# Biomolecules of Life (Part 1)

## 1. Overview of Topic

Compounds that contain carbon atoms are said to be organic and the branch of chemistry that specializes in the study of carbon compounds is called **organic chemistry**. Most organic compounds also contain hydrogen atoms and also elements oxygen, nitrogen, sulphur and phosphorus. The **Biomolecules of Life** topic in Core Idea 1 explores how carbon atoms, by bonding with four other atoms, form a diverse range of organic molecules which forms the basic constituents of cells. Two major types of organic compounds will be covered in this topic: carbohydrates and lipids. Proteins and enzymes will be covered later. Nucleic acids will be covered in the Core Idea 2: **Genetics and Inheritance**.

These four major classes of biomolecules function as molecular building blocks for macromolecules to be assembled. Macromolecules are often called polymers because each polymer molecule is a long molecule consisting of many similar or identical building blocks linked by covalent bonds. Each repeating unit of a smaller molecule is called a monomer.

## 2. Learning Outcomes

a. Describe the structure and properties of the following monomers:
   i. α-glucose and β-glucose (in carbohydrates)
   ii. glycerol and fatty acids (in lipids)
   iii. amino acids (in proteins) (knowledge of chemical formulae of specific R-groups of different amino acids is not required).

b. Describe the formation and breakage of the following bonds:
   i. glycosidic bond
   ii. ester bond
   iii. peptide bond

c. Describe the structures and properties of the following biomolecules and explain how these are related to their roles in living organisms:
   i. starch (including amylose and amylopectin)
   ii. cellulose
   iii. glycogen
   iv. triglyceride
   v. phospholipid

d. Explain primary structure, secondary structure, tertiary structure and quaternary structure of proteins, and describe the types of bonds that hold the molecule in shape (hydrogen, ionic, and disulfide bonds, and hydrophobic interactions).

e. Explain the effects of temperature and pH on protein structure.

f. Describe the molecular structure of the following proteins and explain how the structure of each protein relates to the function it plays:
   i. haemoglobin (transport)
   ii. collagen (structural)

iii. G-protein linked receptor (signalling)
(knowledge of details of the number of amino acids and types of secondary structures present is not required.)

The highlighted Learning Outcomes will be covered in Biomolecules of Life (Part 2) where proteins and enzymes will be presented together in the next series of lectures.

## 3. References

Alberts, B., Johnson, A., Lewis, J., Morgan, D., Raff, M., Roberts, K. and Walter, P. (2014) Molecular Biology of the Cell (Fifth Edition) (Garland Science) ISBN 0815344643

Jones, M. and Jones, G. (2004) Advanced Biology. Chapter 1: The Molecules of Life. Cambridge University Press.

Koolman, J. and Roehm, K. (2005) Color Atlas of Biochemistry (Second Edition) (Thieme Publishing Group) ISBN13 9783131003720

Raven, P. H., Johnson, G. B., Mason, K. A., Losos, J. and Singer S. (2013) Biology (Tenth Edition) (McGraw-Hill) ISBN 007338307

Reece, J. B., Urry, L. A., Cain, M. L., Wasserman, S. A., Minorsky, P. V. and Jackson, R. B. (2011) Campbell Biology (Ninth Edition) (Pearson Higher Education) ISBN 0321739752

## Contents

## 4. Carbohydrates

Carbohydrates are organic compounds consisting of the elements carbon, hydrogen and oxygen, with atoms in the ratio of C:H:O = 1:2:1. Its general formula is $(CH_2O)_n$. They can be classified in different ways.

| Classification | |
|---|---|
| Complexity | Simple carbohydrates : Monosaccharides containing one monomer<br>Disaccharides containing two monomers<br>Complex carbohydrates: Oligosaccharides containing 3-10 monomers<br>Polysaccharides containing >100 monomers |
| Number of C atoms | Triose (3-carbon sugars)<br>Tetrose (4-carbon sugars)<br>Pentose (5-carbon sugars)<br>Hexose (6-carbon sugars)<br>Heptoses (7-carbon sugars) |
| Reducing properties | Reducing sugars<br>Non-reducing sugars |
| Position of Carbonyl (C=O) group | Aldose (Sugars having an aldehyde group)<br>Ketose (Sugars having a ketone group) |

Important Monosaccharides in the H2 Biology Syllabus

| Number of C atoms | General Name | Chemical Formula | Name | Significance |
|---|---|---|---|---|
| 3 | Triose sugar | $C_3H_6O_3$ | Glyceraldehyde | Intermediate compound in respiration & photosynthesis |
| 5 | Pentose sugar | $C_5H_{10}O_5$ | Ribose | Component of RNA and ATP |
| | | | Deoxyribose | Component of DNA |
| 6 | Hexose sugar | $C_6H_{12}O_6$ | Glucose | Main source of energy for cellular respiration |
| | | | Fructose | An energy source.<br>Component of sucrose. |
| | | | Galactose | Component of lactose.<br>Found in dairy products. |

