Chapter 8 - Carbohydrates

Hydrates of Carbon: $C_m(H_2O)_n$

Saccharides: Latin: *Saccharum* = Sugar

1. Energy transport and storage.

2. Structural *e.g.* bacterial cell walls, cellulose.

3. Information *e.g.* signals on proteins and membranes.

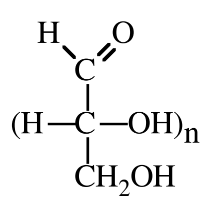
Naming: Monosaccharide, 1 unit; disaccharide, 2 units …

Oligosaccharides: several sugar units.

Polysaccharides: long chains of 100s – 1000s.

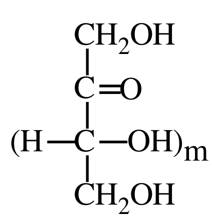
Triose, tetrose, pentose refers to the # of C in 1 unit.

2 Families



Aldose

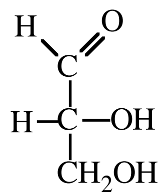
n = 1 - 4

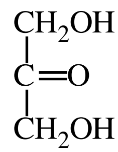


Ketose

m = 0 - 3

The **Aldoses** derive from *D*-Glyceraldehyde, the **Ketoses** from Dihydroxyacetone:





Aldotrioses and ketotrioses have 3 C’s in the backbone.

Aldotetroses and ketotetroses have 4 C’s.

Pentoses and hexoses have 5 and 6 C’s.

Fig. 8.3 shows the family of *D*-aldoses.

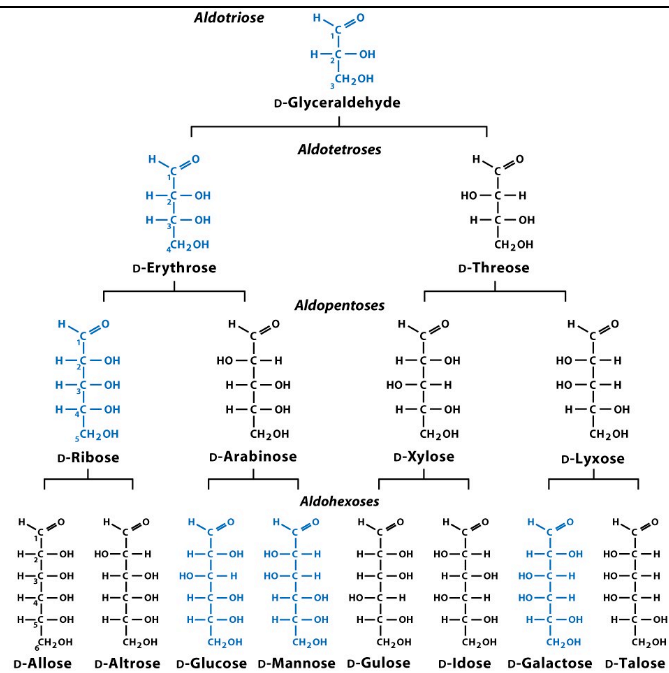
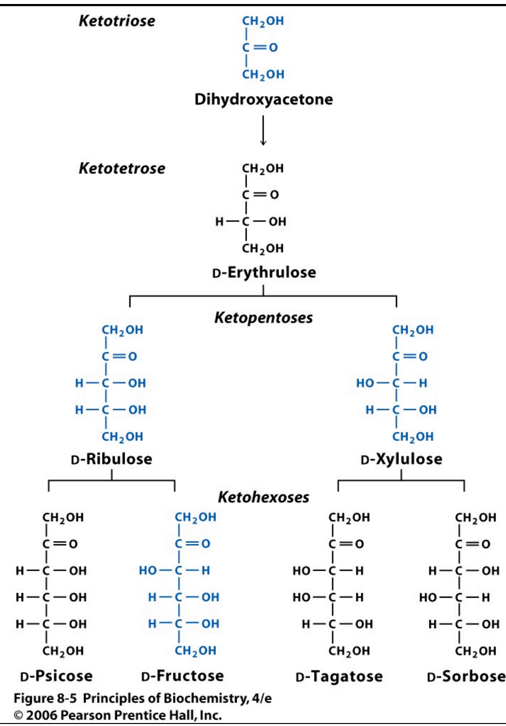


Figure 8-3 Principles of Biochemistry, 4/e

Fig. 8-5 shows
the family of *D*-ketoses.



