called scala media is filled with endolymph. At the base of the cochlea, the scala vestibuli ends at the oval window, while the scala tympani terminates at the round window which opens to the middle ear.

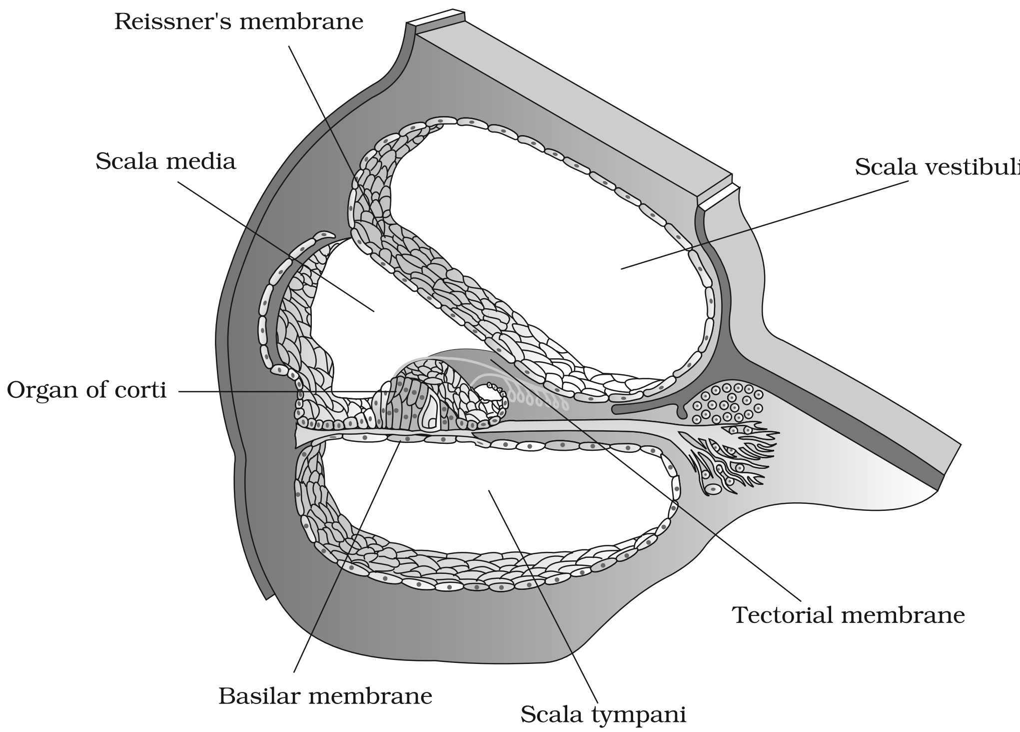


Figure 21.8 Diagrammatic representation of the sectional view of cochlea

The **organ of corti** is a structure located on the basilar membrane which contains **hair cells** that act as auditory receptors. The hair cells are present in rows on the internal side of the organ of corti. The basal end of the hair cell is in close contact with the afferent nerve fibres. A large number of processes called stereo cilia are projected from the apical part of each hair cell. Above the rows of the hair cells is a thin elastic membrane called **tectorial membrane**.

The inner ear also contains a complex system called **vestibular apparatus**, located above the cochlea. The vestibular apparatus is composed of three **semi-circular canals** and the **otolith organ** consisting of the saccule and utricle. Each semi-circular canal lies in a different plane at right angles to each other. The membranous canals are suspended in the perilymph of the bony canals. The base of canals is swollen and is called ampulla, which contains a projecting ridge called **crista ampullaris** which has hair cells. The saccule and utricle contain a projecting ridge called **macula**. The crista and macula are the specific receptors of the vestibular apparatus responsible for maintenance of balance of the body and posture.

20.6.2.1 Mechanism of Hearing

How does ear convert sound waves into neural impulses, which are sensed and processed by the brain enabling us to recognise a sound ? The external ear receives sound waves and directs them to the ear drum. The ear drum vibrates in response to the sound waves and these vibrations are transmitted through the ear ossicles (malleus, incus and stapes) to the oval window. The vibrations are passed through the oval window on to the fluid of the cochlea, where they generate waves in the lymphs. The waves in the lymphs induce a ripple in the basilar membrane. These movements of the basilar membrane bend the hair cells, pressing them against the tectorial membrane. As a result, nerve impulses are generated in the associated afferent neurons. These impulses are transmitted by the afferent fibres via auditory nerves to the auditory cortex of the brain, where the impulses are analysed and the sound is recognised.

SUMMARY

The neural system coordinates and integrates functions as well as metabolic and homeostatic activities of all the organs. Neurons, the functional units of neural system are excitable cells due to a differential concentration gradient of ions across the membrane. The electrical potential difference across the resting neural membrane is called the 'resting potential'. The nerve impulse is conducted along the axon membrane in the form of a wave of depolarisation and repolarisation. A synapse is formed by the membranes of a pre-synaptic neuron and a post-synaptic neuron which may or may not be separated by a gap called synaptic cleft. Chemicals involved in the transmission of impulses at chemical synapses are called neurotransmitters.