## Properties of Monosaccharides

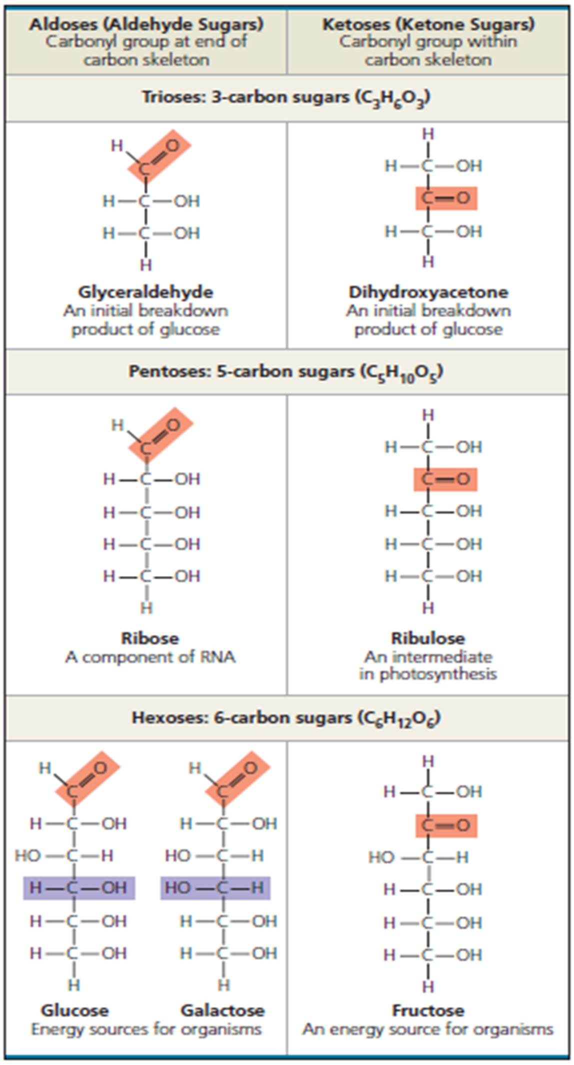
Physical properties:

- Monosaccharides are sweet and have crystalline structures
- Readily soluble due to presence of numerous –OH groups (polar) that can form hydrogen bonds with water
- Pentoses and hexoses can exist as rings which are more stable as building blocks for dissacharides and polysaccharides.

Chemical Properties:

- Monosaccharides are reducing sugars. They contain a carbonyl group (C = O) (aldehyde or ketone group) that donates electrons to $Cu^{2+}$ to $Cu^{+}$ in the Benedict's test.

## Structure of Monosaccharides




The simplest carbohydrate is called the monosaccharide. It is active alone or serves as a monomer for forming disaccharides, oligosaccharides and polysaccharides.

Also known as simple sugars, monosaccharides have molecular formulas that are generally some multiple of $CH_2O$. Monosaccharides cannot be hydrolysed further to simpler carbohydrates.

They are classified according to the number of carbon atoms present. Glucose is a biologically important hexose. Ribose is the pentose sugar found in ribonucleic acids. Lactose is the hexose found in milk.

The position of the carbonyl group (C = O) also determines if the sugar is considered an aldose or a ketose sugar. An aldose has a carbonyl group at the end of the carbon chain.

Monosaccharides, particularly glucose, are major nutrients for cells. Simple-sugar molecules are a major fuel source for cells through respiration. Their carbon skeletons also serve as raw material for the synthesis of amino acids and fatty acids. Sugar molecules that are not immediately used are usually incorporated as monomers into disaccharides or polysaccharides.

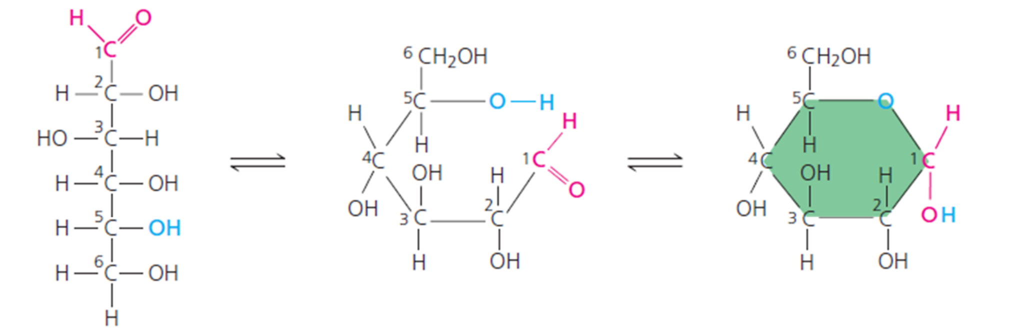
*Note to Self*

*Questions?*

## α- and β-glucose

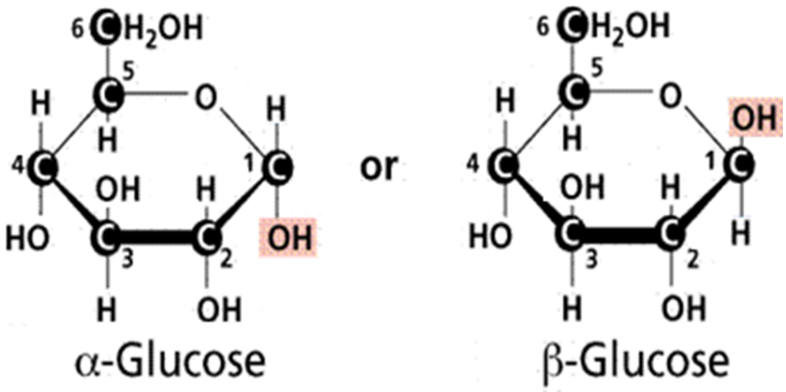
Although it is easy to represent glucose with a linear 6-carbon skeleton, this representation is inaccurate because glucose molecules, as well as most other five- and six-carbon sugars, form rings in aqueous solutions.

The linear glucose carbon chain cyclizes when the C5 hydroxyl (-OH) group attacks the oxygen atom of the C1 aldehyde group (-C=O-H).



**(a) Linear and ring forms.** Chemical equilibrium between the linear and ring structures greatly favors the formation of rings. The carbons of the sugar are numbered 1 to 6, as shown. To form the glucose ring, carbon 1 bonds to the oxygen attached to carbon 5.

The ring structure glucose may exist in two forms. In the α- form, the (-OH) group attached to C1 is below the plane of the ring. In the β- form, the (-OH) group attached to C1 is above the plane of the ring. The ring structured forms are more stable.

