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Paper II: Plant Cell Biology

Unit-II

Lesson: Cell Membrane Structure

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Introduction

- Cell is the smallest living entity of all living organisms, and is delimited from the surrounding cellular environment by **cell membrane**.
- Cell membrane is also known as **plasma membrane** or **cytoplasmic membrane** since it encloses the cellular content called **cytoplasm** (plasma was the original name for cellular content).
- Membranes form the outermost **boundaries** of the animal cells whereas a rigid cell wall is present outside the membrane in plant cells.
- The intracellular organelles in eukaryotic cells are also surrounded by membranes, hence the cell membranes also help in **intracellular compartmentalization** of the eukaryotic cells.
- All membrane compartments have specific functions related to the unique molecular structure of the membrane.
- The cell membrane regulates the **transport** of the substances into and out of the cell. The exchange of nutrients, ions, gases, water and other substances takes place through the membranes.
- Plasma membrane provides **differential** or **selective** permeable barrier which allows only selective molecules to cross the membrane. Unrestricted exchange of molecules is not possible through the membrane.
- Cellular waste is also removed through the membrane hence helps in **excretion** of waste.
- **Intercellular interaction** in a multicellular organism is possible through the cell membrane since each cell is connected to its adjacent cell.
- In animals and plants, cell-to-cell communication is possible through the **gap junctions** and **plasmodesmata** respectively.
- The outer surface of the membrane plays key role in **signal transduction** (both electrical and chemical). This includes both the detection of specific signals on the outer surface of the cell and the response that results within the cell.

Membrane Models (A Historical Overview)

Several models have been proposed to explain the structure of membranes. The models are proposed based on experimental observations and results. With the rapid progress in scientific research and technology one model may replace another, but it does not imply that earlier models are worthless. Every model has to face new challenges, which inspire experiments leading to the proposal of new model to explain the challenges faced by earlier models. Therefore, all the historical models are of immense importance for understanding the precise structure and function of the membrane.

- E. Overton (1899) did extensive studies on the penetration of more than 500 different chemical compounds in both plant and animal cells. He established that the membranes of both plants and animals are 'impregnated' by lipid like material since, compounds soluble in organic solvents entered the cell more rapidly than water-soluble compounds. Overton later suggested that the two important lipids present in the membrane might be cholesterol and lecithins.

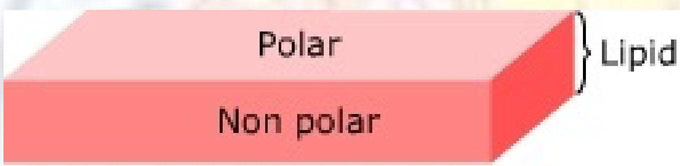


Figure: Lipid nature of membrane
Source: Author

- Irving Langmuir (1917) made the second important advancement by spreading the lipid molecules in a monolayer on water surface in a specially designed apparatus called **Langmuir Trough**. This helped in measuring the area occupied by a single lipid molecule along with the surface area of the entire thin film of lipid. He later received Nobel Prize in chemistry in 1932. This important technique was widely used in the study of specific membrane lipids.

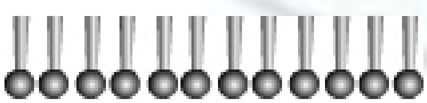


Figure: Lipid monolayer
Source :Author

- E. Gorter and F. Grendel did extensive studies on the organization of membrane lipids in red blood cells (erythrocytes) from a variety of mammals including dogs, sheep, rabbit, goat, human and obtained consistent results. Using Langmuir trough, the lipids from the erythrocytes, were allowed to form a tightly packed monolayer and the surface area of the lipid monolayer was calculated. His experiment led to an interesting finding that the total surface area of the monolayer is almost twice that of the surface area of the individual erythrocyte plasma membrane. Gorter and Grendel then proposed that the lipids of the cell membrane are organised in a **bimolecular lipid** sheet. They also added that the membrane lipids have hydrophobic (non-polar) and a hydrophilic (polar) ends which result in such an arrangement where all cell membranes face aqueous environment on their either side resulting in the polar ends of the lipids facing the outer surface of the membranes keeping the non-polar ends of the lipids embedded in the centre. This model named **bimolecular lipid leaflet model** got support even after the use of advance scientific techniques like X-ray diffraction, ESR, Freeze fracture etc.

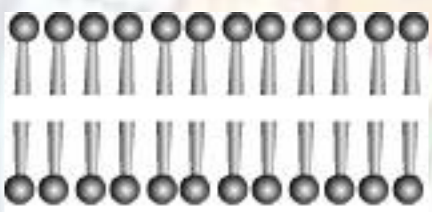


Figure: Lipid bilayer – the hydrophobic tails are positioned inwards while the hydrophilic heads point outwards
Source: Author