Human neural system consists of two parts : (i) central neural system (CNS) and (ii) the peripheral neural system. The CNS consists of the brain and spiral cord. The brain can be divided into three major parts : (i) forebrain, (ii) midbrain and (iii) hindbrain. The forebrain consists of cerebrum, thalamus and hypothalamus. The cerebrum is longitudinally divided into two halves that are connected by the corpus callosum. A very important part of the forebrain called hypothalamus controls the body temperature, eating and drinking. Inner parts of cerebral hemispheres and a group of associated deep structures form a complex structure called limbic system which is concerned with olfaction, autonomic responses, regulation of sexual behaviour, expression of emotional reactions, and motivation. The midbrain receives and integrates visual, tactile and auditory inputs. The hindbrain comprises pons, cerebellum and medulla. The cerebellum integrates information received from the semicircular canals of the ear and the

auditory system. The medulla contains centres, which control respiration, cardiovascular reflexes, and gastric secretions. Pons consist of fibre tracts that interconnect different regions of the brain. The entire process of involuntary response to a peripheral nervous stimulation is called reflex action.

Information regarding changes in the environment is received by the CNS through the sensory organs which are processed and analysed. Signals are then sent for necessary adjustments. The wall of the human eye ball is composed of three layers. The external layer is composed of cornea and sclera. Inside sclera is the middle layer, which is called the choroid. Retina, the innermost layer, contains two types of photoreceptor cells, namely rods and cones. The daylight (photopic) vision and colour vision are functions of cones and twilight (scotopic) vision is the function of the rods. The light enters through cornea, the lens and the images of objects are formed on the retina.

The ear can be divided into the outer ear, the middle ear and the inner ear. The middle ear contains three ossicles called malleus, incus and stapes. The fluid filled inner ear is called the labyrinth, and the coiled portion of the labyrinth is called cochlea. The organ of corti is a structure which contains hair cells that act as auditory receptors and is located on the basilar membrane. The vibrations produced in the ear drum are transmitted through the ear ossicles and oval window to the fluid-filled inner ear. Nerve impulses are generated and transmitted by the afferent fibres to the auditory cortex of the brain. The inner ear also contains a complex system located above the cochlea called vestibular apparatus. It is influenced by gravity and movements, and helps us in maintaining balance of the body and posture.

EXERCISES

1. Briefly describe the structure of the following:
   (a) Brain (b) Eye (c) Ear
2. Compare the following:
   (a) Central neural system (CNS) and Peripheral neural system (PNS)
   (b) Resting potential and action potential
   (c) Choroid and retina
3. Explain the following processes:
   (a) Polarisation of the membrane of a nerve fibre
   (b) Depolarisation of the membrane of a nerve fibre
   (c) Conduction of a nerve impulse along a nerve fibre
   (d) Transmission of a nerve impulse across a chemical synapse
4. Draw labelled diagrams of the following:
   (a) Neuron (b) Brain (c) Eye (d) Ear

5. Write short notes on the following:
   (a) Neural coordination (b) Forebrain (c) Midbrain
   (d) Hindbrain (e) Retina (f) Ear ossicles
   (g) Cochlea (h) Organ of Corti (i) Synapse
6. Give a brief account of:
   (a) Mechanism of synaptic transmission
   (b) Mechanism of vision
   (c) Mechanism of hearing
7. Answer briefly:
   (a) How do you perceive the colour of an object?
   (b) Which part of our body helps us in maintaining the body balance?
   (c) How does the eye regulate the amount of light that falls on the retina.
8. Explain the following:
   (a) Role of Na^+ in the generation of action potential.
   (b) Mechanism of generation of light-induced impulse in the retina.
   (c) Mechanism through which a sound produces a nerve impulse in the inner ear.
9. Differentiate between:
   (a) Myelinated and non-myelinated axons
   (b) Dendrites and axons
   (c) Rods and cones
   (d) Thalamus and Hypothalamus
   (e) Cerebrum and Cerebellum
10. Answer the following:
    (a) Which part of the ear determines the pitch of a sound?
    (b) Which part of the human brain is the most developed?
    (c) Which part of our central neural system acts as a master clock?
11. The region of the vertebrate eye, where the optic nerve passes out of the retina, is called the
    (a) fovea
    (b) iris
    (c) blind spot
    (d) optic chaisma
12. Distinguish between:
    (a) afferent neurons and efferent neurons
    (b) impulse conduction in a myelinated nerve fibre and unmyelinated nerve fibre
    (c) aqueous humor and vitreous humor
    (d) blind spot and yellow spot
    (f) cranial nerves and spinal nerves.

Chapter 22

Chemical Coordination and Integration

You have already learnt that the neural system provides a point-to-point rapid coordination among organs. The neural coordination is fast but short-lived. As the nerve fibres do not innervate all cells of the body and the cellular functions need to be continuously regulated; a special kind of coordination and regulation has to be provided. This function is carried out by hormones. The neural system and the endocrine system jointly coordinate and regulate the physiological functions in the body.

22.1 Endocrine Glands and Hormones

Endocrine glands lack ducts and are hence, called ductless glands. Their secretions are called hormones. The classical definition of hormone as a chemical produced by endocrine glands and released into the blood and transported to a distantly located target organ has current scientific definition as follows: **Hormones are non-nutrient chemicals which act as intercellular messengers and are produced in trace amounts**. The new definition covers a number of new molecules in addition to the hormones secreted by the organised endocrine glands. Invertebrates possess very simple endocrine systems with few hormones whereas a large number of chemicals act as hormones and provide coordination in the vertebrates. The human endocrine system is described here.