The 4C and 5C ketoses are named after the aldoses with the addition of – ul – Ribose → Ribulose Xylose → Xylulose

Abbreviations

Glucose	Glc
Glucosamine	GlcN
Glucuronic Acid	GlcA
Fructose	Fru
Galactose	Gal
Galactosamine	GalN
N-Acetylglucosamine	GlcNac
Mannose	Man
Ribose	Rib

Except for dihydroxyacetone, all the aldoses and ketoses have **asymmetric = chiral** carbons.

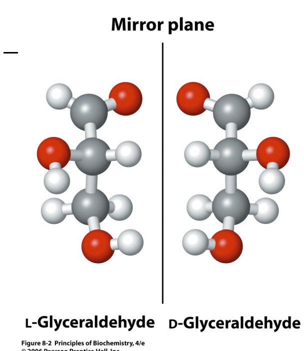
In nature, most sugars are *D*- most AA are *L*-.

D- and *L*-glyceraldehyde are reference molecules for assignment of stereochemistry (absolute configuration).

L-Glyceraldehyde D-Glyceraldehyde

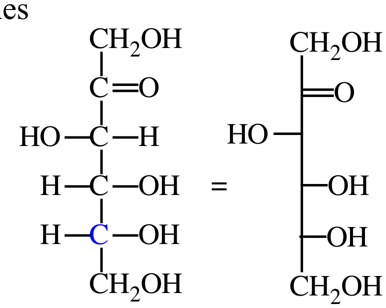
These are nonsuperimposable mirror images – **enantiomers**.

The diagrams above are called "**perspective formulae**".



Fisher projection formulae retain the stereochemical information but use lines for the bonds. See fructose below:

Why *D*-? The **chiral C** furthest from the C=O has the same configuration as *D*-glyceraldehyde.

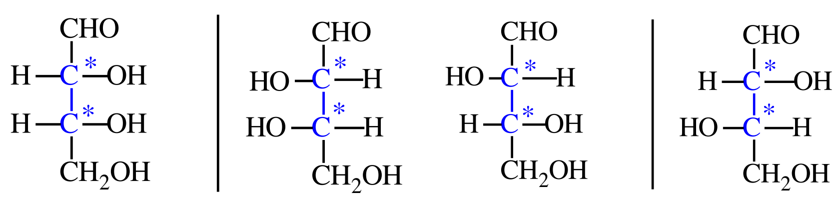


D-Fructose

These molecules are optically active: they rotate the plane of monochromatic plane-polarized light in opposite directions. dextrorotatory (+) or levorotatory (-). For example,

D-(+)-glucose (dextrose) *D*-(-)-fructose (levulose)

Erythrose Threose



D-	*L*-	*D*-	*L*-
1	2	3	4

1 & 2 are enantiomers. 3 & 4 are enantiomers.

Diastereomers: Non-mirror image stereoisomers.

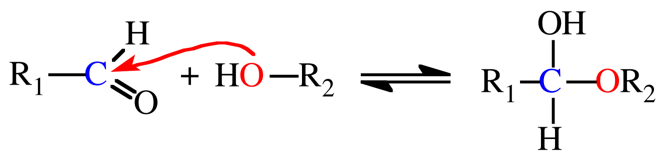
1 & 3 1&4 2&3 2&4

Epimers: Diastereomers that differ in configuration at 1 C.

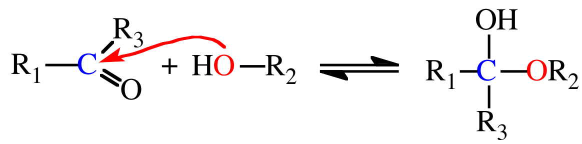
1 & 3 @ C2 1 & 4 @ C3 2 & 3 @ C3 2 & 4 @ C2

Cyclic Forms:

In general,



Aldehyde + Alcohol ⇌ Hemiacetal



Ketone + Alcohol ⇌ Hemiketal

A second alcohol can add to form an Acetal / Ketal, respectively.