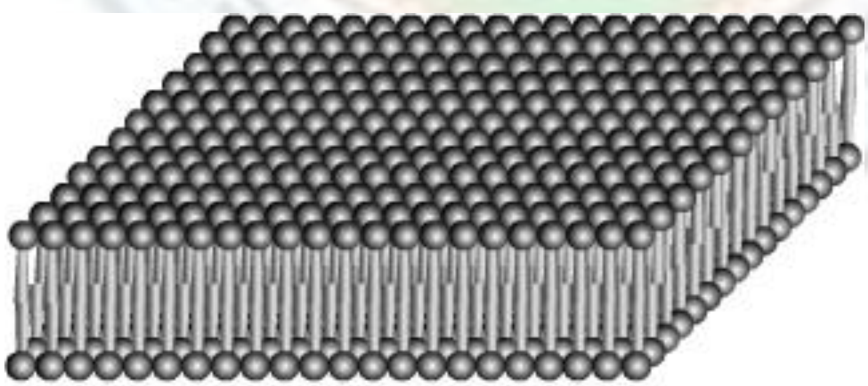


Figure: Lipid bilayer (3-D view)
Source: Author

- J.F . Danielli and E.N. Harvey (1935) noticed the presence of other inclusions in the lipid bilayer and added that the polar surface of the bilayer consists of monomolecular layers of protein, which interact with the hydrated molecules to form an organized layer. This finding was based on the observation that the cell membrane showed consistent low surface tension compared to bimolecular lipid leaflet.

- J. Danielli and H. Davson (1935) also realized that only lipid bilayer cannot account for all the essential properties of the membranes like selective permeability and electrical resistance, hence they suggested that plasma membranes might be composed of lipid- protein bilayers instead of only lipid layer. One such lipid-protein layer faces the interior of the cell (towards cytoplasm) and the other faces the external milieu. They also added that the polar ends of the lipid molecules maintain electrostatic interactions with the charged amino acid side chains of protein layers. The selective permeability of the cell membrane can be explained in such membrane, since any other group of molecules could bind to the outer protein surface by electrostatic or van der waals forces.

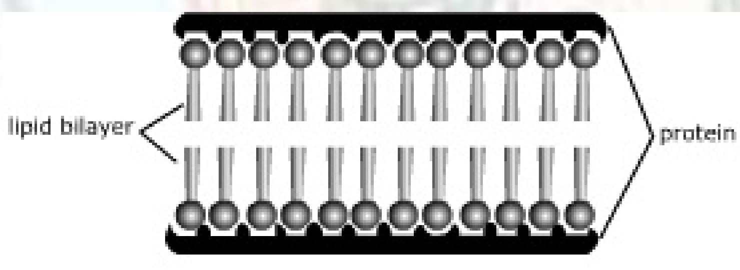


Figure: Danielli- Davson model
Source :Author

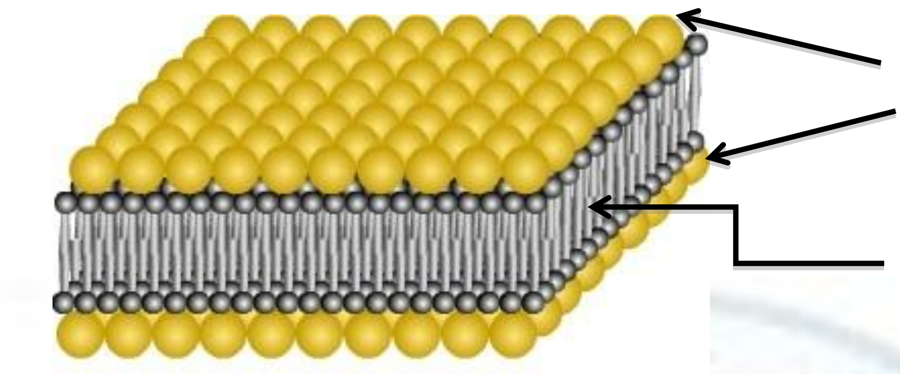


Figure: 3-D depiction of a lipid bilayer plus protein sheets as described by Danielli and Davson

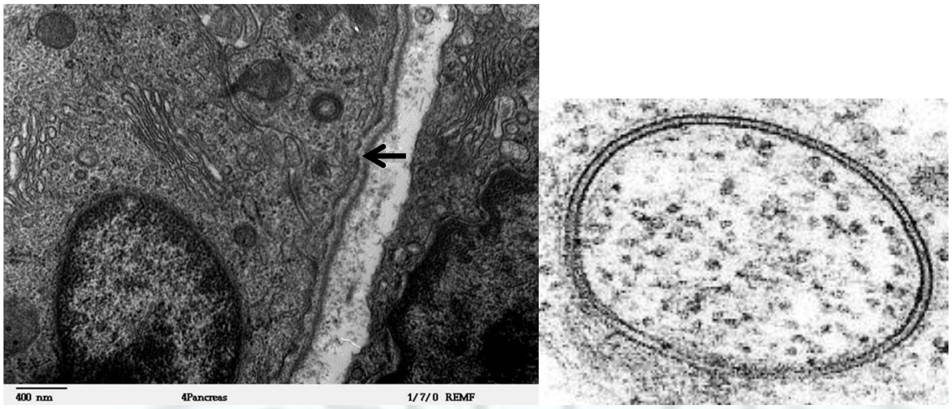
Source :Author

- In 1950 Danielli and Davson made several modifications in their model:

  (1) They reported the presence of adsorbed glycoproteins on the outer surface of the membrane which they said accounted for the antigenic properties of the cell membranes.

  (2) Exchange of materials between a cell and its environment was presumed to be due to the presence of periodic discontinuities between the outer and inner protein layers forming channels which open through pores on the membrane surface.