22.2 HUMAN ENDOCRINE SYSTEM

The endocrine glands and hormone producing diffused tissues/cells located in different parts of our body constitute the endocrine system. Pituitary, pineal, thyroid, adrenal, pancreas, parathyroid, thymus and gonads (testis in males and ovary in females) are the organised endocrine bodies in our body (Figure 22.1). In addition to these, some other organs, e.g., gastrointestinal tract, liver, kidney, heart also produce hormones. A brief account of the structure and functions of all major endocrine glands and hypothalamus of the human body is given in the following sections.

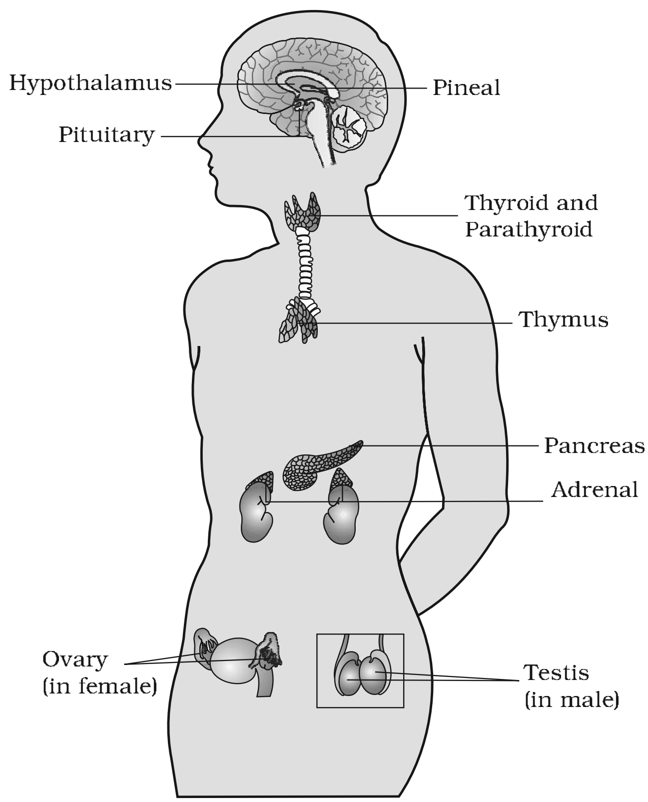


Figure 22.1 Location of endocrine glands

22.2.1 The Hypothalamus

As you know, the hypothalamus is the basal part of diencephalon, forebrain (Figure 22.1) and it regulates a wide spectrum of body functions. It contains several groups of neurosecretory cells called nuclei which produce hormones. These hormones regulate the synthesis and secretion of pituitary hormones. However, the hormones produced by hypothalamus are of two types, the releasing hormones (which stimulate secretion of pituitary hormones) and the inhibiting hormones (which inhibit secretions of pituitary hormones). For example a hypothalamic hormone called Gonadotrophin releasing hormone (GnRH) stimulates the pituitary synthesis and release of gonadotrophins. On the other hand, somatostatin from the hypothalamus inhibits the release of growth hormone from the pituitary. These hormones originating in the hypothlamic neurons, pass through axons and are released from their nerve endings. These hormones reach the pituitary gland through a portal circulatory system and regulate the functions of the anterior pituitary. The posterior pituitary is under the direct neural regulation of the hypothalamus (Figure 22.2).

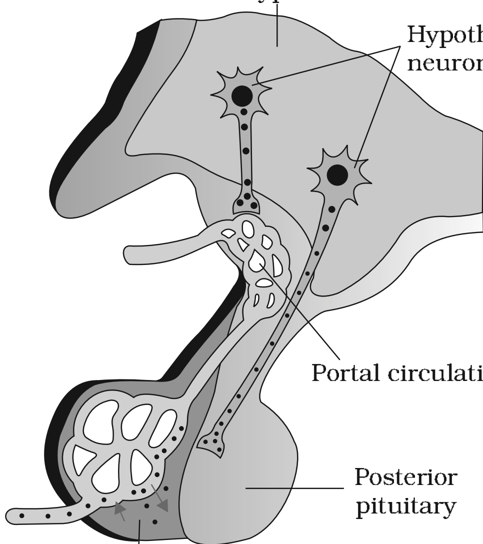


Figure 22.2 Diagrammatic representation of pituitary and its relationship with hypothalamus

22.2.2 The Pituitary Gland

The pituitary gland is located in a bony cavity called sella tursica and is attached to hypothalamus by a stalk (Figure 22.2). It is divided anatomically into an **adenohypophysis** and a **neurohypophysis**. Adenohypophysis consists of two portions, pars distalis and pars intermedia. The pars distalis region of pituitary, commonly called anterior pituitary, produces **growth hormone** (GH), **prolactin** (PRL), **thyroid stimulating hormone** (TSH), **adrenocorticotrophic hormone** (ACTH), **luteinizing hormone** (LH) and **follicle stimulating hormone** (FSH). Pars intermedia secretes only one hormone called **melanocyte stimulating hormone** (MSH). However, in humans, the pars intermedia is almost merged with pars distalis. Neurohypophysis (pars nervosa) also known as posterior pituitary, stores and releases two hormones called **oxytocin** and **vasopressin,** which are actually synthesised by the hypothalamus and are transported axonally to neurohypophysis.