Notes:

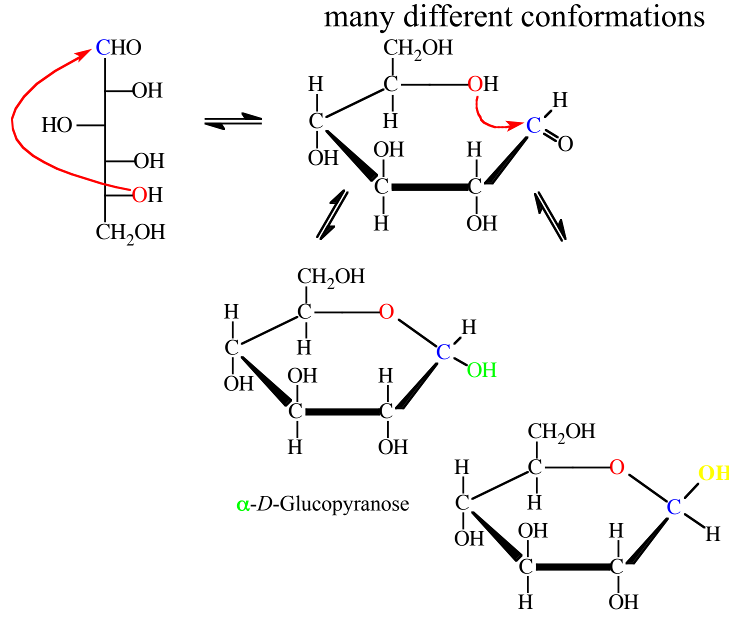
1. New chiral centres have been created.

2. The above reactions are **intermolecular**.

3. In aldoses and ketoses **intramolecular** hemiketals / hemiacetals form in solution.

D-Glucose

Rotation about C-C bonds gives rise to many different conformations

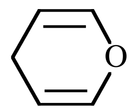


α-*D*-Glucopyranose

β-*D*-Glucopyranose

These are called "**Haworth**" diagrams. They illustrate some aspects of the stereochemistry of these molecules.

4. The 6-membered ring is much more stable than the 5-membered ring.

5. They are called pyranoses because of pyran: 

6. **C1** is a new asymmetric C: Isomers that differ only at the hemiacetal or hemiketal C are called **anomers** and the C is the **anomeric C**.

7. α-anomer: **OH** on C1 is on the **opposite** side of the ring to C6.
β-anomer: **OH** on C1 is on the **same** side of the ring as the C6.

8. OH on asymmetric C on the "**right**" in the Fisher diagrams are "**down**" in the Haworth Diagrams.

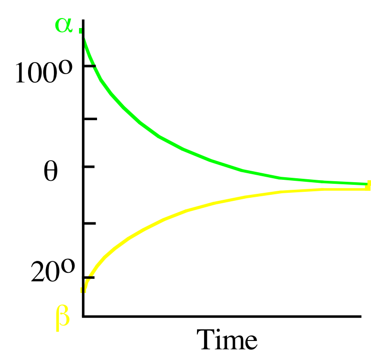
9. Fisher diagrams (straight chain) are correct for sugars with 3 or 4 C, otherwise ring structures are more stable.

10. In water all three forms of glucose exist in equilibrium:

α ⇌ Chain ⇌ β

36% 0.01% **64%**

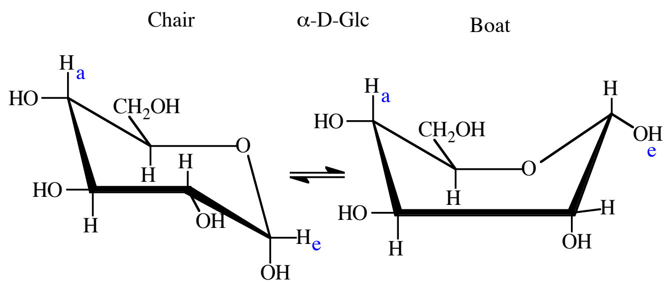
The interconversion is called **Mutarotation** and can be measured by the rotation of plane-polarized light.