- J.D. Robertson (1950) who was a pioneer in the field of studying membrane ultrastructure showed that osmium tetraoxide (a heavy metal stain used for electron microscopic studies) fixed membranes and revealed the typical **trilaminar** appearance of the membrane consisting of two parallel outer dark (osmophilic) layers and a central light (osmophobic) layer. Each osmophilic layer measured 2.0-2.5 nm in thickness and the osmophobic layer measured 2.5-3.5 nm yielding a total thickness of 6.5-8.5 nm. Such a thickness of the membrane could also be predicted based on its chemical studies. Many other cellular membranes like endoplasmic membrane also revealed trilaminar pattern of the membrane. Robertson proposed the term **unit membrane** model in view of the underlying unity in the appearance of all cell membranes. Unit membranes consisted of bimolecular lipid leaflet sandwiched between the two protein layers on either side. The unit membrane model was presumed to be universal for all cell membranes, though the existence of certain chemical differences between different membranes was acknowledged by Robertson.



A. **B.**

Figure: Electron micrographs showing the trilaminar nature of cell membrane. The parallel outer dark (osmophilic) layers separate a central light (osmophobic) layer.

Source: A. http://php.med.unsw.edu.au/cellbiology/images/2/26/Tem_cellstructures2.jpg

B. http://upload.wikimedia.org/wikipedia/commons/7/7b/Annular_Gap_Junction_Vesicle.jpg

- S.J. Singer and G. Nicholson (1972)-Intensive studies on membranes revealed that not only the membrane proteins are globular in nature but they also differ in their size, shape and content in different types of membranes. The observation was inconsistent with the concept of layer or sheets of protein on either surface of the membrane . The various other findings led to the concept of membrane fluidity. The widely accepted fluid mosaic model of the membrane, was first proposed by S.J. singer and G. Nicholson. As the name suggests the membrane is a fluid structure in which a **mosaic** of different types of proteins are discontinuously embedded. The basic lipid bilayer concept as proposed in earlier models as proposed in earlier models is retained. However, the proteins of the membranes are not present as a continuous sheet on the its surface. The chemical composition of the membrane can also be correlated with the fluid mosaic model. Recent research suggests that the membrane may be “more mosaic than fluid”. This is due to the presence of multiple proteins, semi-permanently associated in specialized patches for carrying common functions. The membrane may be more packed with proteins than imagined in the classic mosaic model.

