

**River Valley High School
2025 JC1 H2 Biology**

Lecture Topic 3: Biomolecules of Life - Carbohydrates

Name: _____ () Class: 25J_____ Date: _____

References

Title

Biology (9th Edition)

Biological Science 1. Organisms, Energy and Environment (3rd Edition)

Longman A-Level Course in Biology: Core Syllabus Vol. 1

Understanding Biology for Advanced Level (4th Edition)

Authors

Campbell and Reece

Taylor, Green, Stout and Soper

Hoh

G. Toole and S. Toole

H2 Biology Syllabus 9477 (2025)

Candidates should be able to use the knowledge gained in the following section(s) in new situations or to solve related problems.

Related Topics

Biomolecules of Life and Cellular Transport

Transformation of Energy between the Environment and Organisms

Concepts

The structure of carbohydrates, lipids and proteins and their roles in living organisms

Synthesis of carbohydrates from carbon dioxide and water during photosynthesis

The need for energy in living organisms

Learning Outcomes

1B. Biomolecules of Life and Cellular Transport

- g. Describe the structure and properties of the following monomers:
- α -glucose and β -glucose (in carbohydrates)
 - glycerol and fatty acids (in lipids)
 - amino acids (in proteins) (chemical formulae of specific R-groups of different amino acids are not required)
- h. Describe the formation and breakage of the following bonds:
- glycosidic bond
 - ester bond
 - peptide bond
- i. Describe the structures and properties of the following biomolecules and explain how these are related to their roles in living organisms:
- starch (including amylose and amylopectin)
 - cellulose
 - glycogen
 - triglyceride
 - phospholipid

For practical, candidates should be able to:

- carry out tests for reducing and non-reducing sugars using acid hydrolysis and Benedict's solution (including quantitative use of the Benedict's test) and the iodine in potassium iodide solution test for starch.

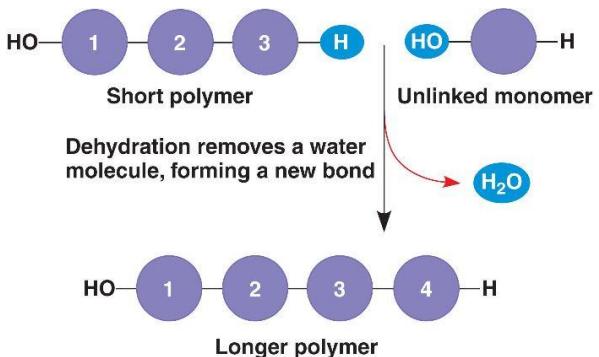
Lecture Outline

- I. Biomolecules
- II. Importance of Carbohydrates
- III. Nature of Carbohydrates
- IV. Monosaccharides
 - A. Aldose vs Ketose
 - B. Linear vs Ring Structures
 - C. Isomerism: α vs β Isomers
- V. Disaccharides
- VI. Polysaccharides
 - A. Storage Polysaccharides – relating structure to function
 - B. Structural Polysaccharides – relating structure to function

I. Biomolecules

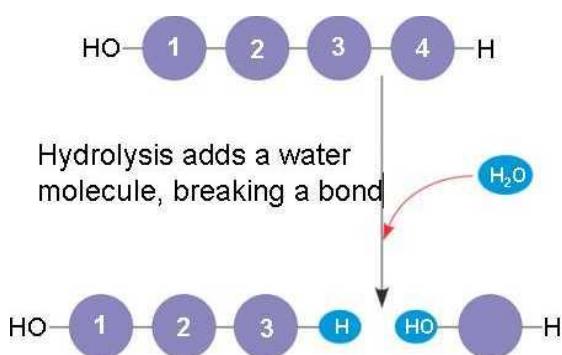
- The enormous diversity of molecules in organisms fall into four main classes:
 1. Carbohydrates
 2. Lipids
 3. Proteins
 4. Nucleic acids
- These molecules are involved in maintenance and metabolic processes of all living things, and are known as **biological molecules**.
- Three of the four classes of biological molecules - carbohydrates, proteins and nucleic acids - are chain-like molecules called **polymers**.
 - A polymer is a long molecule consisting of many similar or identical building blocks linked by covalent bonds.
 - The repeating units that serve as the building blocks of a polymer are smaller molecules called **monomers**.
- Large biological molecules exhibit unique properties arising from the orderly arrangement of their monomers and their **functional groups**.
- The classes of polymers differ in the nature of their monomers, but the chemical mechanisms by which cells make and break down polymers are basically the same in all cases. In cells, these processes are facilitated by **enzymes**.

SYNTHESIS OF POLYMER – CONDENSATION / DEHYDRATION REACTION



- Two molecules are covalently bonded to each other through loss of a water molecule.
- When a bond forms between two monomers, one monomer provides a hydroxyl group (–OH), while the other provides a hydrogen (–H).
- This reaction is repeated as monomers are added to the chain one by one, making a polymer

BREAKING DOWN OF POLYMER – HYDROLYSIS



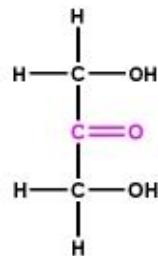
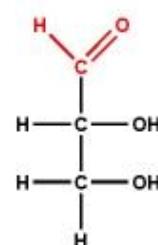
- Bonds between the monomers are broken by the addition of water; with a hydrogen from the water molecule attaching to one monomer, and the hydroxyl group from the water molecule attaching to the other monomer.

II. IMPORTANCE OF CARBOHYDRATES

- In plants, carbohydrates are manufactured from carbon dioxide and water by photosynthesis.
- Plants uses carbohydrates as an energy source (as glucose), as a means of storing energy (as starch) and as supporting material in the form of their cell walls (as cellulose).
- Animals consume carbohydrates as an important component of a balanced diet or synthesise carbohydrates from amino acids via gluconeogenesis. Glucose is the most important carbohydrate:
 - It is the major metabolic fuel of mammals (except ruminants) and a universal fuel of the foetus.
 - It is the precursor for synthesis of all the other carbohydrates in the body, including glycogen for storage; ribose and deoxyribose in nucleic acids; galactose in lactose of milk; in glycolipids; and in combination with protein in glycoprotein and proteoglycans.

III. NATURE OF CARBOHYDRATES

- Carbohydrates are a group of **organic** compounds whose molecules contain atoms of **carbon**, **hydrogen**, and **oxygen** only. The ratio of hydrogen atoms to oxygen atoms is always **2:1**.
- General formula for any carbohydrate molecule: $C_x(H_2O)_y$.
- Note: There are a few carbohydrates do not conform to the formula (e.g. deoxyribose, $C_5H_{10}O_4$)
- Structure – Property Relationship:
 - All carbohydrates are either **aldehydes** or **ketones**
 - All contain several **hydroxyl** groups.