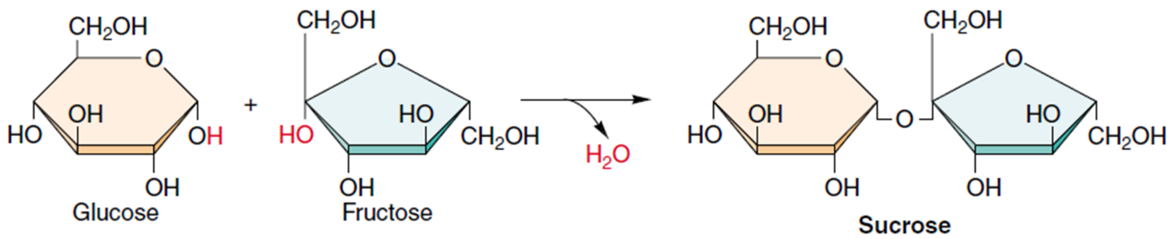



Note to Self

Questions?

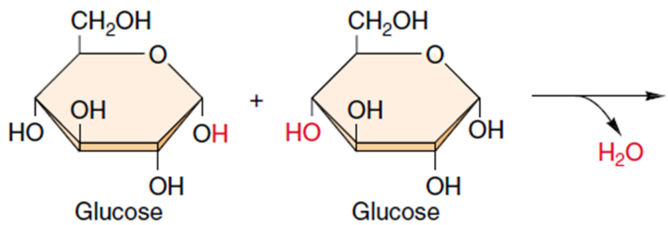
## Disaccharides

A disaccharide consists of two monosaccharides joined by a glycosidic bond (covalent bond) via a condensation reaction. Each monosaccharide component in a disaccharide is called a monomer. The condensation reaction involves the loss of a water molecule, hence is also known as a dehydration reaction. Common disaccharides include maltose, sucrose and lactose.



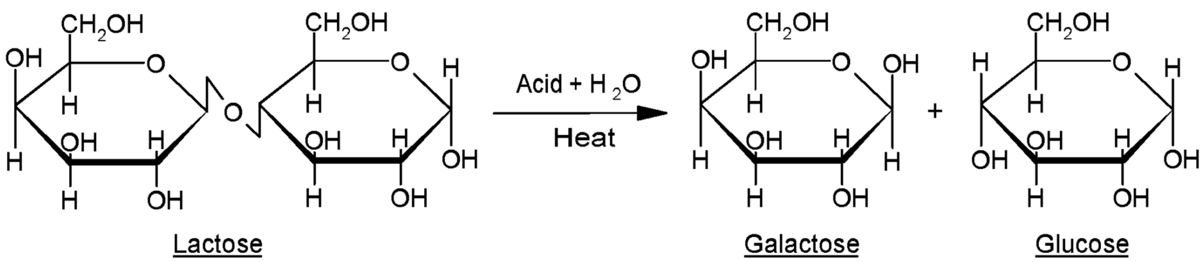

**Try This !**

Complete this diagram depicting the condensation of two glucose molecules.




A larger sugar molecule can also be broken into smaller molecules via hydrolysis.

During hydrolysis, the covalent glycosidic bond can be broken with the addition of one molecule of water. Hydrolysis reactions can be enzymatic (e.g. lactose is hydrolysed into glucose and galactose by lactase). Hydrolysis can also occur via acid hydrolysis. An acid at high temperature can be used to facilitate the cleavage of the glycosidic bond.



## Polysaccharides

Polysaccharides are macromolecules, polymers with a few hundred to a few thousand monosaccharides joined by glycosidic linkages. They do not taste sweet. Their large size makes them insoluble in water and will not exert an osmotic effect within the cell. They are also unable to diffuse out of the cell, thus making them good storage compounds.

They may be folded into compact shapes or highly branched. Some polysaccharides serve as food and energy storage material, and are readily hydrolysed into sugars when required to provide an energy source.

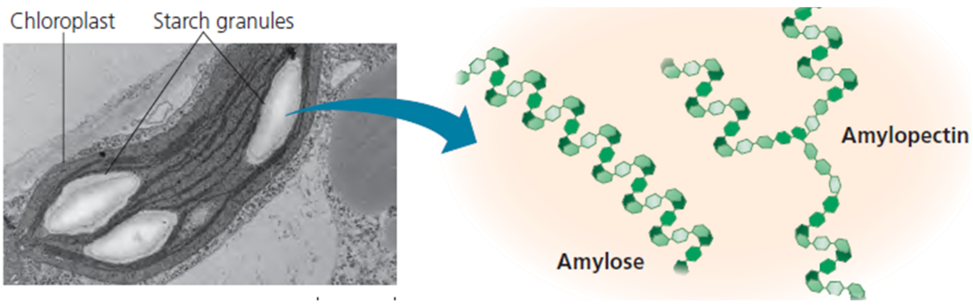
Other polysaccharides serve as building material for structures that protect the cell or the whole organism. Such structural carbohydrates are chains of sugars that are not easily digested.

Note to Self

### Starch

Plants store starch, a polymer of glucose monomers, as starch granules within cellular structures known as plastids (chloroplasts and amyloplasts).