Pure α-*D*-Glc rotates light +112 º, pure β-*D*-Glc rotates +19º, and at equilibrium the mixture rotates light +53º.

$$36\% \, (112^{o}) + 64\% \, (19^{o}) = +53^{o}$$

The pyranose rings are not entirely planar. Each configuration (α, β) can exist in 2 "puckered" **conformations**:



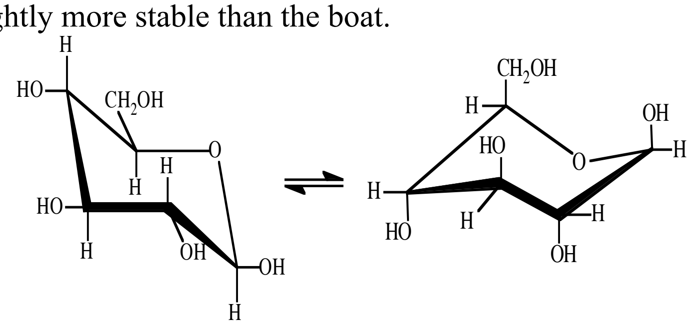
e = equatorial - The group is in the plane, or parallel to, the planar part of the ring.

There is less steric hindrance if bulky groups go in the e positions.

a = axial – The group is perpendicular to the planar part of the ring.

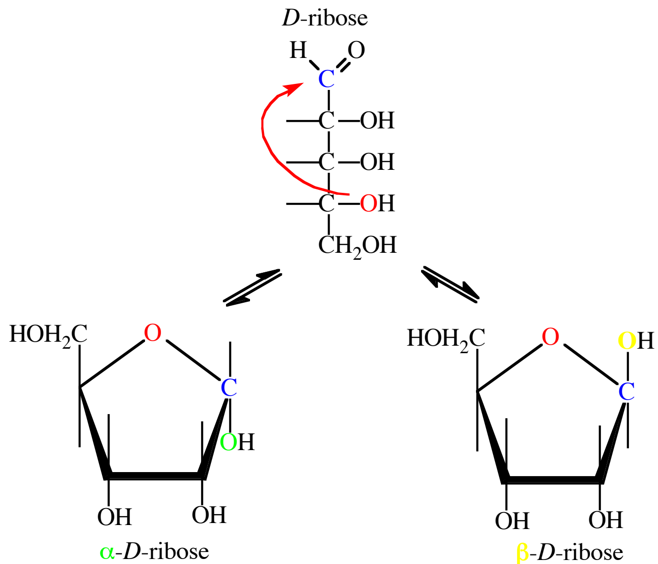
The chair is slightly more stable than the boat.

Here are two possible chair conformations of β-*D*-Glc.



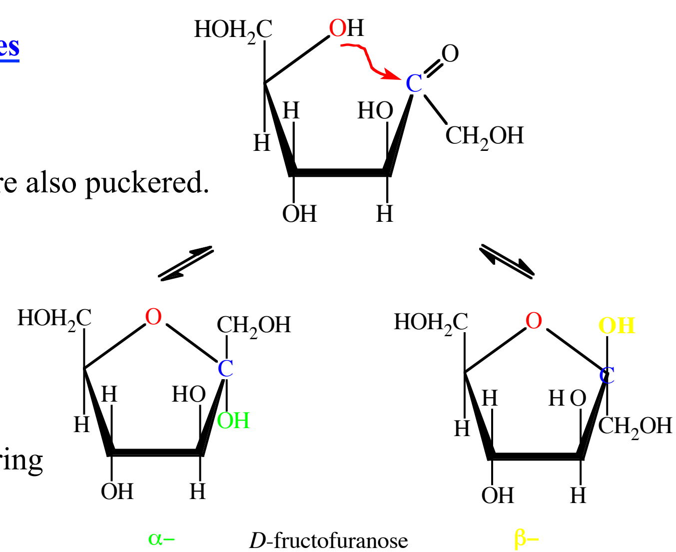
Only β-*D*-Glc can put all bulky substituents in the equatorial position so it is a very stable and abundant molecule.

The pentoses also form hemiacetals:

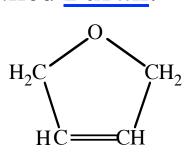


Cyclic Ketoses

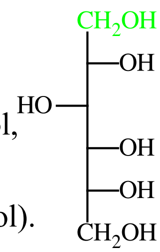
These rings are also puckered.



5-membered ring called **Furan**.