- Therefore, **carbohydrate chemistry** is determined by the **functional groups**.
 - hydroxyl groups are not highly reactive, but they readily form hydrogen bonds and contribute to making sugars soluble in aqueous solution.
 - carbonyl groups are easily oxidized and hence are powerful reducing agents.
- Classification of carbohydrates:
 - monosaccharides**
 - disaccharides**
 - polysaccharides**

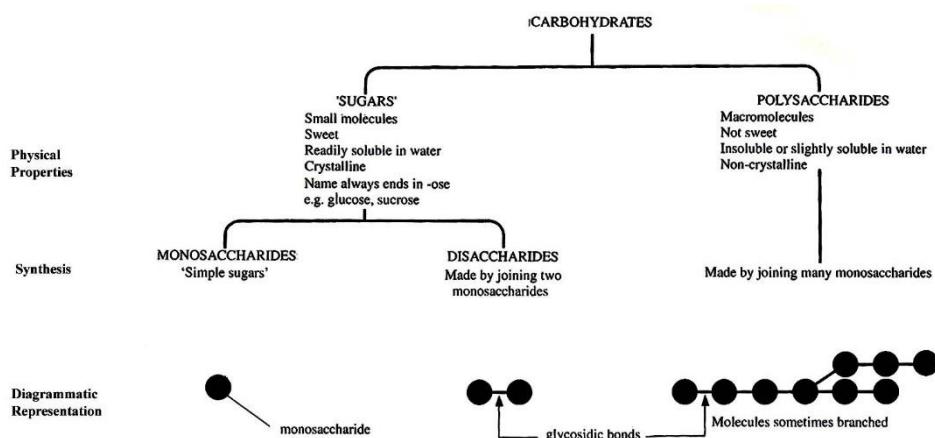


Fig 3.7 Classification of carbohydrates. Note that monosaccharides and disaccharides are both referred to as sugars. They share certain properties, such as sweetness of taste.

Source: Biological Science 1. Organisms, Energy and Environment. 3rd Edition. pp.83

IV. Monosaccharides

- Monosaccharides are the simplest types of carbohydrates.
 - All carbohydrates are composed of simple monomers known as monosaccharides, arranged in repetitive patterns.
 - General formula:** $(CH_2O)_n$, since they have the same number of carbon atoms as oxygen atoms in the molecule.
 - Nomenclature:** Depending on the **number of carbon atoms, n** in the molecule, we have:
 - **Triose** $C_3H_6O_3$, $n = 3$ e.g. glyceraldehyde, dihydroxyacetone
 - **pentose** $C_5H_{10}O_5$, $n = 5$ e.g. ribose, ribulose
 - **hexose** $C_6H_{12}O_6$, $n = 6$ e.g. glucose, galactose, fructose
- Note: Most names for sugars end in -ose.
- Property of monosaccharides:** **All monosaccharides are reducing sugars.**

A. Aldose vs Ketose

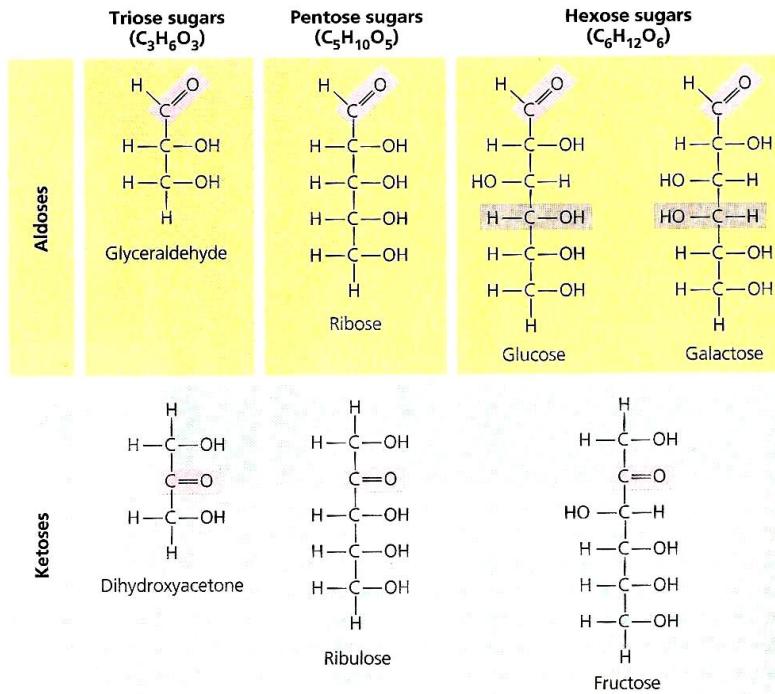
Depending on the location of the carbonyl group ($C=O$), a sugar is either an **aldose** or a **ketose**.

- Aldose** (i.e. an aldehyde sugar) – carbonyl group is located at the end of the carbon skeleton.
- Ketose** (i.e. a ketone sugar) – carbonyl group is located between two carbon atoms.

The presence of an aldehyde or ketone group allows all monosaccharides to exhibit reducing properties.

Glucose is an aldose, i.e. the chain of six carbon atoms is numbered beginning at the carbon of the aldehyde group.

FIGURE 5.3 The structure and classification of some monosaccharides. Sugars may be aldoses (aldehyde sugars) or ketoses (ketone sugars), depending on the location of the carbonyl group (pink). Sugars are also classified according to the length of their carbon skeletons. A third point of variation is the spatial arrangement around asymmetric carbons (compare, for example, the gray portions of glucose and galactose).



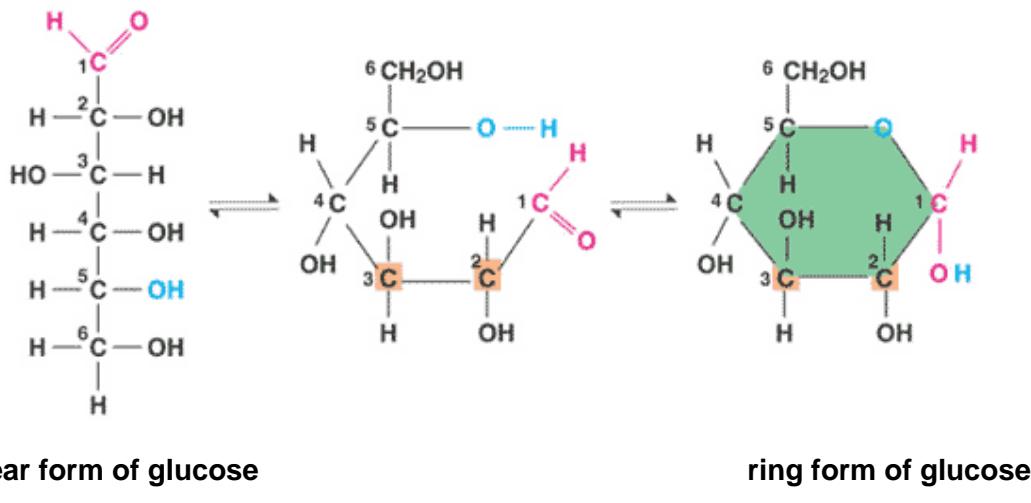
Source: Biology. 8th Edition. pp. 70

B. Linear vs Ring Forms

A hexose such as glucose can exist in linear or ring forms.