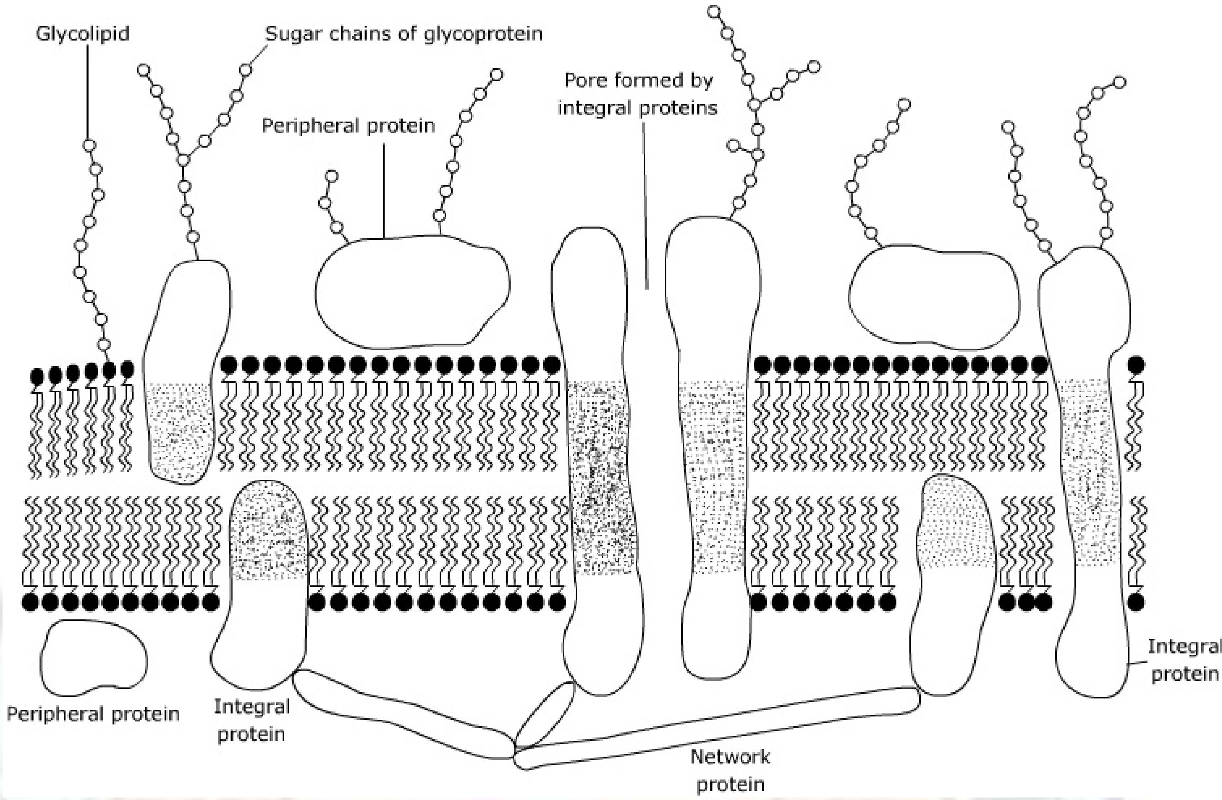


Figure: Fluid-mosaic model of the membrane

Source: Author

Tutorial: Fluid mosaic model

http://www.bio.davidson.edu/people/macampbell/111/memb-swf/membranes.swf

Chemical composition of the membrane

Lipid-protein assemblies make the major composition of all membranes. The structural frame work of the membrane is due to the lipid bilayer, whereas the protein component is responsible for its specific functions. The lipid bilayer acts as a hydrophobic barrier for the free movement of the hydrophilic substances across the membrane. The lipid and protein ratio differ in different cell types. Different cellular organelles show difference in the lipid/protein ratio even in the inner and outer membrane surfaces. Besides lipid and protein, membrane also contains some amount of carbohydrate, present either as glycoproteins or glycolipids.

Membrane lipids

Lipids are esters of alcohol and fatty acids. Membrane lipids can be easily extracted by various organic solvents and can be separated and identified by simple biochemical procedures, hence membrane lipids are well studied and characterized from different membranes. Alec Bagham and his colleagues in 1965 reported that the membrane lipids can be extracted and dispersed as **liposomes,** which are small vesicles about 0.1 nm in diameter and consists of closed spherical lipid bilayers. Liposome is an important tool in the field of membrane research, which helps in the understanding of the structure and function of the various membrane lipids.

All membrane lipids are **amphipathic** that is they contain both hydrophilic and hydrophobic regions. The amphipathic nature of the membrane lipid is responsible for the bilayer nature of the membrane. A cell being aqueous on either side makes the lipids oriented in a bilayer where the hydrophilic ends of the lipid faces outside and the hydrophobic region gets embedded in the centre to avoid the aqueous surroundings .

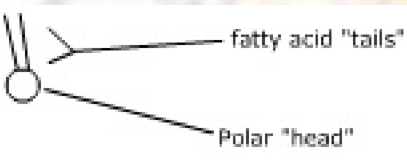


Figure: A representative phospholipid
Source: Author

The three major types of membrane lipids are (a) Phospholipid (b) Sphingolipid (c) Cholesterol.

Phospholipids

As the name suggests, the phospholipid contains a phosphate group, which makes the hydrophilic region of these lipids. All phospholipids are built on a glycerol backbone, hence called **phosphoglycerides.** Unlike triglycerides, which have three fatty acids, the phospholipids are diglycerides where only two of the hydroxyl groups of the glycerol are esterified with two fatty acids and the third hydroxyl group is esterified with phosphoric acid to give the phosphate group. The unsubstituted phosphate group with the two fatty acid chains of a phospholipid is called **phosphatidic acid.** In membrane however, the phosphatidic acid is absent and the phosphate groups are linked to additional hydrophilic groups to make a bigger hydrophilic head. Depending upon the linkage groups, the phosphatidic acids are named differently. The most common phospholipids found in all membranes are:

a) Phosphatidylcholine (PO_4 group linked to choline)
b) Phosphatidylinositol (PO_4 group linked to inositol)
c) Phosphatidylethanolamine (PO_4 group linked to ethanolamine)
d) Phosphatidylserine (PO_4 group linked to serine)

These small hydrophilic groups together with the charged phosphate to which these are attached, form a highly water-soluble domain at one end of the lipid molecule called the head group. The fatty acid chains in contact are long, unbranched hydrocarbons, which are highly hydrophobic. One of the two fatty acid chains of the phosphoglycerides is saturated whereas the other is slightly unsaturated with one or two double bonds. This unsaturation results in a small 'Kink' (molecular bend) in one of the two hydrocarbon chains of fatty acids which prevent the two adjacent fatty acid tails to be tightly fitted.