Over-secretion of GH stimulates abnormal growth of the body leading to gigantism and low secretion of GH results in stunted growth resulting in pituitary dwarfism. Prolactin regulates the growth of the mammary glands and formation of milk in them. TSH stimulates the synthesis and secretion of thyroid hormones from the thyroid gland. ACTH stimulates the synthesis and secretion of steroid hormones called **glucocorticoids** from the adrenal cortex. LH and FSH stimulate gonadal activity and hence are called **gonadotrophins**. In males, LH stimulates the synthesis and secretion of hormones called **androgens** from testis. In males, FSH and androgens regulate spermatogenesis. In females, LH induces ovulation of fully mature follicles (graafian follicles) and maintains the corpus luteum, formed from the remnants of the graafian follicles after ovulation. FSH stimulates growth and development of the ovarian follicles in females. MSH acts on the melanocytes (melanin containing cells) and regulates pigmentation of the skin. Oxytocin acts on the smooth muscles of our body and stimulates their contraction. In females, it stimulates a vigorous contraction of uterus at the time of child birth, and milk ejection from the mammary gland. Vasopressin acts mainly at the kidney and stimulates resorption of water and electrolytes by the distal tubules and thereby reduces loss of water through urine (diuresis). Hence, it is also called as **anti-diuretic hormone** (ADH).

22.2.3 The Pineal Gland

The pineal gland is located on the dorsal side of forebrain. Pineal secretes a hormone called **melatonin**. Melatonin plays a very important role in the regulation of a 24-hour (diurnal) rhythm of our body. For example, it helps in maintaining the normal rhythms of sleep-wake cycle, body temperature. In addition, melatonin also influences metabolism, pigmentation, the menstrual cycle as well as our defense capability.

22.2.4 Thyroid Gland

The thyroid gland is composed of two lobes which are located on either side of the trachea (Figure 22.3). Both the lobes are interconnected with a thin flap of connective tissue called isthmus. The thyroid gland is composed of **follicles** and **stromal tissues**. Each thyroid follicle is composed of follicular cells, enclosing a cavity. These follicular cells synthesise two hormones, **tetraiodothyronine** or **thyroxine** (T_4) and **triiodothyronine** (T_3). Iodine is essential for the normal rate of hormone synthesis in the thyroid. Deficiency of iodine in our diet results in **hypothyroidism** and enlargement of the thyroid gland, commonly called **goitre**. Hypothyroidism during pregnancy causes defective development and maturation of the growing baby leading to stunted growth (cretinism), mental retardation, low intelligence quotient, abnormal skin, deaf-mutism, etc. In adult women, hypothyroidism may cause menstrual cycle to become irregular. Due to cancer of the thyroid gland or due to development of nodules of the thyroid glands, the rate of synthesis and secretion of the thyroid hormones is increased to abnormal high levels leading to a condition called **hyperthyroidism** which adversely affects the body physiology.

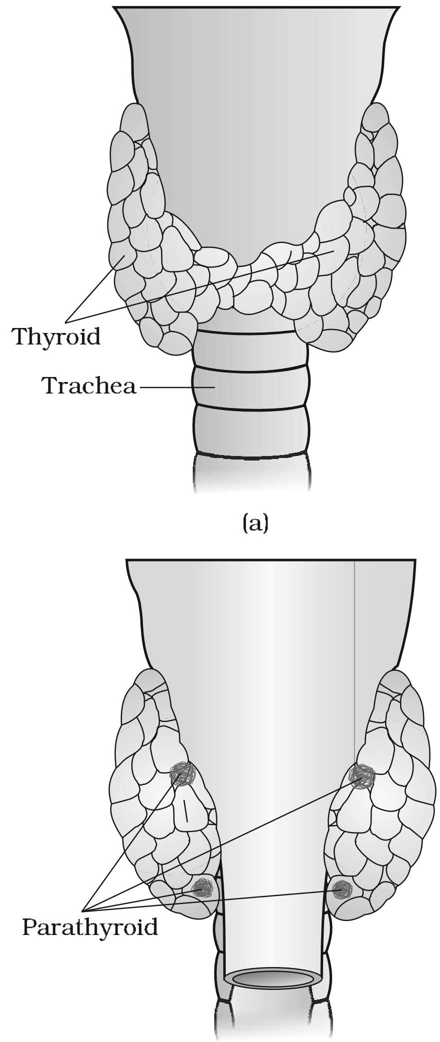


Figure 22.3 Diagrammatic view of the position of Thyroid and Parathyroid
(a) Dorsal side
(b) Ventral side

Thyroid hormones play an important role in the regulation of the basal metabolic rate. These hormones also support the process of red blood cell formation. Thyroid hormones control the metabolism of carbohydrates, proteins and fats. Maintenance of water and electrolyte balance is also influenced by thyroid hormones. Thyroid gland also secretes a protein hormone called thyrocalcitonin (TCT) which regulates the blood calcium levels.