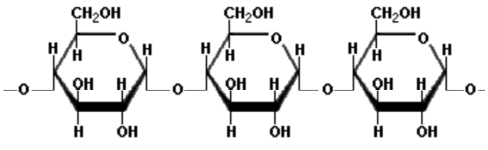
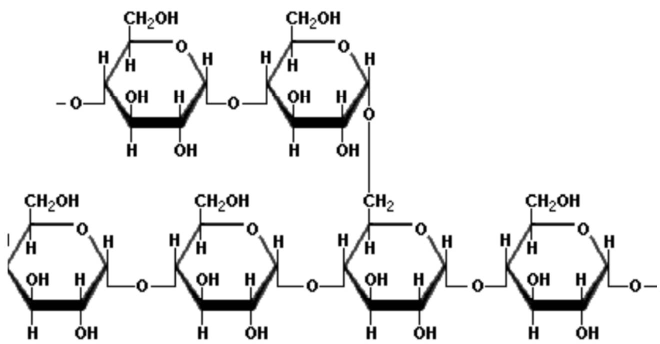
**Starch: a plant polysaccharide.** This micrograph shows part of a plant cell with a chloroplast, the cellular organelle where glucose is made and then stored as starch granules. Amylose (unbranched) and amylopectin (branched) are two forms of starch.




Starch consists of a mixture of 2 types of polymers: Amylose & Amylopectin.

Amylose, the unbranched form, has α-glucose monomers are joined by α-1,4 glycosidic linkages. In amylopectin, it is a highly branched molecule, consisting α-glucose linked by α-1,4 glycosidic bonds and α-1,6 glycosidic bonds at branch points. Branching occur every 24-30 residues, resulting in compact polymer that has twice as many glucose residues as amylose.

Questions?

| Feature | Amylose | Amylopectin |
|---|---|---|
| Monomer | Made up of $\alpha$-glucose monomers. | Made up of $\alpha$-glucose monomers. |
| Branching | Exist as unbranched polymers. | Exist as branched polymers. |
| Bonding | Glucose monomers are linked by $\alpha$-1,4 glycosidic bonds. | Glucose monomers are linked by $\alpha$-1,4 glycosidic bonds within a branch and $\alpha$-1,6 glycosidic bonds at the branch points. |
| Shape of polymer | Each amylose molecule is coiled into a helix.   Amylose | Similar helical structure with additional helical side chains attached at branch points (~every 20-30 glucose units)   |
| Number of monomers per polymer | Typically contains 200 to 20,000 glucose monomers per molecule. | Typically contains up to 106 glucose monomers per molecule. |

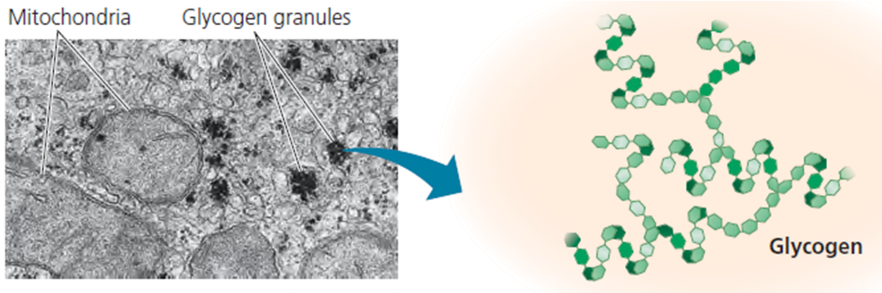
## Glycogen

Glycogen is an animal storage polysaccharide and the main energy storage compound in animals. The structure is very similar to that of amylopectin, a branched polymer made up entirely of α-glucose monomers.

The monomers are linked by α-1,4 glycosidic bonds within a branch. α-1,6 glycosidic bonds are present at the branch points. Glycogen is even more extensively branched than amylopectin, resulting in a highly compact structure.

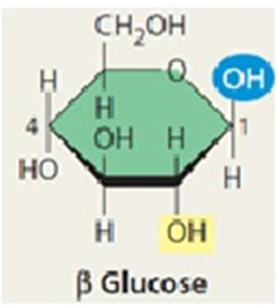
It accumulates as glycogen granules in liver and muscle cells. Glycogen is converted to glucose when glucose level is low. Its conversion back to glucose is controlled by the hormone insulin.

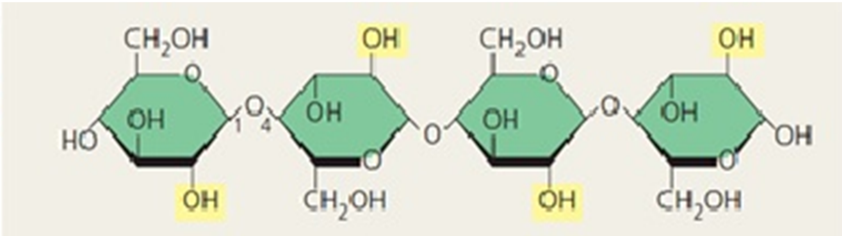
**Glycogen: an animal polysaccharide.** Animal cells stockpile glycogen as dense clusters of granules within liver and muscle cells, as shown in this micrograph of part of a liver cell. Mitochondria are cellular organelles that help break down glucose released from glycogen. Note that glycogen is more branched than amylopectin starch.