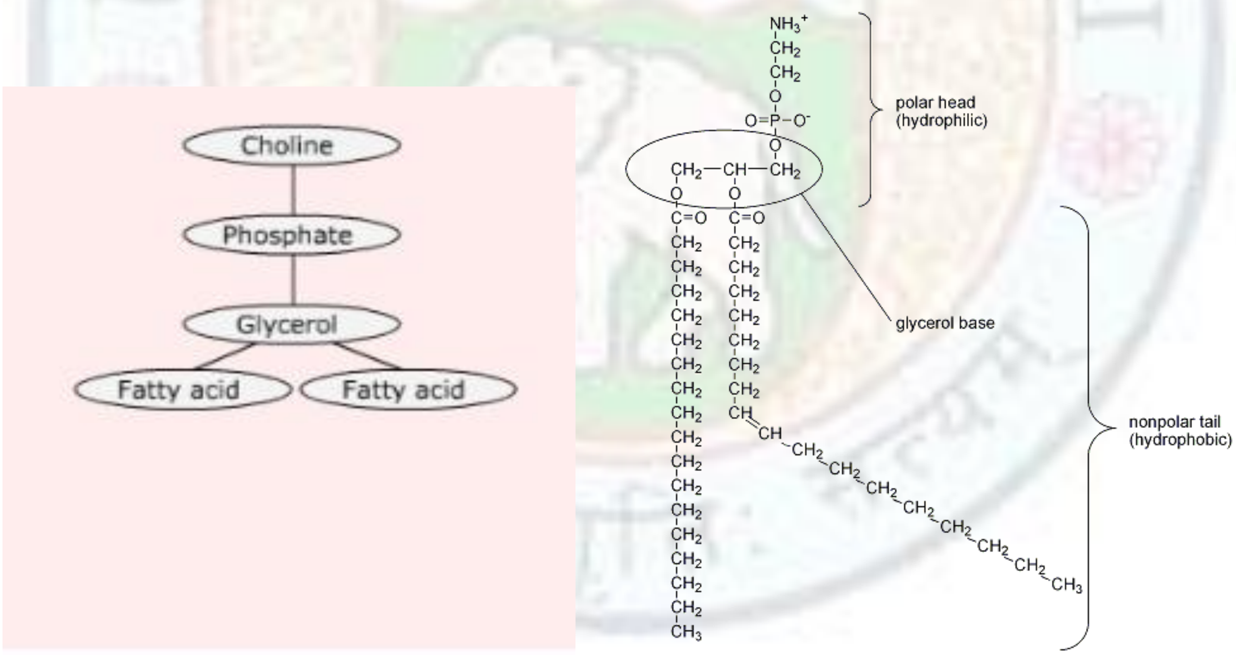


Figure: A typical phospholipid. Notice the presence of the kink (bend) because of the double bond in between.
Source: Author

Sphingolipids

This is a group of lipids derived from sphingosines, an amino alcohol that contains long hydrocarbon chain. Spingosine is linked to a fatty acid by its amino group in sphingolipids, which is known as **ceramide.** Various spingosine-based lipids having additional groups esterified to the terminal alcohol of the sphingosine moiety are named differently. Sphingomyelin is the only phospholipid of the membrane which, does not have a glycerol backbone, since it is a spingolipid where the substitute group is a phosphorylcholine.

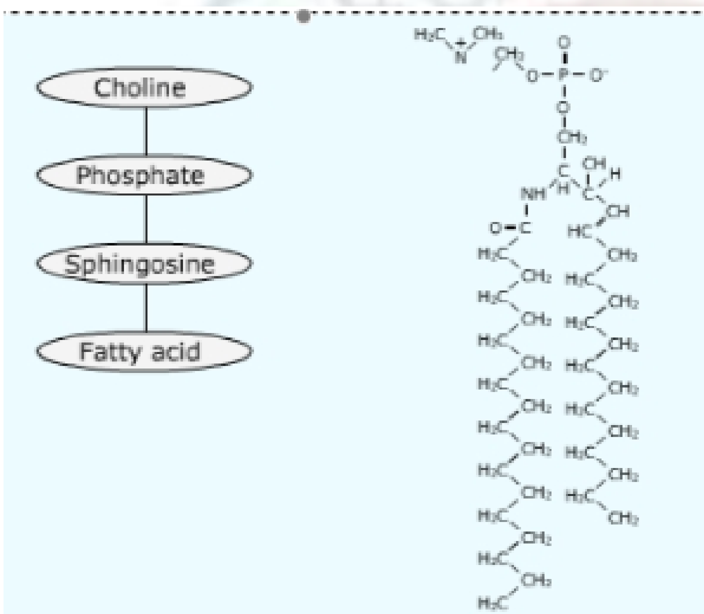


Figure:A Sphingolipid
Source: Author

Cholesterol

Cholesterol is smaller than other lipids and predominantly present in animal cell. It may constitute upto 50% of the total membrane lipid molecules. Cholesterol is absent in plants and prokaryotic bacterial cells. It is a steroid based lipid, which is highly hydrophobic in nature. One hydroxyl group at one end of the steroid ring gives the slight hydrophobic nature of the head group. To the other end of the rigid steroid ring (fused cyclohexane and cyclopentane ring), a short hydrocarbon tail is attached which makes the cholesterol molecules highly hydrophobic .

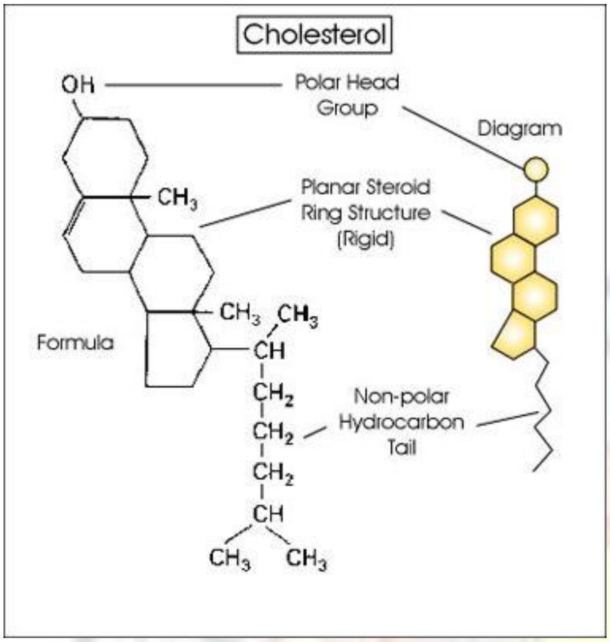


Figure: Cholesterol

Source: http://www.nfsdsystems.com/w3bio315/images/content/lectures/lecture2/Cholesterol1.jpg