22.2.5 Parathyroid Gland

In humans, four parathyroid glands are present on the back side of the thyroid gland, one pair each in the two lobes of the thyroid gland (Figure 22.3b). The parathyroid glands secrete a peptide hormone called **parathyroid hormone** (PTH). The secretion of PTH is regulated by the circulating levels of calcium ions.

Parathyroid hormone (PTH) increases the Ca^{2+} levels in the blood. PTH acts on bones and stimulates the process of bone resorption (dissolution/ demineralisation). PTH also stimulates reabsorption of Ca^{2+} by the renal tubules and increases Ca^{2+} absorption from the digested food. It is, thus, clear that PTH is a hypercalcemic hormone, i.e., it increases the blood Ca^{2+} levels. Along with TCT, it plays a significant role in calcium balance in the body.

22.2.6 Thymus

The thymus gland is a lobular structure located on the dorsal side of the heart and the aorta. The thymus plays a major role in the development of the immune system. This gland secretes the peptide hormones called **thymosins**. Thymosins play a major role in the differentiation of **T-lymphocytes**, which provide **cell-mediated immunity**. In addition, thymosins also promote production of antibodies to provide **humoral immunity**. Thymus is degenerated in old individuals resulting in a decreased production of thymosins. As a result, the immune responses of old persons become weak.

22.2.7 Adrenal Gland

Our body has one pair of adrenal glands, one at the anterior part of each kidney (Figure 22.4 a). The gland is composed of two types of tissues. The centrally located tissue is called the **adrenal medulla**, and outside this lies the **adrenal cortex** (Figure 22.4 b).

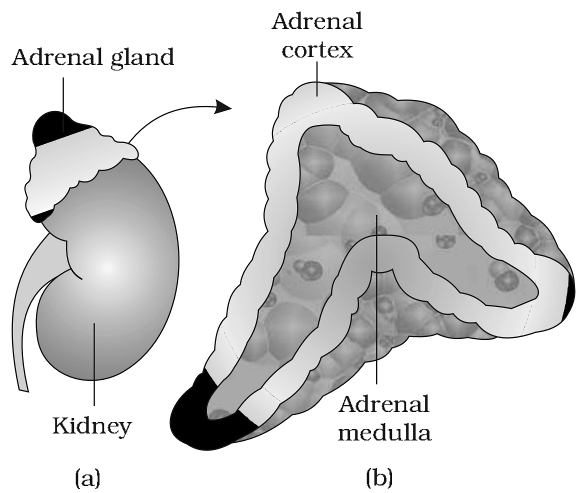


Figure 22.4 Diagrammatic representation of : (a) Adrenal gland on kidney (b) Section showing two parts of adrenal gland

The adrenal medulla secretes two hormones called **adrenaline** or **epinephrine** and **noradrenaline** or **norepinephrine**. These are commonly called as **catecholamines**. Adrenaline and noradrenaline are rapidly secreted in response to stress of any kind and during emergency situations and are called **emergency hormones** or **hormones of Fight or Flight**. These hormones increase alertness, pupilary dilation, piloerection (raising of hairs), sweating etc. Both the hormones increase the heart beat, the strength of heart contraction and the rate of respiration. Catecholamines also stimulate the breakdown of glycogen resulting in an increased concentration of glucose in blood. In addition, they also stimulate the breakdown of lipids and proteins.

The adrenal cortex can be divided into three layers, called **zona reticularis** (inner layer), **zona fasciculata** (middle layer) and **zona glomerulosa** (outer layer). The adrenal cortex secretes many hormones, commonly called as **corticoids**. The corticoids, which are involved in carbohydrate metabolism are called glucocorticoids. In our body, cortisol is the main glucocorticoid. Corticoids, which regulate the balance of water and electrolytes in our body are called mineralocorticoids. Aldosterone is the main mineralocorticoid in our body.

Glucocorticoids stimulate, gluconeogenesis, lipolysis and proteolysis; and inhibit cellular uptake and utilisation of amino acids. Cortisol is also involved in maintaining the cardio-vascular system as well as the kidney functions. Glucocorticoids, particularly cortisol, produces anti-inflamatory reactions and suppresses the immune response. Cortisol stimulates the RBC production. Aldosterone acts mainly at the renal tubules and stimulates the reabsorption of Na^+ and water and excretion of K^+ and phosphate ions. Thus, aldosterone helps in the maintenance of electrolytes, body fluid volume, osmotic pressure and blood pressure. Small amounts of androgenic steroids are also secreted by the adrenal cortex which play a role in the growth of axial hair, pubic hair and facial hair during puberty.

22.2.8 Pancreas

Pancreas is a composite gland (Figure 22.1) which acts as both exocrine and endocrine gland. The endocrine pancreas consists of 'Islets of Langerhans'. There are about 1 to 2 million Islets of Langerhans in a normal human pancreas representing only 1 to 2 per cent of the pancreatic tissue. The two main types of cells in the Islet of Langerhans are called **α-cells** and **β-cells**. The α-cells secrete a hormone called **glucagon**, while the β-cells secrete **insulin**.