## Cellulose

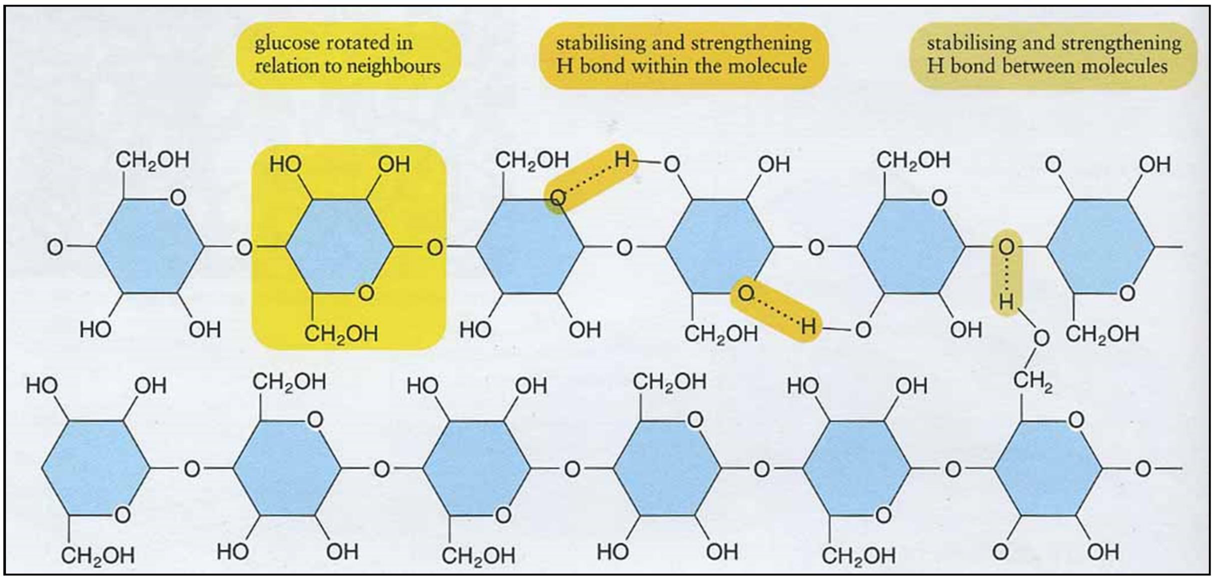
It is a straight, unbranched chain consisting of β-glucose monomers linked by β-1,4 glycosidic bonds. Adjacent glucose molecules are rotated 180° with respect to each other due to the projection of the -OH groups on the C atom.




**Cellulose: 1–4 linkage of β glucose monomers.** In cellulose, every β glucose monomer is upside down with respect to its neighbors.

Each cellulose molecule contains about 10,000 β-glucose residues and has hydroxyl groups projecting outwards in both directions. Within each cellulose molecule, intra-chain hydrogen bonds occurs between –OH and O of adjacent β-glucose residues.

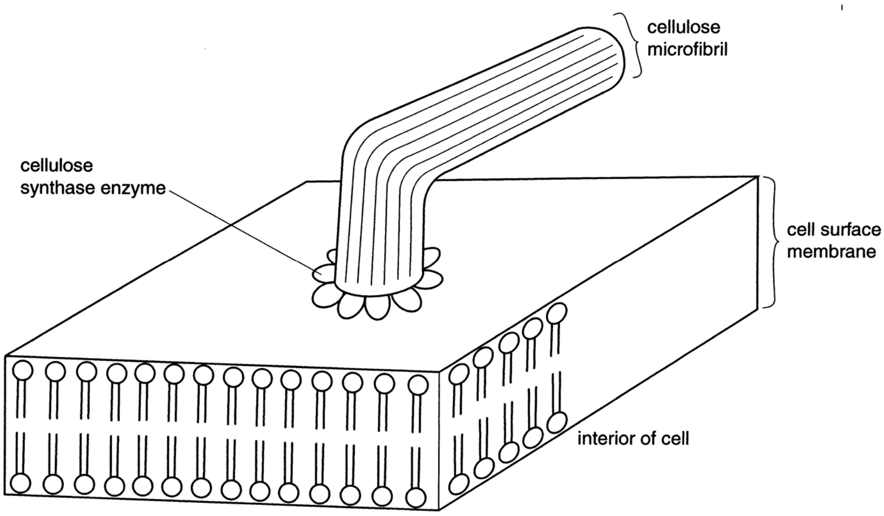



Straight chains of β glucose run parallel to each other. Inter-chain hydrogen bonds exist between –OH groups projecting outwards from each chain and O of parallel chain. The numerous cross-linking binds the chains rigidly together. About 80 molecules of cellulose molecules associate this way to from a cellulose microfibril.

*Note to Self*

Microfibrils are arranged in larger bundles to form macrofibrils or larger-sized cellulose microfibrils. A meshwork of such criss-crossing macrofibrils forms a layer. Successive layers are interwoven and embedded and tethered by other cell wall polysaccharides such as hemicellulose, pectin, and lignin in a gel-like matrix. The structure confers to cellulose tremendous tensile strength.

Cellulose is synthesized by large membrane-bound enzyme complexes called rosette cellulose synthase. These complexes are found in the plasma membrane of plant cells. Cellulose molecules are synthesized by the enzyme complex and simultaneously associated into microfibrils bundles and laid down on the outside of the cell.




Here is a link with a 4-minute video depicting how cellulose is synthesized when a plant cell elongates.
http://sites.sinauer.com/cooper7e/animation1501.html

**Thinking Boxes**

Why do you think cellulose is synthesized on the cell membrane and laid outside of the cell membrane and not the inner side facing the cytoplasm?

- Being large macromolecules, if the cellulose molecules are synthesised in the interior of the cell, energy resources will have to be allocated to transporting them to the edge of the cell.
- Cellulose molecules are insoluble and long, if they are assembled on the interior of the cell, it would be difficult transport them across the cell membrane.
- If the cellulose is laid on the interior side of the side, the tensile strength of the cellulose, and the cross-linking mesh-like nature of the molecules will prevent plant cells from growing bigger in size too.
- Thus it makes economic sense to the plant cell to directly synthesise and assemble them on the outside of the side cell.

BROYO

# Are polysaccharides soluble in water ?

While monosaccharides and disaccharides are soluble, polysaccharides are generally insoluble. Monosaccharides and disaccharides are small, and can dissolve in water because they contain polar functional groups such as -OH groups that can form hydrogen bonds with the polar water molecules.

We often state that polysaccharides are insoluble and suitable as storage or structural molecules. Cellulose is insoluble partly because of the numerous cross-linking of fibrils and do not have many -OH groups to form hydrogen bonds with water. Due to its insoluble nature, cellulose is a good structural polysaccharide because it cannot dissolve in water.