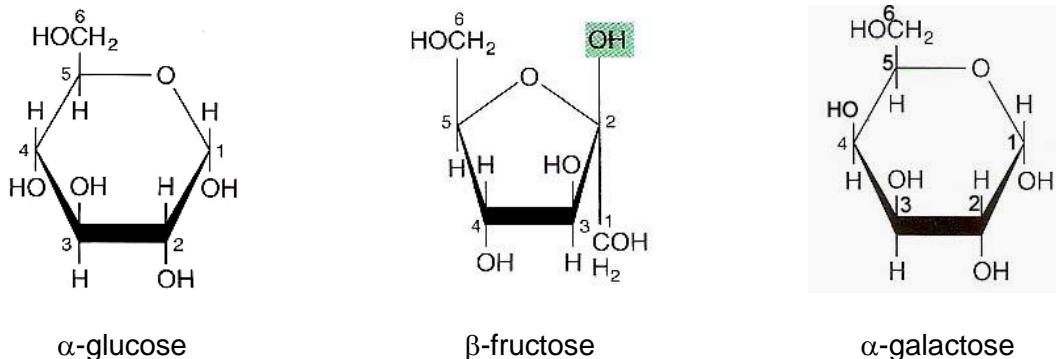
- In aqueous solution, most hexose exist as rings rather than linear molecules as the ring structure requires the least amount of energy to maintain.
 - The ring structure can be a **five-sided** (i.e. furanose) or **six-sided** (i.e. pyranose) ring. The ring structure is the form used to make disaccharides and polysaccharides.

In **glucose**, the first carbon atom (i.e. C1) combines with the oxygen atom on carbon atom number five (i.e. C5) to give a six-sided pyranose ring. Note that oxygen is part of the ring and that carbon atom number six (i.e. C6) sticks out of the ring.



Source: *Biology*. 9th Edition. pp.117

Common Monosaccharides (Ring Forms):



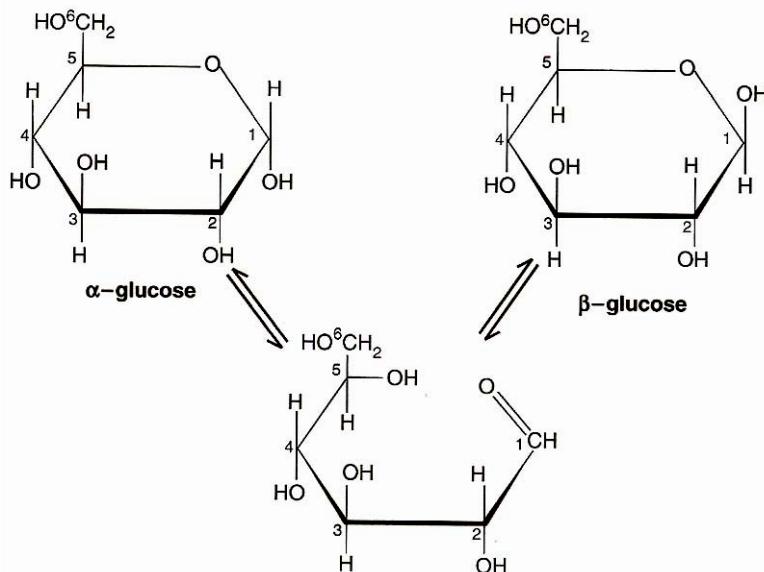
Source: Harper's Illustrated Biochemistry. 27th Edition. pp.114-5

C. Isomers

Molecules that have the same chemical formula but which differ in the arrangement of the atoms are known as **isomers**. Such **differing arrangements** give the molecules **different shapes** and hence, **different properties**.

Alpha (α) vs Beta (β) Isomers (a.k.a Anomers)

- Different isomers arise when a carbon atom has four different groups attached to it – such carbon atom is called an **asymmetric / anomeric carbon atom**.
- An anomeric carbon atom arises when glucose forms a ring structure, i.e. **carbon atom number 1 (C1)**, which is attached to:
 1. an oxygen atom;
 2. a carbon atom (i.e. C2);
 3. a hydrogen atom; and
 4. a hydroxyl group.
- The **hydroxyl group (-OH)** can be attached to C1 above or below the plane of the ring.



Source: Longman A-Level Course in Biology: Core Syllabus Volume 1. pp.53

- The α -isomer has the **hydroxyl group below the plane of the ring**, whereas the β -isomer has the hydroxyl group **above the plane of the ring**.
- The α - and β -isomers of glucose are **interconvertible** in aqueous solution.
- Significance:

Despite the relatively small differences in structure between α - and β -glucose, there are important consequences in terms of functions. α -glucose is used to synthesise the storage polysaccharide starch, whereas β -glucose is used to synthesise the structural polysaccharide cellulose, molecules which have very different properties.