Glucagon is a peptide hormone, and plays an important role in maintaining the normal blood glucose levels. Glucagon acts mainly on the liver cells (hepatocytes) and stimulates glycogenolysis resulting in an increased blood sugar (**hyperglycemia**). In addition, this hormone stimulates the process of gluconeogenesis which also contributes to hyperglycemia. Glucagon reduces the cellular glucose uptake and utilisation. Thus, glucagon is a **hyperglycemic hormone**.

Insulin is a peptide hormone, which plays a major role in the regulation of glucose homeostasis. Insulin acts mainly on hepatocytes and adipocytes (cells of adipose tissue), and enhances cellular glucose uptake and utilisation. As a result, there is a rapid movement of glucose from blood to hepatocytes and adipocytes resulting in decreased blood glucose levels (**hypoglycemia**). Insulin also stimulates conversion of glucose to glycogen (**glycogenesis**) in the target cells. The glucose homeostasis in blood is thus maintained jointly by the two – insulin and glucagons.

Prolonged hyperglycemia leads to a complex disorder called **diabetes mellitus** which is associated with loss of glucose through urine and formation of harmful compounds known as ketone bodies. Diabetic patients are successfully treated with insulin therapy.

22.2.9 Testis

A pair of testis is present in the scrotal sac (outside abdomen) of male individuals (Figure 22.1). Testis performs dual functions as a primary sex organ as well as an endocrine gland. Testis is composed of **seminiferous tubules** and **stromal or interstitial tissue.** The **Leydig cells** or **interstitial cells**, which are present in the intertubular spaces produce a group of hormones called **androgens** mainly **testosterone.**

Androgens regulate the development, maturation and functions of the male accessory sex organs like epididymis, vas deferens, seminal vesicles, prostate gland, urethra etc. These hormones stimulate muscular growth, growth of facial and axillary hair, aggressiveness, low pitch of voice etc. Androgens play a major stimulatory role in the process of spermatogenesis (formation of spermatozoa). Androgens act on the central neural system and influence the male sexual behaviour (libido). These hormones produce anabolic (synthetic) effects on protein and carbohydrate metabolism.

22.2.10 Ovary

Females have a pair of ovaries located in the abdomen (Figure 22.1). Ovary is the primary female sex organ which produces one ovum during each menstrual cycle. In addition, ovary also produces two groups of steroid hormones called **estrogen** and **progesterone**. Ovary is composed of ovarian follicles and stromal tissues. The estrogen is synthesised and secreted mainly by the growing ovarian follicles. After ovulation, the ruptured follicle is converted to a structure called **corpus luteum**, which secretes mainly **progesterone**.

Estrogens produce wide ranging actions such as stimulation of growth and activities of female secondary sex organs, development of growing ovarian follicles, appearance of female secondary sex characters (e.g., high pitch of voice, etc.), mammary gland development. Estrogens also regulate female sexual behaviour.

Progesterone supports pregnancy. Progesterone also acts on the mammary glands and stimulates the formation of alveoli (sac-like structures which store milk) and milk secretion.

22.3 HORMONES OF HEART, KIDNEY AND GASTROINTESTINAL TRACT

Now you know about the endocrine glands and their hormones. However, as mentioned earlier, hormones are also secreted by some tissues which are not endocrine glands. For example, the atrial wall of our heart secretes a very important peptide hormone called **atrial natriuretic factor** (ANF), which decreases blood pressure. When blood pressure is increased, ANF is secreted which causes dilation of the blood vessels. This reduces the blood pressure.

The juxtaglomerular cells of kidney produce a peptide hormone called **erythropoietin** which stimulates erythropoiesis (formation of RBC).

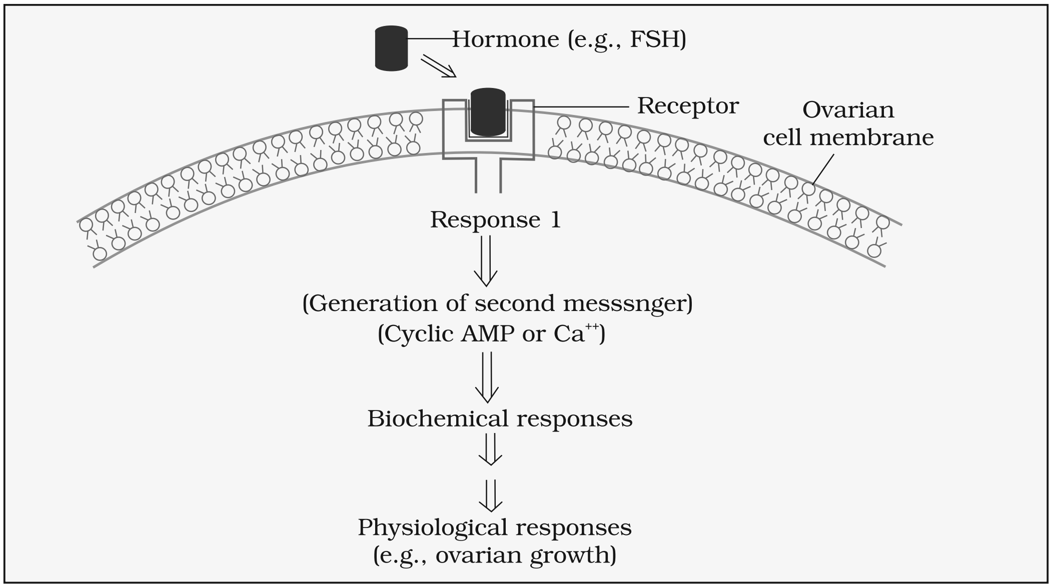
Endocrine cells present in different parts of the gastro-intestinal tract secrete four major peptide hormones, namely **gastrin**, **secretin**, **cholecystokinin** (CCK) and **gastric inhibitory peptide** (GIP). Gastrin acts on the gastric glands and stimulates the secretion of hydrochloric acid and pepsinogen. Secretin acts on the exocrine pancreas and stimulates secretion of water and bicarbonate ions. CCK acts on both pancreas and gall bladder and stimulates the secretion of pancreatic enzymes and bile juice, respectively. GIP inhibits gastric secretion and motility. Several other non-endocrine tissues secrete hormones called **growth factors.** These factors are essential for the normal growth of tissues and their repairing/regeneration.