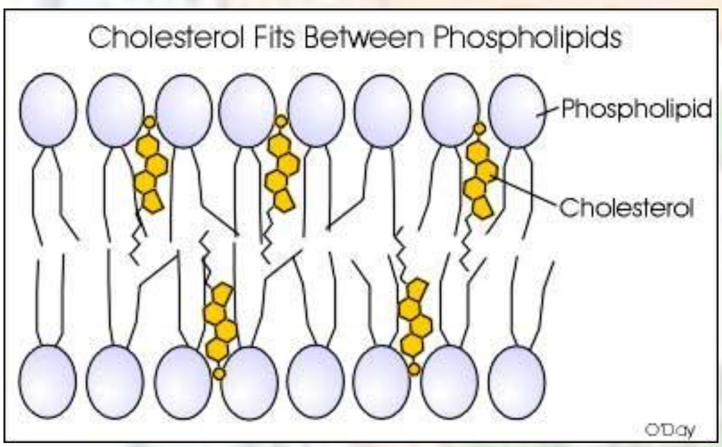


Figure: The cholesterol molecules interpolate between the lipid molecules and increases membrane fluidity

Source http://www.nfsdsystems.com/w3bio315/images/content/lectures/lecture2/Bilayer2.jpg

Membrane proteins

Protein forms the mosaic part of the membrane in the fluid mosaic model. Proteins are embedded in a nearly fluid matrix of lipid bilayer. Each cell has a unique collection of protein and types of proteins differ in different cells. There are two major types of proteins present in all membranes .

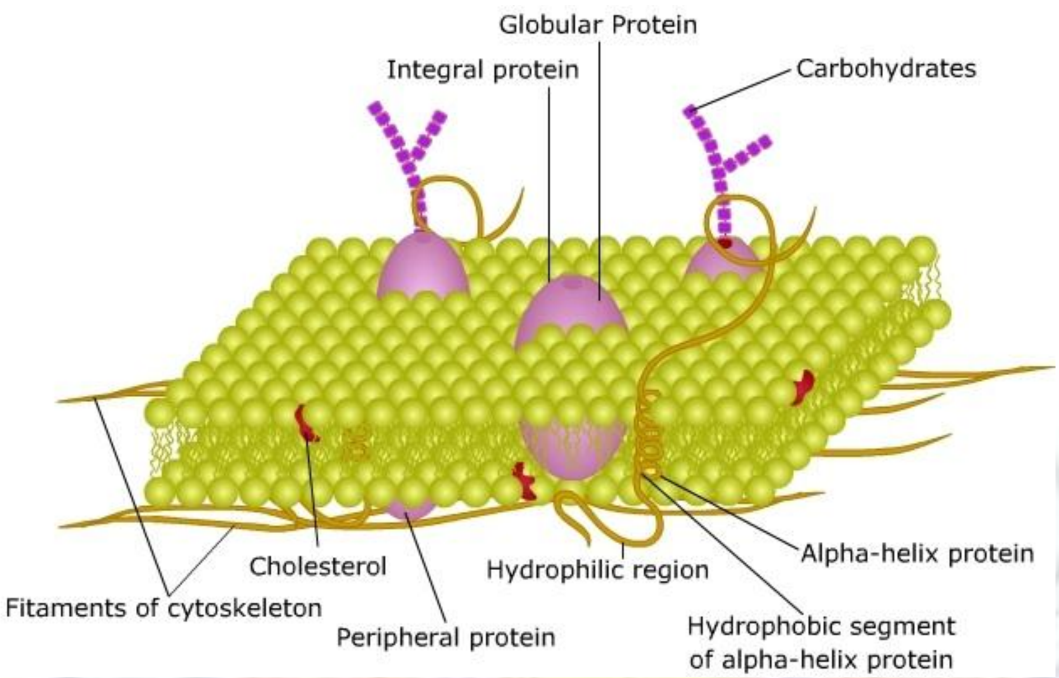


Figure: Model showing the arrangement of proteins in the lipid bilayer
Source: Author

1. Peripheral (Extrinsic) Protein

These proteins, as the name suggests, are usually bound to the hydrophilic surface of the membrane. They are not embedded within the lipid bilayer but are exposed to the surface of the membrane. Peripheral proteins are rich in amino acids with hydrophilic side chains which permit them to interact with the polar surface of the lipid bilayer. They are present both on the exterior surface and on the cytoplasmic side of the plasma membrane. Often the peripheral proteins are held in place by attaching with the cytoskeleton (proteinaceous thread-like structure in cytoplasm) towards the inside and to the fibres of the extracellular matrix on the outside. Being loosely bound, peripheral proteins can be readily removed and identified as compared to the other types of membrane proteins.

2. Integral (Intrinsic) Protein

These proteins are embedded within the hydrophobic core of the lipid bilayer. Some of the integral proteins are **transmembrane** proteins, that span the entire membrane while the others may be partly embedded in the hydrophobic core, which are exposed either to the interior or to the exterior surface of the membrane. Integral proteins contain both hydrophobic and hydrophilic amino acids depending on their position. Some of the integral proteins may project beyond the surface of the lipid bilayer and are rich in hydrophilic amino acids, whereas the proteins embedded in the hydrophobic interior of the membrane contain stretches of non-polar amino acids. It is presumed that the transmembrane proteins, that are embedded within the hydrophobic lipid core may have the secondary structure in the form of alpha-helix or beta sheet. In alpha-helix conformation, the polypeptide backbones are hydrogen bonded with one another whereas in beta sheet, hydrogen bonds are formed between amino and carboxyl groups in stretches of polypeptide that lie parallel to one another.