Lecture Practice 1

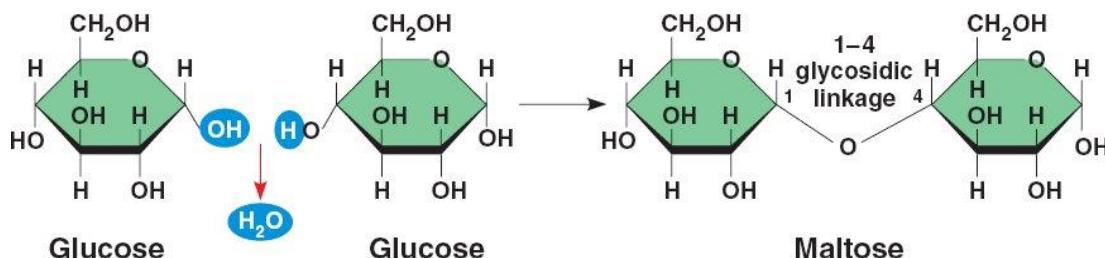
You are expected to be able to draw and label the ring structure of a glucose molecule. Refer to the following steps:

1. draw a **hexagon**:
2. add the **oxygen atom** on the top right-hand corner:
3. add and **label the carbon atoms** clockwise:
Note: C6 sticks out of the ring.
4. add the **hydroxyl groups**:
Note:
 - At **C1**: -OH group is below the plane of the ring for α -glucose but above the plane of the ring for β -glucose
 - At **C2** and **C4**: -OH group is below the plane of the ring
 - At **C3**: -OH group is above the plane of the ring
 - At **C5**: the primary alcohol (i.e. -CH₂OH) group is above the plane of the ring, i.e. C6 is subsumed under the -CH₂OH group
5. add the **hydrogen atoms**. Each carbon atom has formed a total of 4 single bonds:

α -glucose	β -glucose

V. Disaccharides

- Two monosaccharides combine to form a disaccharide by means of a **condensation** reaction. **One molecule of water is removed** in the process.
- The monosaccharide units are called **residues** once they have been linked.
- The bond formed between the two reacting monosaccharide units is called a **glycosidic bond**.
- The bond is normally formed between carbon atom 1 (i.e. the anomeric carbon atom) and carbon atom 4 of neighbouring α -glucose units, it is called a **α -1,4 glycosidic bond**.
- Condensation reaction** in the synthesis of maltose
 - The hydroxyl group of carbon 1 (anomeric hydroxyl group) on one α -glucose molecule and the hydroxyl group of carbon 4 on another α -glucose molecule react
 - to form a **α -1,4 glycosidic bond**
 - with the elimination of one water molecule.



- General formula:** $C_n(H_2O)_{n-1}$, since a molecule of water had been removed in condensation.
- Conversely, a disaccharide molecule can be broken down into monosaccharides during a **hydrolysis** reaction. **One molecule of water is added** in the process.
 - A disaccharide can be hydrolysed to its constituent monosaccharide units by the following methods:
 - Chemical method**, i.e. incubating the disaccharide with dilute acid at 100 °C.
 - Enzymatic method**, i.e. incubating the disaccharide with an enzyme at room temperature.

Disaccharide	Monosaccharides	Enzyme Used
Maltose a.k.a malt sugar	glucose + glucose	maltase
Sucrose a.k.a cane sugar	glucose + fructose	sucrase invertase
Lactose a.k.a milk sugar	glucose + galactose	lactase

- Properties of disaccharides:**
 - They are sweet.
 - They are crystalline in appearance.
 - They are readily soluble in water.
 - Maltose and lactose are **reducing sugars**, whereas sucrose is a **non-reducing sugar**.

Common Disaccharides:

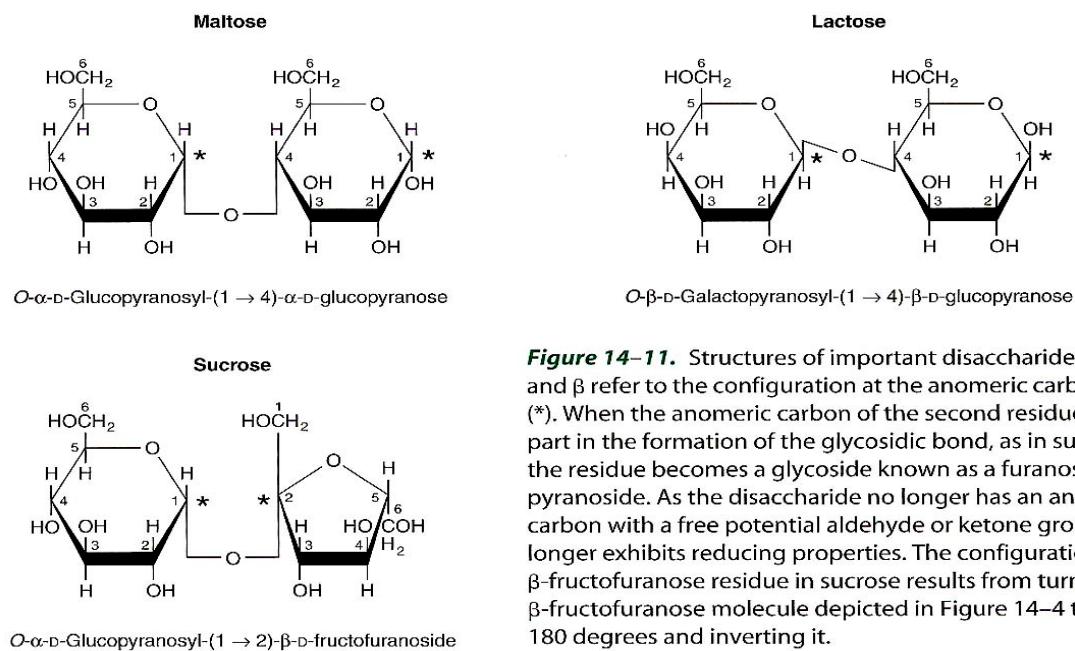


Figure 14-11. Structures of important disaccharides. The α and β refer to the configuration at the anomeric carbon atom (*). When the anomeric carbon of the second residue takes part in the formation of the glycosidic bond, as in sucrose, the residue becomes a glycoside known as a furanose or a pyranose. As the disaccharide no longer has an anomeric carbon with a free potential aldehyde or ketone group, it no longer exhibits reducing properties. The configuration of the β -fructofuranose residue in sucrose results from turning the β -fructofuranose molecule depicted in Figure 14-4 through 180 degrees and inverting it.

Source: Harper's Illustrated Biochemistry. 27th Edition. pp.117

Test for Reducing Sugars

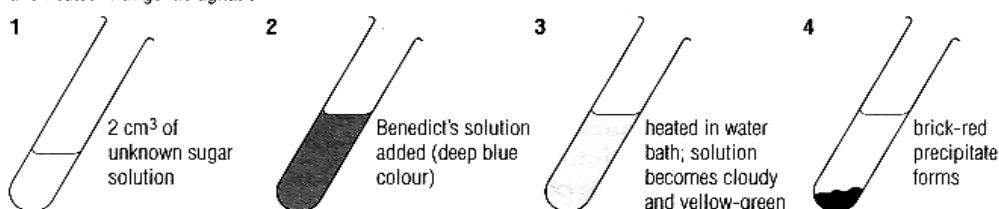
- Two common tests for reducing sugars, **Benedict's Test** and Fehling's Test make use of the ability of reducing sugars to reduce copper from the +2 to +1 oxidation state.
- The free **aldehyde or ketone** group of the sugar **reduces Cu²⁺ to Cu⁺**, and is itself oxidised to a carboxylic (-COOH) group.
- Both tests make use of an alkaline solution of copper (II) sulphate, CuSO₄ (**blue solution**) that is reduced to copper (I) oxide, Cu₂O (**brick-red ppt**).