Sugar Derivitives



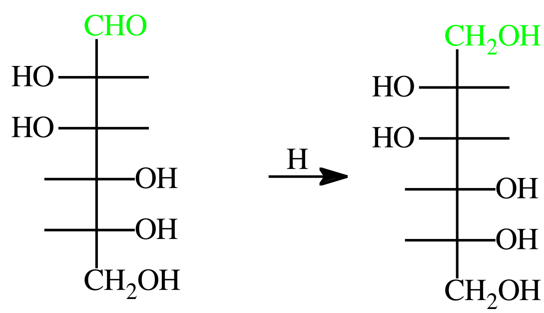
Glucitol

1. Reduction of *D*-glyceraldehyde yields glycerol, an alcohol.

Reduction of *D*-glucose yields *D*-glucitol (Sorbitol).

Reduction of mannose yields mannitol.

Note that Glc and Man are epimers at C2.



D-mannose

D-mannitol

Mannitol and sorbitol are used as low calorie sweeteners. They are only very slowly metabolized to glucose and stimulate little insulin secretion, a property helpful to diabetics.

They have a positive heat of solution giving them a **"cool"** sensation.

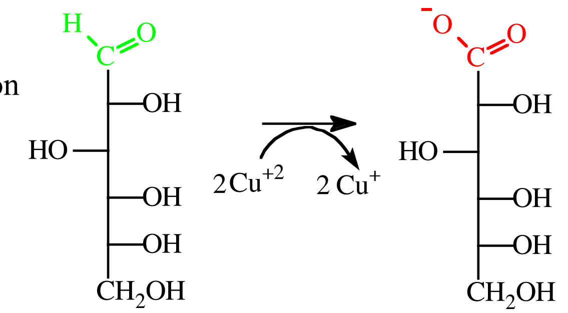
Any excess, unabsorbed sugar alcohols have a laxative effect as they prevent absorption of water.

2. Monosaccharides are **reducing agents**.

They give up electrons and are themselves oxidized. Oxidation of aldols yields the **Aldonic acid** family. This can be detected in an alkaline solution of Copper.

Cu^{+} is insoluble and precipitates from solution as brick-red Cu_2O.

"Benedict's Test"
Experiment 4.



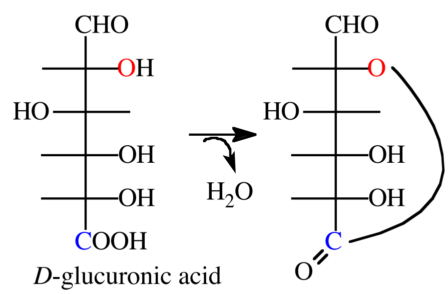
D-Glucose *D*-Gluconate

Only the straight chain forms of the sugars are reactive.

The ketoses will react slowly because they must isomerize to the aldehyde.

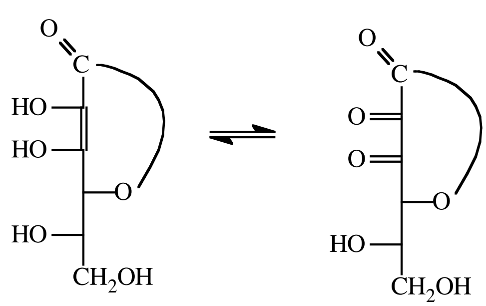
Oxidation at C6 produces the **Uronic acid** family. *E.g. D*-glucuronic acid.

3. Aldonic and uronic acids form stable intramolecular esters called **sugar lactones**:



D-glucuronic acid D-glucuronolactone

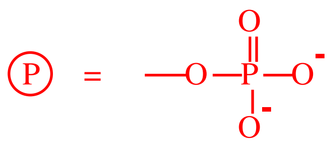
Vitamin C = *L*-ascorbic acid
a sugar acid lactone:

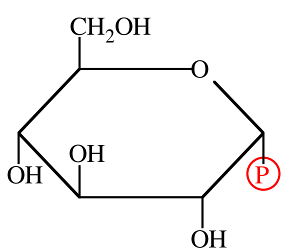


Primates and fruit bats have lost the ability to make Vitamin C so it is an **essential nutrient**.

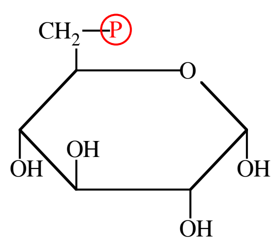
Humans have also lost the ability to oxidise uric acid so some of the antioxidant function of Vitamin C may have been taken over by uric acid. The ancient DNA encoding *L*-glucuronolactone oxidase is still present in the human genome.