22.4 Mechanism of Hormone Action

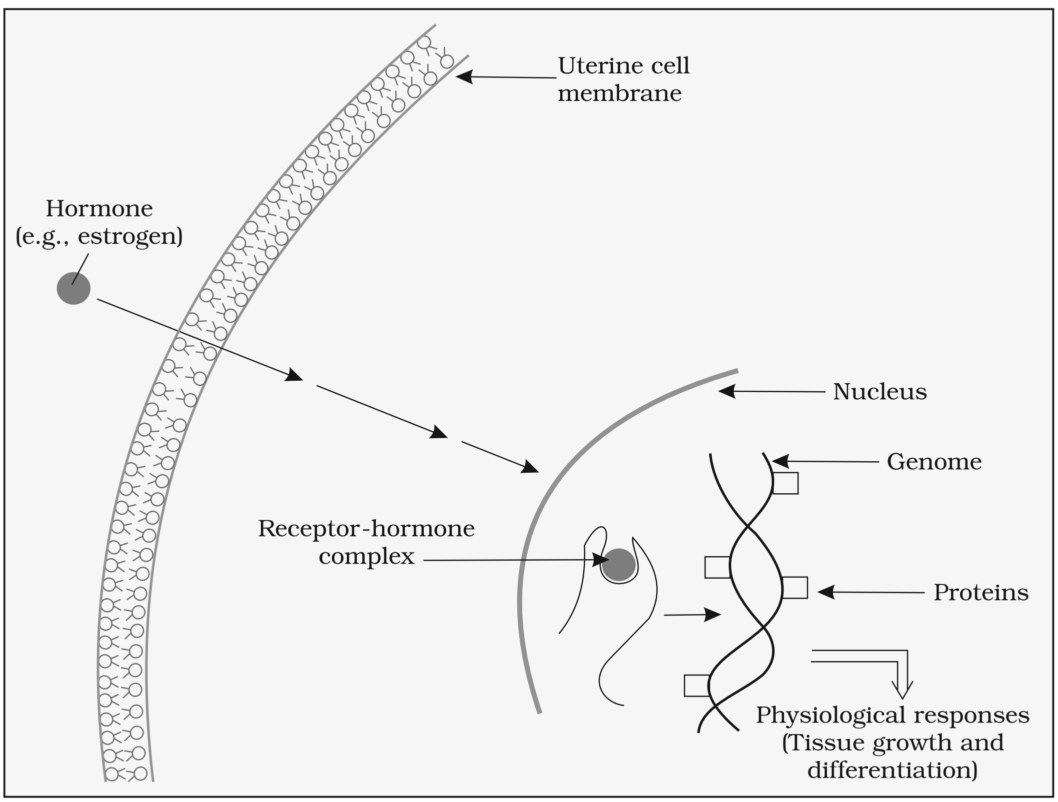
Hormones produce their effects on target tissues by binding to specific proteins called **hormone receptors** located in the target tissues only. Hormone receptors present on the cell membrane of the target cells are called membrane-bound receptors and the receptors present inside the target cell are called intracellular receptors, mostly nuclear receptors (present in the nucleus). Binding of a hormone to its receptor leads to the formation of a **hormone-receptor complex** (Figure 22.5 a, b). Each receptor is specific to one hormone only and hence receptors are specific. Hormone-Receptor complex formation leads to certain biochemical changes in the target tissue. Target tissue metabolism and hence physiological functions are regulated by hormones. On the basis of their chemical nature, hormones can be divided into groups :

(i) **peptide, polypeptide, protein hormones** (e.g., insulin, glucagon, pituitary hormones, hypothalamic hormones, etc.)
(ii) **steroids** (e.g., cortisol, testosterone, estradiol and progesterone)
(iii) **iodothyronines** (thyroid hormones)
(iv) **amino-acid derivatives** (e.g., epinephrine).

Hormones which interact with membrane-bound receptors normally do not enter the target cell, but generate second messengers (e.g., cyclic AMP, IP_3, Ca^{++} etc) which in turn regulate cellular metabolism (Figure 22.5a). Hormones which interact with intracellular receptors (e.g., steroid hormones, iodothyronines, etc.) mostly regulate gene expression or chromosome function by the interaction of hormone-receptor complex with the genome. Cumulative biochemical actions result in physiological and developmental effects (Figure 22.5b).