REDUCING AND NON-REDUCING SUGARS

All monosaccharides and some disaccharides are reducing sugars.

The test for a reducing sugar

2 cm³ of a solution of the sugar to be tested is added to an equal volume of Benedict's solution; the solutions are mixed, and heated with gentle agitation



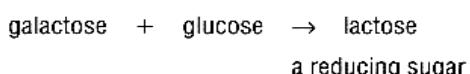
a colour change from blue to a cloudy yellow-green and the formation of a brick-red precipitate indicates that a reducing sugar is present

Explanation

Benedict's solution (blue) is an alkaline solution of copper(II) sulphate (CuSO₄). The aldehyde or ketone group of a monosaccharide sugar is able to reduce Cu²⁺ ions to Cu⁺, itself being oxidised to a carboxyl (—COOH) group. A brick-red precipitate of copper(I) oxide is formed.

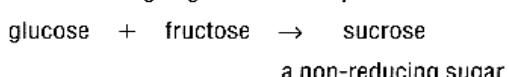
Disaccharides that are reducing sugars

Disaccharides formed by the reaction of the aldehyde group of one monosaccharide with a hydroxyl group of another contain a free aldehyde group, and will reduce Benedict's solution. For example:



Disaccharides that are non-reducing sugars

Disaccharides formed by the reaction of the aldehyde group of one monosaccharide with the aldehyde or ketone group of another are non-reducing sugars. For example:



Testing for a non-reducing sugar

There is no specific test for non-reducing sugars. A disaccharide can, however, be hydrolysed to its constituent monosaccharides by boiling with dilute hydrochloric acid, and the products of hydrolysis will then reduce Benedict's solution (*Study Guide*, Chapter 6).

TABLE 2.4 Relationship between amount of reducing sugar and colour of precipitate on boiling with Benedict's reagent

Amount of reducing sugar	Colour of solution and precipitate
No reducing sugar	Blue
Increasing quantity of reducing sugar	Green
	Yellow
	Brown
	Red

Source: Advanced Biology. Principles and Applications. 2nd Edition. pp.134

VI. Polysaccharides

- Polysaccharides are polymers of a few hundred to a few thousand monosaccharides.
 - Monosaccharides link up through glycosidic bonds by condensation to form polysaccharides.
- Based on the monomeric constituents, polysaccharides are classified as:
 - **Homopolysaccharide** = composed of only a **single type** of monomer.
 - **Heteropolysaccharide** = composed of two or more **different types of** monomers.
- Properties of polysaccharides:
 - They are not sweet
 - All are non-reducing sugar
- Polysaccharides can be classified in term of their **functions** into:
 - **storage** polysaccharides, e.g. starch, glycogen
 - **structural** polysaccharides, e.g. cellulose, chitin

A. Storage Polysaccharides

Storage polysaccharides are **convenient storage molecules** for several reasons:

- their **large size** makes them insoluble in water, so they exert no osmotic or chemical influence on the cell.
- they **fold** into compact shapes, so as to store many glucose molecules within a small volume in the cell.
- they are **easily hydrolysed by enzymes** back into their constituent monosaccharides, which are used as respiratory substrates.

Starch

Starch is a polysaccharide found in **plant** in the form of insoluble **starch granules**. These are found within chloroplasts of leaves, in storage organs such as the potato tuber and in seeds of legumes and cereals.

- Starch is a **food reserve formed from any excess glucose** during photosynthesis.
- Structures:
 - Starch is a polymer of α -glucose (i.e. homopolysaccharide).
 - α -glucose monomers are joined by **glycosidic bonds**.
 - Starch has two components: **amylose** and **amylopectin**.
 - Most forms of starch in nature are 10 – 30 % α -amylose, 70 – 90 % amylopectin and 1 % of other substances such as phosphates and fatty acids.

Source: *Biology (9th Edition)*, pp118

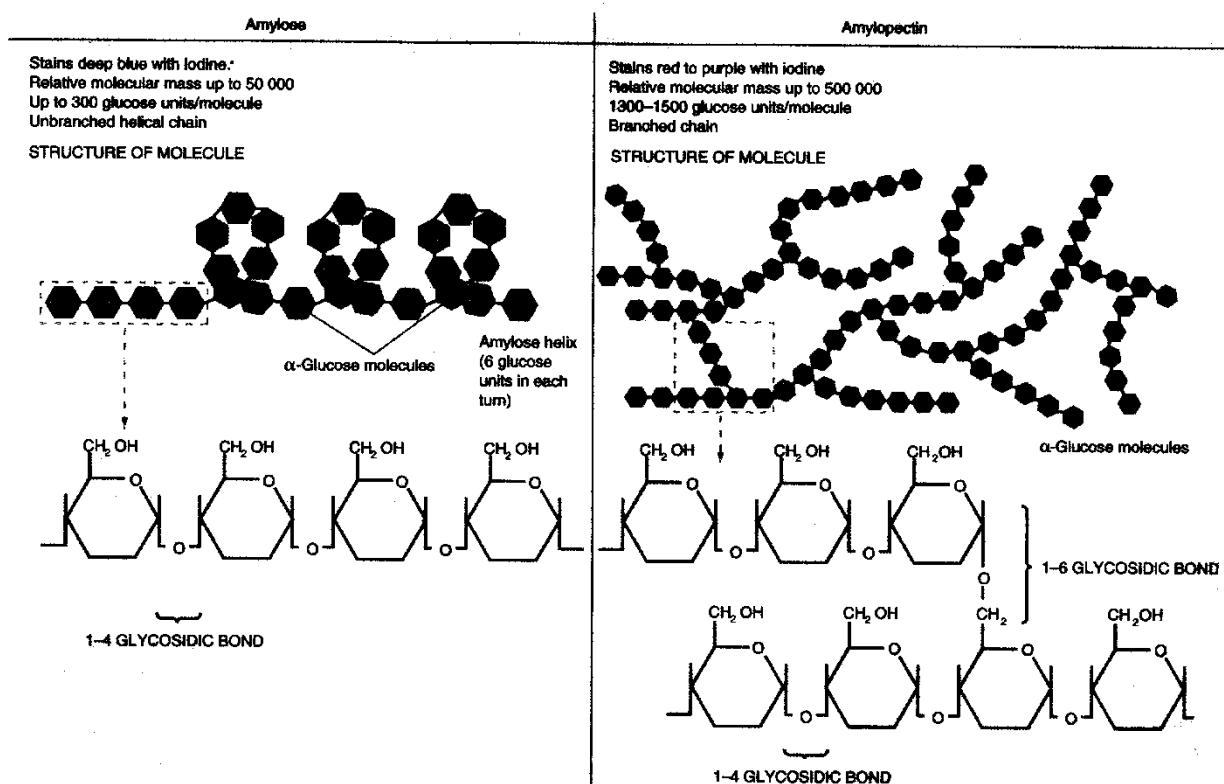
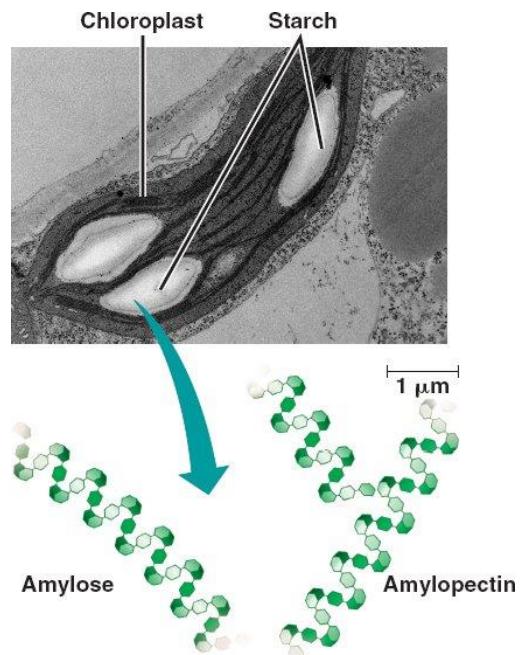
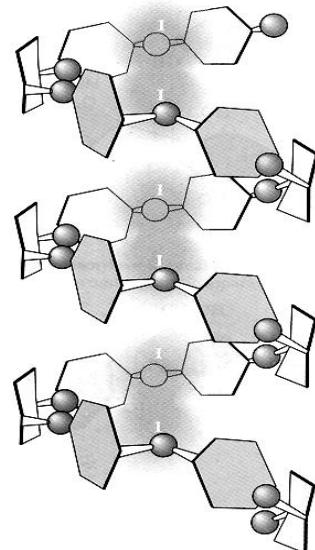