4. Sugar Phosphate esters are intermediates in sugar synthesis that prevent transport of the sugar across hydrophobic membranes.



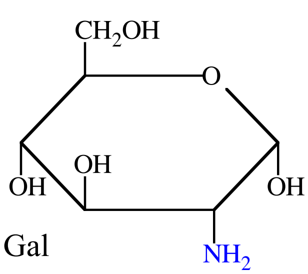


Glc-1-P

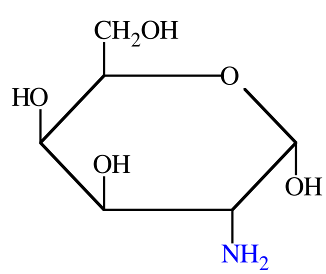


Glc-6-P

5. Amino Sugars



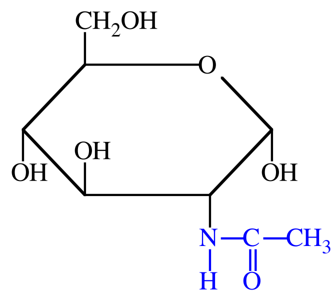
α-D-glucosamine



α-D-galactosamine

Note that Glc and Gal are epimers at C4.

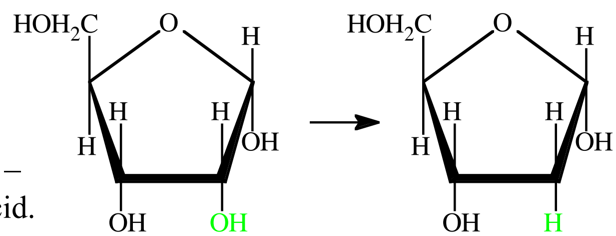
6. Sugar Amides



N-acetyl-glucosamine

7. Deoxy-sugars

This is the sugar component of DNA – deoxyribonucleic acid.



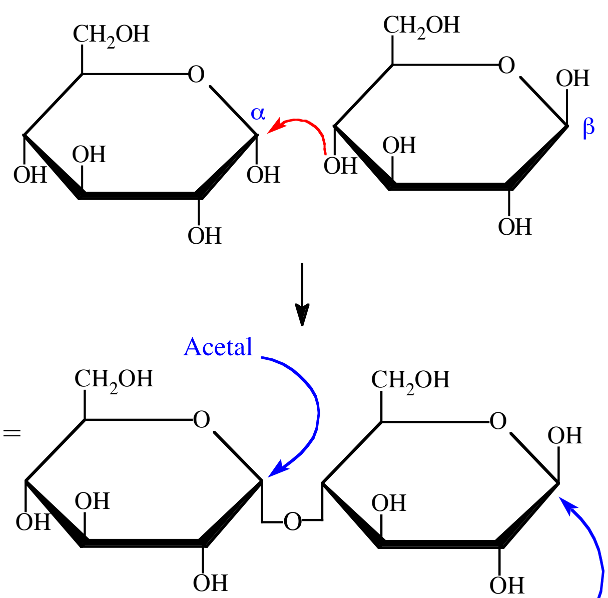
α-*D*-ribose α-*D*-2-deoxyribose

Disaccharides

Maltose

A reducing sugar.

Maltose (β-form) = Glc(α1→4)Glc



= O-α-*D*-glucopyranosyl-(1→4) β-*D*-glucopyranose

Hemiacetal

It is made from starch by the enzyme *amylase*.

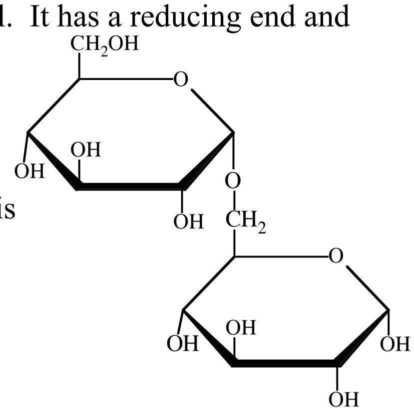
Notes: 1. The left Glc is an acetal. It is non-reducing and non-mutatrotating.