Starch in particular is a good storage polysaccharide for plants precisely because it is insoluble in water and does not affect the osmotic potential of the plant cell.

Well, there is a catch. Starch is insoluble in cold water. We already know that starch contains both amylose and amylopectin and are stored as granules. If you delve deeper into the chemistry of starch, you will soon realise not all starch are made the same. Some plant species has larger starch granules, some species contain different percentages of amylose and amylopectin.

Here is the catch - starches become soluble in water when heated! At higher water temperatures, some of the hydrogen bonds between the starch molecules in the starch granule become weaker and break. This allows water to enter the granule, the absorbed water swell and burst the starch granule. As the branched amylopectin are much larger, they remain in the starch granule. The smaller chains of amylose, however, can to leach out into the surrounding water. The amylose forms a network that holds the water molecules together and increasing the viscosity of water. Think about the thickened gravy when you eat hor fun, that’s how the chefs thicken the soup into gravy. This process is called starch gelatinisation!

Go find out what Playdoh’s got to do with starch!

## 5. Lipids

Lipids form a large and heterogeneous group of substances that made up of carbon, hydrogen and oxygen atoms. Due to the large variety, lipids do not have a general formula.

Lipids can be classified based on whether they can be hydrolysed. Hydrolysable lipids can undergo hydrolytic cleavage of the ester bonds, to yield the smaller components. Important biological examples that you would need to know are the triglyceride, glycolipids and phospholipids. Non-hydrolysable lipids include fatty acids, steroids, which an example is cholesterol.

*Note to Self*

### Properties of Lipids

Fat vs lipid

Lipids are poorly soluble or insoluble in water as they are non-polar. This is due to even distribution of electrons and the lack of polarizing atoms such as O, N, S, and P. Fatty acid chains contain C-H bonds that are non-polar and do not form hydrogen bonds with water molecules. By contrast, lipids easily dissolved in organic solvents such as methanol, acetone, chloroform, and benzene due to the ability form hydrophobic interactions with lipids.

The molecular structure of some molecules results in uneven distribution of shared electrons. Polar molecules have ends that are either positively or negatively charged. Non-polar substances have uniform, neutral electric charge in all parts of the molecule and lipids are non-polar.

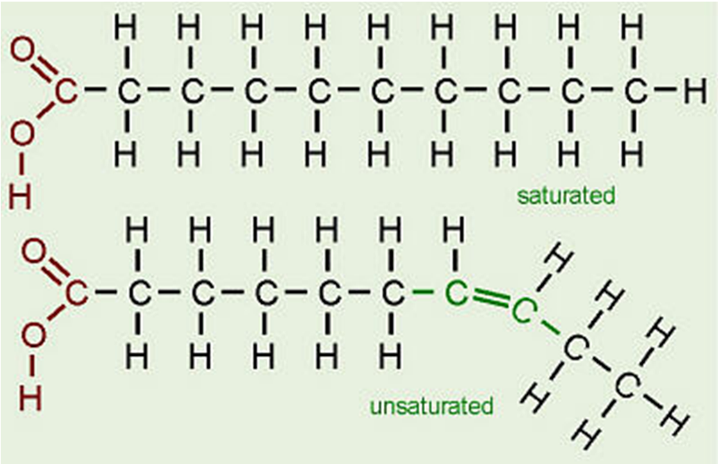
As lipids have lower density and insoluble in water, they tend to congregate to exclude water, accounting for why oil floating on the surface of water. If ethanol is added to lipid, the lipid will mix well with ethanol. Any addition of water to the lipid-ethanol mixture, an emulsion will be observed.

### Structure of Lipids

A fatty acid is a naturally-occurring carboxylic acid with hydrocarbon chains consisting of 4 to 24 carbon atoms. When a fatty acid chain contains one or more carbon-carbon (C=C) double bonds, they are known as an unsaturated fatty acid.

*Questions?*

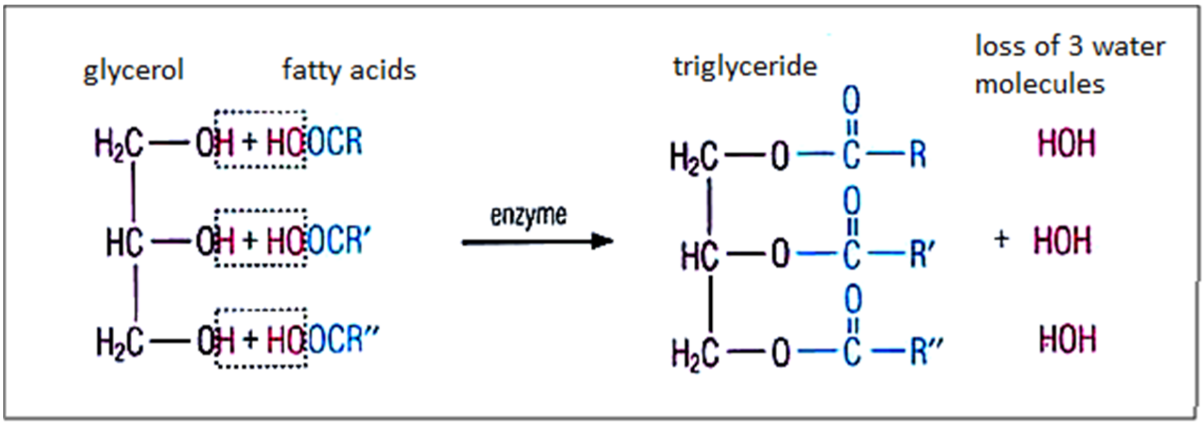
The (C=C) present, resulting in a kink that prevent the tight packing of fatty acid chains. Common unsaturated fatty acids are oleic acid and linoleic acid.



A fatty acid is often esterified with alcohols. Hydrolysable lipids are formed by condensation reactions between fatty acids and alcohol.