Fig. 2.3. Comparison of the properties and structures of amylose and amylopectin

Source: *Understanding Biology for Advanced Level. 4th Edition*. pp. 18.

AMYLOSE

- Amylose is composed of unbranched chains, each consisting of approximately 300 glucose units linked by α -1,4 glycosidic bonds.
- These bonds cause the chain to coil into a helix with six glucose units in every turn, into a **more compact structure**.
- Test with iodine-potassium iodide solution:**
 - A suspension of amylose in water gives a blue-black colour with iodine-potassium iodide solution.
 - Iodine-potassium iodide molecules pack inside the core of the helix.



Source: *Principles of Biochemistry with A Human Focus*. pp. 222

Figure 7.22 Suspensions of amylose in water adopt a helical conformation. Iodine (I_2) can insert into the middle of the amylose helix to give a blue color that is characteristic and diagnostic for starch.

AMYLOPECTIN

- Amylopectin is a highly branched chain of α -glucose residues (~1300).
- The **linear linkages** in amylopectin are α -1,4, whereas the **branch linkages** are α -1,6.

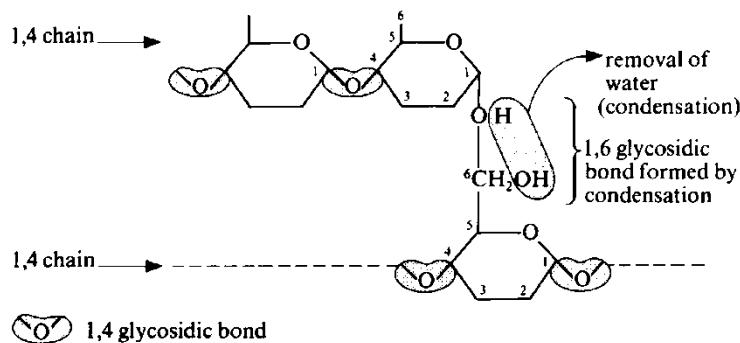


Fig 5.15 Structure of amylopectin showing formation of one branch

Source: *Biological Science 1. Organisms, Energy and Environment*. 3rd Edition. pp 87.

- Branches occur in these chains every 25 to 30 residues. The many branch ends allow a number of enzymes to act on it at any one time so that it can be easily broken.
- Test with iodine-potassium iodide solution:**
 - A suspension of amylopectin in water gives a red-violet colour with iodine-potassium iodide solution.

- Relating structure of starch to its storage role:

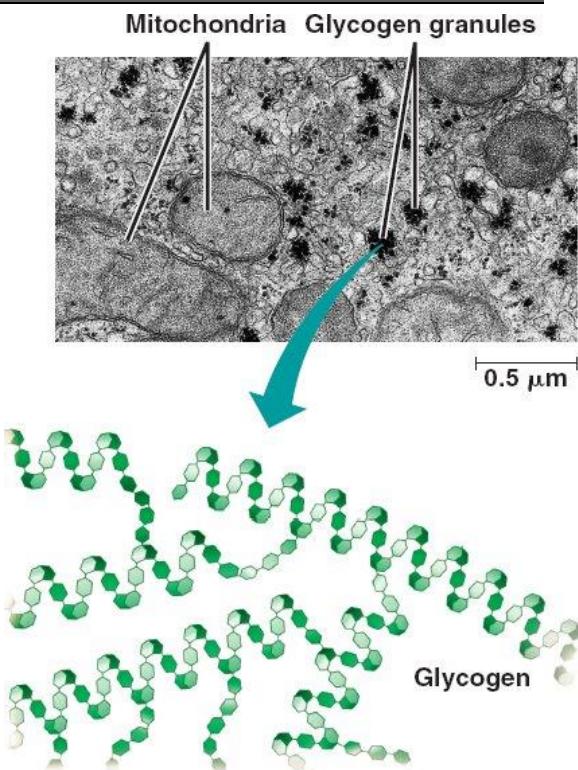
Structure	Significance
	<ul style="list-style-type: none"> • <u>Insoluble in water</u>: does not exert osmotic or chemical influence on the cell. • <u>Stores large amounts of carbon / energy</u>. Hydrolysis of starch gives glucose molecules, a <u>main respiratory substrate</u>.
	<ul style="list-style-type: none"> • The bonds can be hydrolysed by enzymes present in plants and most organisms. • The bonds result in <u>helical coil</u> so that structure is more <u>compact</u> and ideal for storage.
	<ul style="list-style-type: none"> • <u>Stable / unreactive</u> compound.
	<ul style="list-style-type: none"> • Branching allows many enzymes to act on amylopectin at one time, therefore <u>many sites</u> for hydrolysis. • This allows <u>rapid release</u> of glucose residues • Branching also makes it <u>more compact</u> (as multiple chains fold and stack tightly within a relatively small space).