(a)



(b)

Figure 22.5 Diagramatic representation of the mechanism of hormone action : (a) Protein hormone (b) Steroid hormone

SUMMARY

There are special chemicals which act as hormones and provide chemical coordination, integration and regulation in the human body. These hormones regulate metabolism, growth and development of our organs, the endocrine glands or certain cells. The endocrine system is composed of hypothalamus, pituitary and pineal, thyroid, adrenal, pancreas, parathyroid, thymus and gonads (testis and ovary). In addition to these, some other organs, e.g., gastrointestinal tract, kidney, heart etc., also produce hormones. The pituitary gland is divided into three major parts, which are called as pars distalis, pars intermedia and pars nervosa. Pars distalis produces six trophic hormones. Pars intermedia secretes only one hormone, while pars nervosa (neurohypophysis) secretes two hormones. The pituitary hormones regulate the growth and development of somatic tissues and activities of peripheral endocrine glands. Pineal gland secretes melatonin, which plays a very important role in the regulation of 24-hour (diurnal) rhythms of our body (e.g., rhythms of sleep and state of being awake, body temperature, etc.). The thyroid gland hormones play an important role in the regulation of the basal metabolic rate, development and maturation of the central neural system, erythropoiesis, metabolism of carbohydrates, proteins and fats, menstrual cycle. Another thyroid hormone, i.e., thyrocalcitonin regulates calcium levels in our blood by decreasing it. The parathyroid glands secrete parathyroid hormone (PTH) which increases the blood Ca^{2+} levels and plays a major role in calcium homeostasis. The thymus gland secretes thymosins which play a major role in the differentiation of T-lymphocytes, which provide cell-mediated immunity. In addition, thymosins also increase the production of antibodies to provide humoral immunity. The adrenal gland is composed of the centrally located adrenal medulla and the outer adrenal cortex. The adrenal medulla secretes epinephrine and norepinephrine. These hormones increase alertness, pupilary dilation, piloerection, sweating, heart beat, strength of heart contraction, rate of respiration, glycogenolysis, lipolysis, proteolysis. The adrenal cortex secretes glucocorticoids and mineralocorticoids. Glucocorticoids stimulate gluconeogenesis, lipolysis, proteolysis, erythropoiesis, cardio-vascular system, blood pressure, and glomerular filtration rate and inhibit inflammatory reactions by suppressing the immune response. Mineralocorticoids regulate water and electrolyte contents of the body. The endocrine pancreas secretes glucagon and insulin. Glucagon stimulates glycogenolysis and gluconeogenesis resulting in hyperglycemia. Insulin stimulates cellular glucose uptake and utilisation, and glycogenesis resulting in hypoglycemia. Insulin deficiency and/or insulin resistance result in a disease called diabetes mellitus.

The testis secretes androgens, which stimulate the development, maturation and functions of the male accessory sex organs, appearance of the male secondary sex characters, spermatogenesis, male sexual behaviour, anabolic pathways and erythropoiesis. The ovary secretes estrogen and progesterone. Estrogen stimulates

growth and development of female accessory sex organs and secondary sex characters. Progesterone plays a major role in the maintenance of pregnancy as well as in mammary gland development and lactation. The atrial wall of the heart produces atrial natriuretic factor which decreases the blood pressure. Kidney produces erythropoietin which stimulates erythropoiesis. The gastrointestinal tract secretes gastrin, secretin, cholecystokinin and gastric inhibitory peptide. These hormones regulate the secretion of digestive juices and help in digestion.

EXERCISES

1. Define the following:
   (a) Exocrine gland
   (b) Endocrine gland
   (c) Hormone
2. Diagrammatically indicate the location of the various endocrine glands in our body.
3. List the hormones secreted by the following:

(a) Hypothalamus	(b) Pituitary	(c) Thyroid	(d) Parathyroid
(e) Adrenal	(f) Pancreas	(g) Testis	(h) Ovary
(i) Thymus	(j) Atrium	(k) Kidney	(l) G-I Tract

4. Fill in the blanks:

Hormones	**Target gland**
(a) Hypothalamic hormones	__________________
(b) Thyrotrophin (TSH)	__________________
(c) Corticotrophin (ACTH)	__________________
(d) Gonadotrophins (LH, FSH)	__________________
(e) Melanotrophin (MSH)	__________________

5. Write short notes on the functions of the following hormones:

(a) Parathyroid hormone (PTH)	(b) Thyroid hormones
(c) Thymosins	(d) Androgens
(e) Estrogens	(f) Insulin and Glucagon

6. Give example(s) of:
   (a) Hyperglycemic hormone and hypoglycemic hormone
   (b) Hypercalcemic hormone
   (c) Gonadotrophic hormones
   (d) Progestational hormone
   (e) Blood pressure lowering hormone
   (f) Androgens and estrogens

7. Which hormonal deficiency is responsible for the following:

   (a) Diabetes mellitus (b) Goitre (c) Cretinism

8. Briefly mention the mechanism of action of FSH.

9. Match the following:

Column I	**Column II**
(a) T_4	(i) Hypothalamus
(b) PTH	(ii) Thyroid
(c) GnRH	(iii) Pituitary
(d) LH	(iv) Parathyroid