### Triglycerides

Triglycerides are formed by condensation reactions. When the carboxyl group of a fatty acid and hydroxyl group of glycerol reacts, an ester bond/linkage is formed. This process is called esterification. Subsequent esterification results in condensation of 3 fatty acid molecules with 1 glycerol molecule with the loss of 3 water molecules producing a triglyceride molecule.




Note to Self

The length of the fatty acid residues and the number of their double bonds affect the melting point of the fats. Shorter fatty acid chains lower their melting points of the lipid. The more unsaturated the fatty acid chain is, i.e. contains more double bonds, the lower the melting point of the lipid.

### *Properties of Triglycerides*

**Melting points**: Triglycerides can be classified as fats (solid) or oils (liquid) at 20°C

- Fats are usually triglycerides that consist of long fatty acid chains, with saturated fatty acids. Structurally, they are more compact and there are more hydrophobic interactions. Thus they have higher melting points to overcome these hydrophobic interactions.
- Oils consist of relatively short fatty acid chains, with unsaturated fatty acids. The kinks caused by the C=C double bonds, result in molecules that are packed less tightly, and are less compact. They have less hydrophobic interactions. This results in a lower melting point as less energy is needed to overcome these interactions.

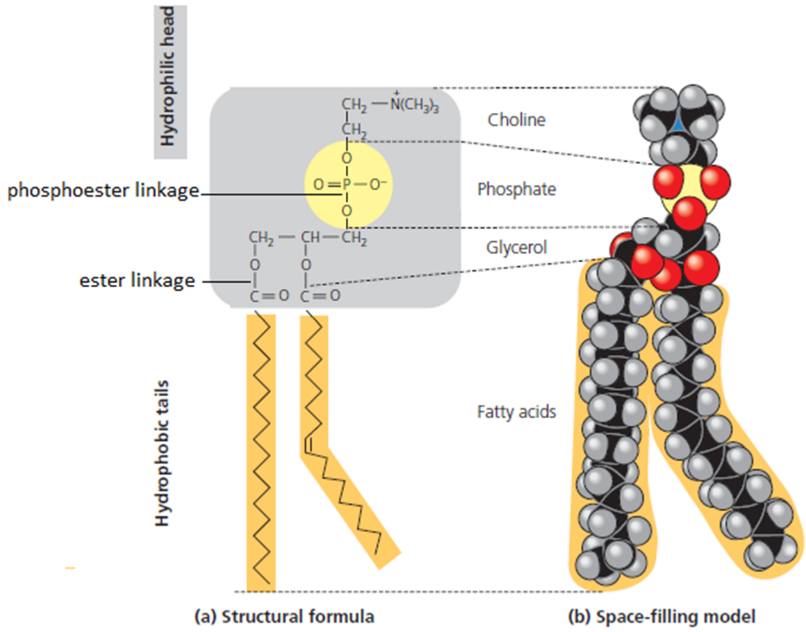
**Solubility**: Triglycerides are insoluble in water and are considered non-polar.

**Density**: Oils are less dense than water. The molecules that make up oil are larger than molecules that make up water, and molecules in oil pack less tightly together compared with water. Oils take up more space per unit area and are less dense.

## Phospholipids

A phospholipid is similar to a triglyceride molecule but has only two fatty acids attached to glycerol rather than three. The third hydroxyl group of glycerol is joined to a phosphoric acid instead of fatty acid. The phosphate group attached has a negative electrical charge in the lipid molecule.

They are formed by a condensation reaction resulting in two ester bonds and a phosphoester bond.




A phospholipid is an amphipathic molecule because it possesses both a polar and a non-polar group. This is an important feature that will guide how phospholipids arrange themselves in the presence of water. A phospholipid exhibit different behaviour toward water because the hydrocarbon tails are hydrophobic and are excluded from water, however, the phosphate group with the negative charge is hydrophilic and is attracted to water. This results in them congregating to form micelles and membrane bilayers when placed in water.

Phospholipids are the main constituent in biological membranes. Phosphatidylcholine (lecithin) is the most abundant phospholipid in membranes. The bilayer structure forms by self-assembly of phospholipids in an aqueous environment and the phospholipid bilayer and its associated Fluid Mosaic Model will be covered in the Topic of Membrane Transport.

*Note to Self*

*Questions?*

## Glycolipids

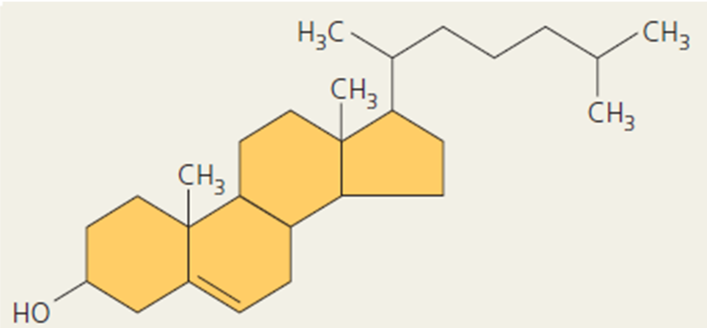
The prefix glycol- refers to the presence of carbohydrate. It usually refers to any lipid that has a short sugar chain (< 15 sugar units) that is covalently bonded to lipids via a glycosidic bond.

Lipids in a cell acquire carbohydrate moieties in the lumen of an organelle called the Golgi Apparatus, and the glycolipids formed are transported to the cell membrane with the glycolipid becomes part of the cell membrane. Glycolipids are mainly found on the outside of the plasma membrane and play communicative role, often acting as markers for cellular recognition.