Glycogen

Glycogen is the major form of storage polysaccharide in **animals**. It is found mainly in the **liver** (where it amounts to as much as 10 % of liver mass) and **skeletal muscle** (where it accounts for 1 - 2 % of the muscle mass) in the form of **cytoplasmic granules**.

- Structure:
 - Like starch, glycogen is a polymer of α -glucose.
 - Similar to **amylopectin** in structure but has **shorter branch chains** (10 – 20 glucose residues).
 - It is more **highly branched** than amylopectin.
 - Like amylopectin, a suspension of glycogen in water gives a red-violet colour with iodine-potassium iodide solution.

Source: *Biology (9th Edition)*. pp 118.



- Biological roles:

As a storage of energy

- Glycogen is found in animal cells where **glucose needs to be readily available in large amounts.**
- These include skeletal muscle cells (where energy demand can surge suddenly with vigorous exercise) and hepatocytes (the liver being the organ responsible for homeostatic regulation of glucose level).
- Glycogen is stored in the form of **glycogen granules** in the liver and muscles.

B. Structural Polysaccharides

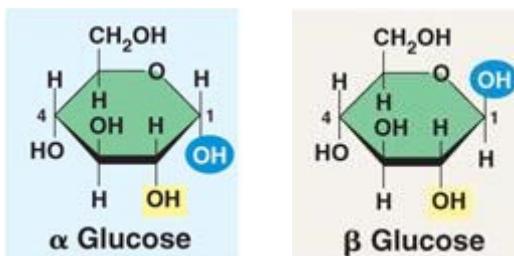
Organisms build **strong materials** from structural polysaccharides. It is awe-inspiring to look at a large tree and realise the amount of weight supported by polymeric structures derived from sugars and organic acids.

Cellulose

Cellulose is one of the principal components of cell walls (typically comprising up to 50% of cell wall material) of plants, **providing structure and strength.**

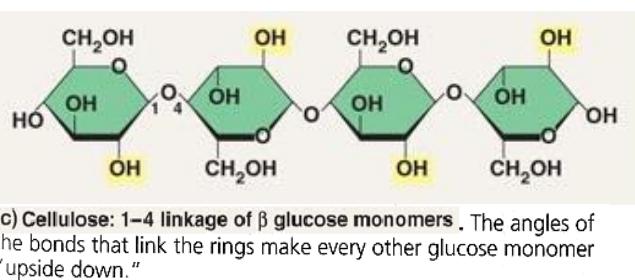
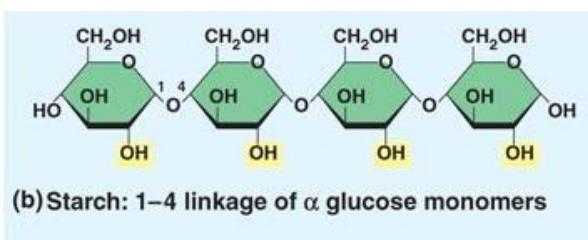
Differences in composition between cellulose and starch

- **Cellulose** has dramatically **different properties** from those of the storage polysaccharides such as starch, even though the **compositions of these two classes are similar.**
 - Both polymers are homopolysaccharides made up of **glucose monomers**, which are linked by **1,4 glycosidic bonds**.
- In **starch**, all the glucose monomers are in the α configuration.
In **cellulose**, however, all the glucose monomers are in the β configuration.



Therefore, we get:

- α -1,4 glycosidic bonds in **starch**; and
- β -1,4 glycosidic bonds in **cellulose**.

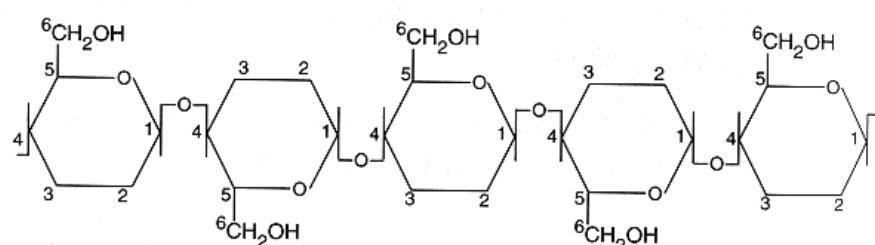
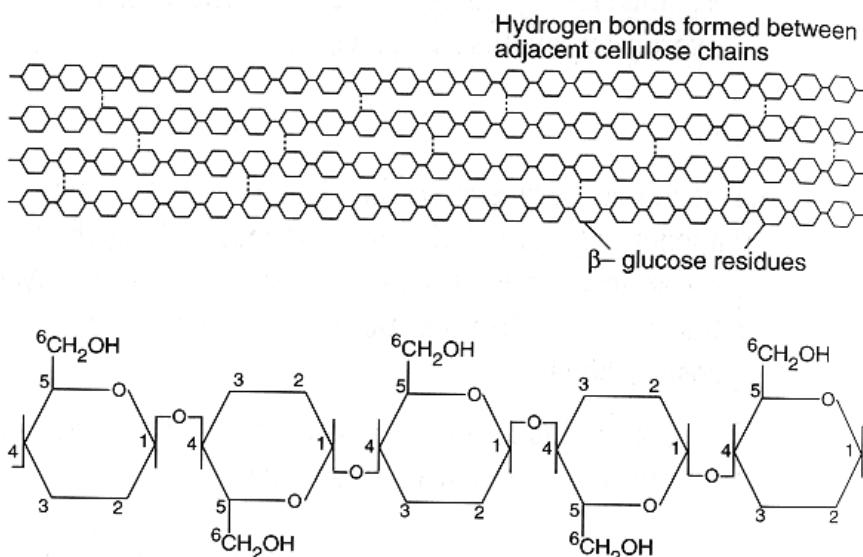


- This **variation in the geometry of the glycosidic links** results in starch and cellulose having very **different three-dimensional shapes** and therefore very **different properties and functions**.