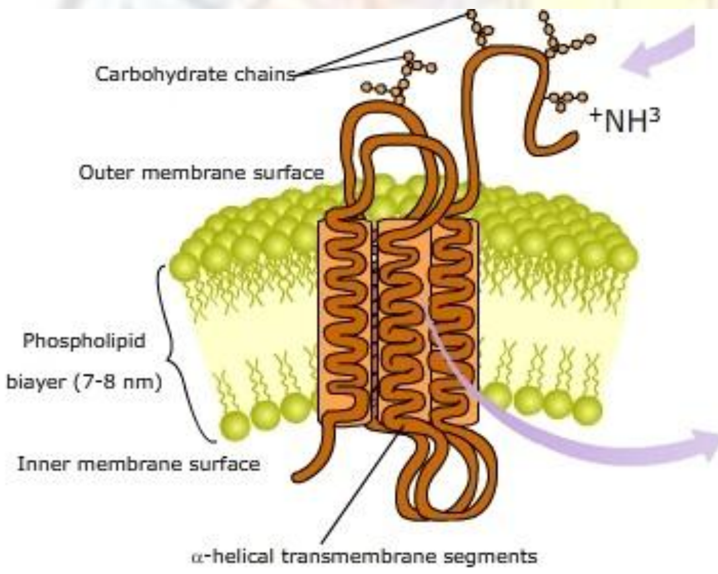


Figure: A transmembrane protein having a alpha-helix conformation

Source: Author

Video:

Source: http://freevideolectures.com/Course/2933/General-introduction-to-cell-structure-and-function-Spring-2010/5

Functions of membrane Proteins

Membrane proteins are responsible for the important functions of the cell membrane. Six major functions are described below:

- **Transport**: Transmembrane proteins provide a **hydrophilic** channel across the membrane that is selective for some polar solutes. Other transport protein may act as a **carrier** protein to shuttle substances from one side to another.
- **Enzymatic activity:** Membrane proteins can behave as enzymes with active sites and take part in the sequential steps of a metabolic pathway.
- **Signal transduction:** Protein present on either surface of the membrane can act as **receptors** with specific binding sites for chemical messengers such as hormones. The external messenger (signal molecules) may change the conformation of the protein, causing a relay of message to the interior of the cell and make the cell response accordingly.
- **Cell-cell recognition**: Some glycoproteins, which are cell-specific serve as identification tags that can be recognized by the protein present in other cells.
- **Inter-cellular joining**: In multicellular animals, the neighbouring cells are joined together by various gap junctions, made of membrane proteins.
- **Attachment to the cytoskeleton and extracellular matrix** (ECM): Cytoskeleton fibres of the cytoplasm are attached to membrane protein to maintain the shape of the cells. In addition the membrane protein can bind with the ECM to coordinate the extra and intracellular changes.

Membrane Carbohydrate

Carbohydrates present in the membrane are either attached to the membrane lipids or proteins thus forming **glycolipids** and **glycoproteins** respectively. These are present as short oligosaccharides, either branched or unbranched and are only present on the exterior surface of the membrane. The interior surface is devoid of any carbohydrates.

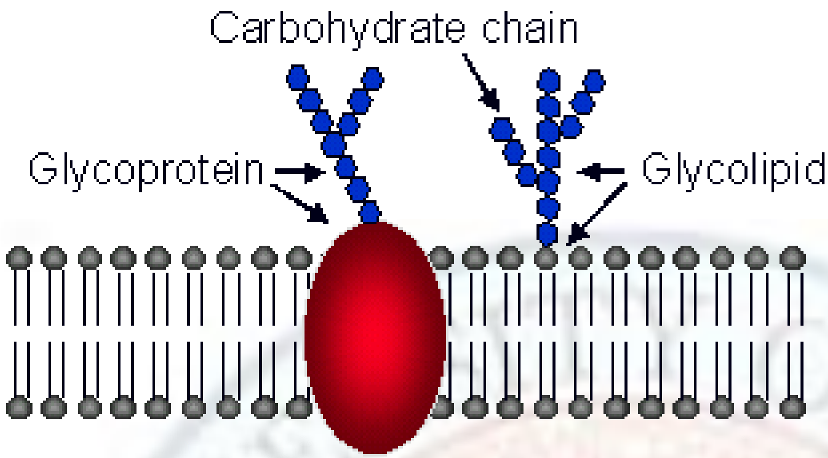


Figure: Carbohydrate residues are attached on the glycolipids and glycoproteins surface.

Source: http://animalcellbiology.files.wordpress.com/2011/08/membrane-lipids-and-proteins.gif?w=460

There are six principal sugars present in the oligosaccharide namely D-galactose, D-mannose, L-fucose, N-acetylneuraminic acid (sialic acid), N-acetyl-D-glucosamine and N-acetyl-D-galactosamine (all are derivatives of glucose).