Glycolipids play important roles in cell-cell interaction and recognition, and cell adhesion. In the ABO blood group system, the four blood groups are determined by the type of the sugar moiety of glycolipids. E.g. In individuals with blood group B, the antigens recognised consist of galactose as the terminal sugar in the glycolipid embedded on the cell membrane of the erythrocyte.

## Sterols and steroids

Sterols and steroids are non-polar and insoluble in water, and soluble is organic solvents.  They are considered non-hydrolysable lipids and cannot be further hydrolysed into smaller components. These lipids characterized by a carbon skeleton consisting of four fused rings. Different steroids contain different chemical groups attached to this carbon rings.



Structure of cholesterol

Cholesterol is a sterol present in all animal tissues, and particularly in neural tissue. It is a major constituent of biological membranes and regulates fluidity. Cholesterol is also an important precursor from which other compounds such as bile salts and sex hormones are synthesized.

Note to Self

Questions?

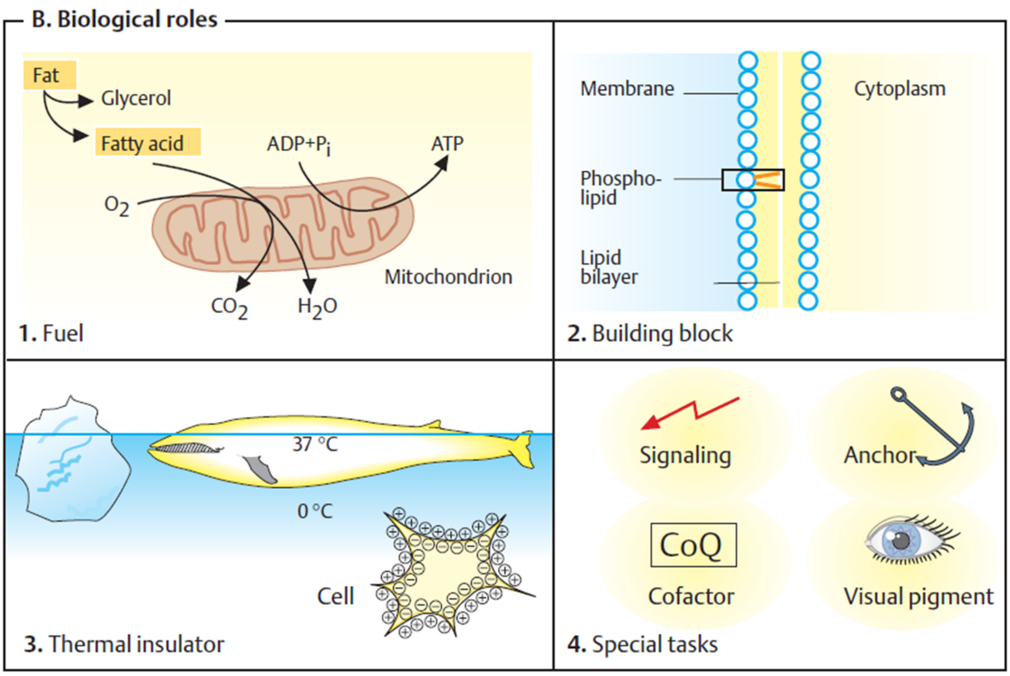
## Functions of Lipids in Biological Systems

**1. Fuel.** Lipids are an important source of energy in the diet, representing the principal energy reserve in animals in specialized cells called adipocytes. When needed, lipids in the form of triglycerides are hydrolysed to release fatty acids. Fatty acids are then oxidized in the mitochondria when oxygen is present.

**2. Building blocks.** Amphipathic lipids such as phospholipids, glycolipids, and also cholesterol are used to build membranes. As the principal constituent of cell membranes, phospholipids also insulate cells from their environment mechanically and electrically by regulating the movement of various molecules. Phospholipids form the basic structure of surface and internal membranes of cells. The phospholipid bilayer will be covered more extensively in the topic of Membrane and Transport.

**3. Insulation.** In the mammals, triglycerides stored in the subcutaneous tissue and around various organs serve as excellent mechanical and thermal insulators. As the principal constituent of cell membranes, phospholipids also insulate cells from their environment mechanically and electrically.

**4. Specialised Function**
- Some lipids play roles in cell signalling. They serve as hormones (e.g. oestrogen and testosterone) and second messengers (PIP, IP3 will be covered in the topic of Cell Signalling )
- Some lipids form anchors to attach proteins to membranes
- Lipids also serve as a medium of transport for fat-soluble vitamins
- Some lipids also produce cofactors important for enzymatic reactions— e. g. ubiquinone, an important component of the electron transport chain in cellular respiration.




Note to Self

Questions?

**BROYO**

## If cholesterol is a lipid and insoluble in water, how do doctors find and measure cholesterol in blood?

Cholesterol, while it is hydrophobic and insoluble in water (blood), there are proteins in blood that bind to cholesterol and aid in the transport of cholesterol around the body. High density lipoprotein (HDL) binds to cholesterol and transport cholesterol from body tissues to the liver while low density lipoprotein (LDL) transports cholesterol from the liver to body tissues.

What then is a lipoprotein? Lipo = lipids. A lipoprotein is a cluster of small spherules that consist of phospholipid, proteins that can bind to lipids, cholesterol, cholesteryl esters and triglycerides.

So when someone refers to good or bad cholesterol, it is actually inaccurate. The lipid panel blood tests actually measure the amount of HDL and LDL (lipoproteins) as proxy of how much cholesterol are there in the blood. HDL are considered good because they play numerous roles in lipid metabolism, support the immune system and facilitate excess cholesterol to be removed and converted to bile salts in the liver and excreted into the duodenum and eventually egested.

So, doctors use a lipid panel blood test which measures the amount of triglycerides, HDL and LDL as a predictive measure of heart disease while taking into considerations other factors such as age, smoking, diet, blood pressure and weight.