Structures:

- In order to obtain **β -1,4 glycosidic bonds** in cellulose, every other β -glucose must be **inverted**.
 - ⇒ In doing so, cellulose forms a long, unbranched straight chain.
- Cellulose is a polymer of about 10 000 β -glucose molecules forming **long unbranched chain**. Many chains run **parallel** to each other and their **hydroxyl groups (-OH)** project **outwards from each chain in all directions**.
 - ⇒ In doing so, extensive hydrogen bonds form between neighbouring chains.
 - ⇒ This establishes rigid cross linkages between chains.
- The chains associate in groups (of ~ 60-70) to form **microfibrils**, which are later arranged in larger bundles to form **macrofibrils**.

(a)



(b)



A cellulose chain consists of about 1000 β -linked glucose residues.

A micelle consists of hundreds of cellulose chains.

A microfibril consists of many micelles.

A macrofibril consists of about 400 microfibrils.

Source: Longman A-Level Course in Biology. pp 58.

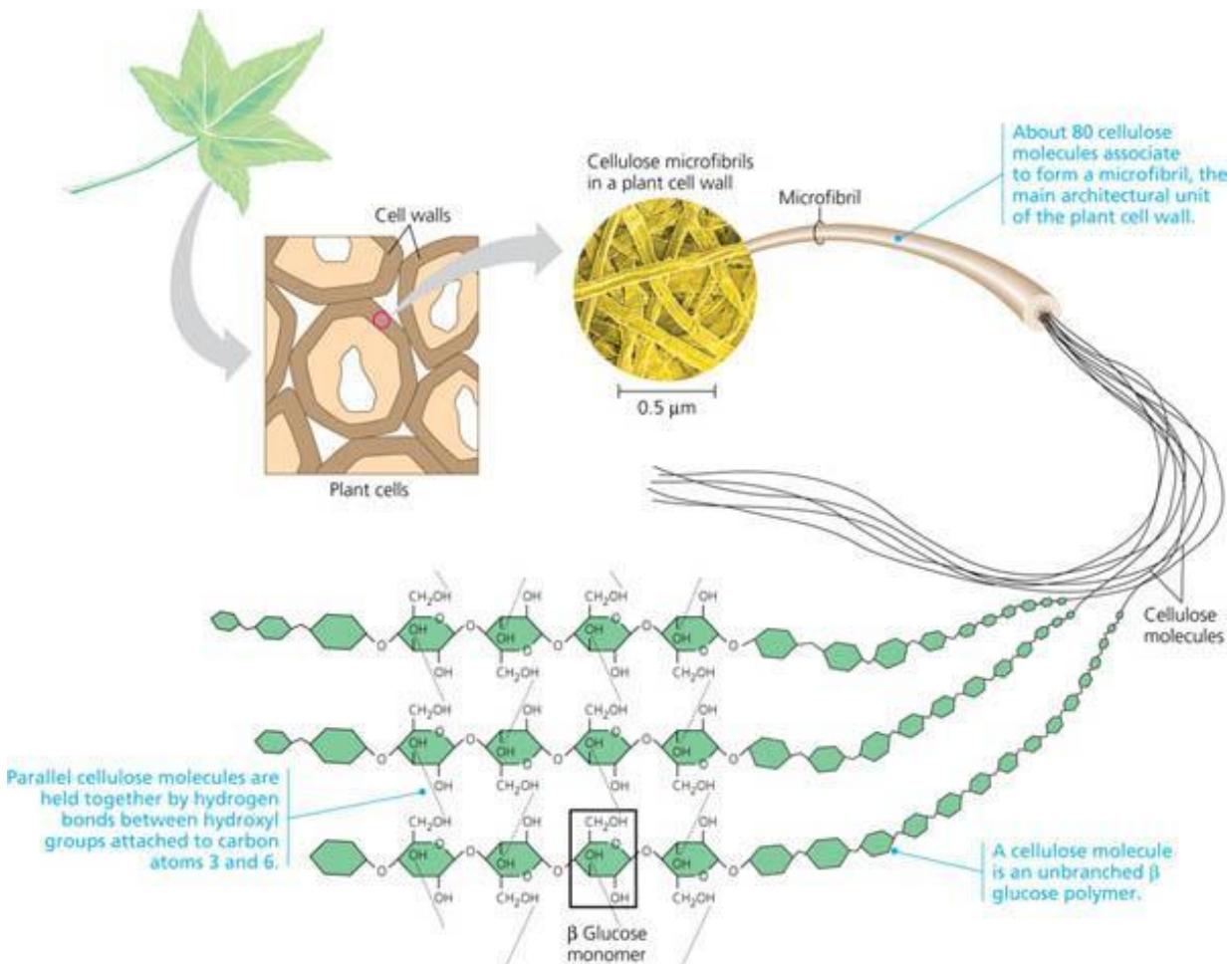
- Biological Properties / Roles:

As a structural scaffold

- Cellulose has tremendous tensile strength and considerable stability, which makes it a valuable structural material.
- Despite their combined strength, the layers are fully permeable to water and solutes – an important property for the proper functioning of plant cells.

As a storage of energy

- The enzyme **cellulase** catalyses digestion of cellulose to glucose. Cellulose is thus an important **food source** for animals (ruminants, snails, insects), algae, bacteria and fungi.



Source: Biology (9th Edition). pp119

- Relating structure of cellulose to its function:

Structure	Significance
	<ul style="list-style-type: none"> • <u>Insoluble in water</u>: does not exert osmotic or chemical influence on the cell. • <u>Stores carbon/energy</u> for organisms that can feed on it.
	<ul style="list-style-type: none"> • The bonds result in <u>long, straight</u> chains.
	<ul style="list-style-type: none"> • Allows <u>hydrogen bonds</u> to be formed between neighbouring chains. <ul style="list-style-type: none"> ⇒ forms extensive cross linkages in microfibrils and allows microfibrils to be arranged in larger bundles to form macrofibrils. ⇒ results in <u>high tensile strength</u>.

Hydrolysis of Cellulose

Interestingly, **no multicellular animals seem to have developed a cellulase enzyme** capable of breaking the $\beta(1 \rightarrow 4)$ glycosidic bonds of the cellulose polymer. As a result, in many cases this excellent potential source of glucose passes straight through the digestive tract unused.

How, then, do herbivores such as sheep survive on their diet?

Present in the gut of sheep are certain bacteria and protozoa which produce cellulase. The herbivores provide the gut organisms with plentiful supply of cellulose. In return, the microbes produce the breakdown products of cellulose which the herbivores are able to absorb and use.

Chitin

Linear monopolysaccharide of **N-acetyl-D-glucosamine** residues linked by $\beta-1,4$ glycosidic bonds. Chemically and structurally resembles cellulose. Individual chains are bundled together by hydrogen bonding. A major component of the exoskeleton of insects, crustaceans and spiders.