Functions of Membrane Carbohydrates

- The hydrophilic nature of the sugars helps in the orientation of the membrane glycoproteins and glycolipids, which are facing the external aqueous environment.
- Carbohydrates play important physiological roles, where certain membrane glycoproteins act as transport proteins, hormones and enzymes.
- Various human blood groups, e.g. ABO type, MN type etc are due to the carbohydrate chains of the erythrocyte membrane glycoproteins.
- The specific antigenic property of the cell membranes is due to its surface carbohydrates.
- Carbohydrates act as an adhesive, by linking neighbouring cells together and hence maintain the integrity of the tissue. Carbohydrates are believed to function in the cell-cell recognition since they are present in the outer surface of the membrane and are the first to be in contact with external environment.

Summary

All plant and animal cells are surrounded by membrane, known as cytoplasmic membrane or plasma membrane. Membrane forms the outer covering in animal cells whereas it lies inner to the cell wall in case of plant cell. The major composition of all membrane is lipid and protein. The lipids of the membrane are amphipathic in nature, which makes the bilayer arrangement of the lipids. Phospholipids make the bulk of membrane lipid beside cholesterol which is present only in animal cells. The proteins of the membranes are of two types, namely the integral proteins and the peripheral proteins. Presently membrane is believed to be "fluid" in nature. The lipid bilayer forms the basic structural organization of the membrane, within, which the proteins are present in non-covalent interactions. Proteins are responsible for the membrane function of the membrane. Besides proteins and lipids, some amount of carbohydrates, in form of oligosaccharides are attached either to lipid or to protein molecules, only on the outer surface of the membrane. Biological membrane is a highly dynamic structure, involve in a variety of cellular functions like transport across the membrane, cell-cell recognition, signal transduction etc.

Exercises

1. Describe briefly the functions of the cell membrane.
2. With the help of illustrations, describe the membrane models in a chronological sequence.
3. How Irving Langmuir contributed towards the understanding of membrane chemistry?
4. Which experiment led to the bimolecular leaflet model of the cell membrane?
5. Why it was realized that only lipid bilayer cannot form the cell membrane?
6. Explain the Fluid Mosaic Model of the membrane with the help of labelled diagram and justify the name.
7. What do you understand by the statement "membrane may be more mosaic than fluid".
8. Describe the different types of membrane proteins.
9. Elaborate the various functions of the membrane proteins.
10. Write short notes on :
    (a) Amphipathic membrane molecules
    (b) Membrane phospholipids
    (C) Phosphatidic acid
    (d) Cholesterol

(e) Membrane carbohydrates

(f) Probable functions of membrane carbohydrate

11. Fill in the blanks:

(a) --------------- are a class of lipids and are a major component of all cell membranes.

(b) --------------- is a lipid molecule with a characteristic four-ringed steroid structure and an important component of plasma membrane of animal cells.

(c) --------------- is a property of biological membranes that allows them to regulate the passage of substances.

(d) ------------- form the mosaic part of the plasma membrane, which are embedded in a fluid matrix of -----------.

(e) Robertson proposed -------------- model to explain the structure of plasma membrane.

11. Mention one-word answer for the following:

(a) a term describing a chemical compound possessing both hydrophilic and hydrophobic properties.

(b) Fatty acids that contain one or more double/triple C-C bonds.

(c) A protein with one or more carbohydrates covalently attached to it.

(d) A protein loosely bound to the surface of a membrane and not embedded in the lipid bilayer.

(e) Artificially created lipid vesicles, which help in the understanding of structure and function of membrane lipids.

Glossary

Amphipathic: Molecules that have both hydrophilic and hydrophobic regions

Bilayer: It refers to the bimolecular leaflet (two monolayers of lipids) that form the basis of membrane structure.

Cholesterol: a steroid based important animal membrane lipid

Cytoplasm: The fluid portion of the cell enclosed within the membrane

Gap junction: Narrow, tubular channels, that are present on the plasma membrane of the adjacent cells for cell-cell communication in animal cells

Glycolipid: Lipids attached to sugars usually as oligosaccharide, which are polar & hydrophilic

Glycoprotein: Proteins attached to sugars usually as oligosaccharides

Integral protein: Membrane proteins, embedded within the lipid bilayer

Lecithins: An important membrane phospholipid (Phosphatidyl choline)

Lipids: A heterogenous collection of hydrophobic molecules that are highly soluble in organic solvents

Liposomes: An artificially created (by vigorously dispersing lipids in water) lipid bilayer in the form of spherical vesicle

Peripheral protein: Non-covalently (loosely) attached plasma membrane proteins present on the outer surface of the lipid bilayer on either side

Phosphatidic acid: The un-substituted phosphate group with two fatty acid chains

Phospholipid: A diglycerides where two OH groups are esterified with two fatty acids and the third is esterified with phosphoric acid to give the PO_4 group

Plasmodesmata: Protoplasmic channels present in adjacent plant cells, through the cell wall

Protein: Biopolymer of amino acids linked by peptide bonds

Signal transduction: The overall process in which information carried by extracellular messenger molecules are translated into changes that occur inside a cell

Sphingolipid: A class of membrane lipid that consists of a sphingosine (an amino alcohol) molecule attached to a fatty acid by its amino group.

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Web Links

http://www.youtube.com/watch?v=y31DlJ6uGgE

http://www.youtube.com/watch?v=EsNk5Zelr1