2. The right glucose is a hemiacetal. It has a reducing end and mutarotates.

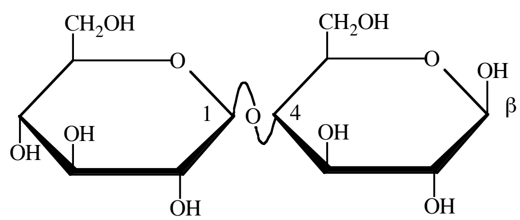
3. **Glycosidic bonds** join sugars.

Iso-maltose is Glc (α1→6) Glc. It is a reducing sugar.

Made from hydrolysis of dextrans.



Cellobiose

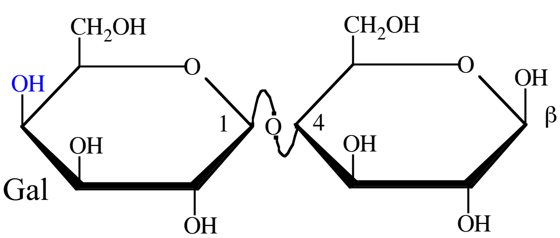


Glc (β1→4) Glc

A reducing sugar, produced by acid hydrolysis of cellulose.

Lactose:

Milk sugar.
A reducing sugar.
Remember, Glc and Gal are epimers at C4.



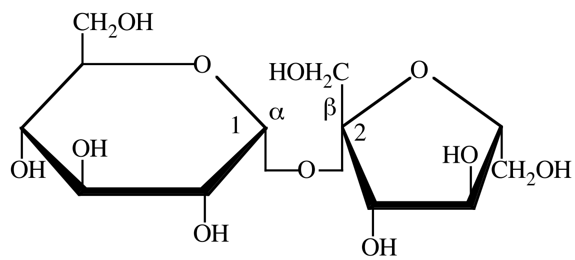
Gal (β1→4) Glc

Adults without the enzyme *lactase* cannot digest lactose and are **Lactose Intolerant**.

In the small intestine, bacteria switch their metabolism to digest lactose (fermentation) producing large amounts of gas and cramping.

Sucrose: A **non-reducing sugar**.

Table Sugar.
Made by plants.



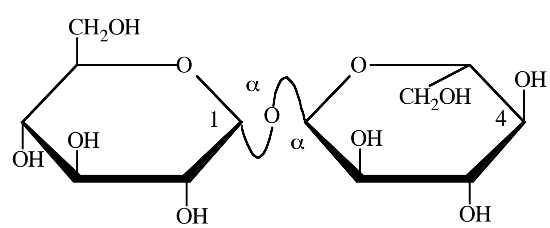
Glc (α1←→β2) Fru
Fru (β2←→α1) Glc

Sucrose rotates light by +66°. Hydrolysis of sucrose results in a mixture that rotates light at -39°, called "*invert sugar*".
~ 2x sweeter than "*sugar*". A popular food additive.

α + β-*D*-Glc are +53° and α + β-*D* Fru are -92°.
Honey is essentially invert sugar. Here is a picture of crystals of honey viewed with polarized light.

Trehalose
A **non-reducing sugar**.

Energy storage in insects.



Glc (α1←→α1) Glc

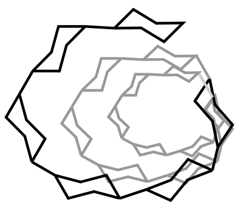
Most sugars are stored as **Polysaccharides** = **Glycans**

They may be branched or unbranched.

Starch: Storage of *D*-Glc in plants; 2 types:

I Amylose: Unbranched chains of α1→4 linked Glc *i.e.* Maltose; up to 4,000 Glc in one chain.

It forms a tightly coiled **helical** structure stabilized by H-bonding with 6 residues per turn.



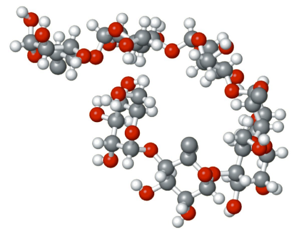
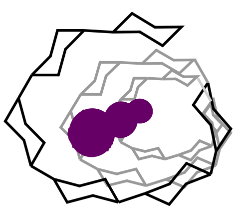
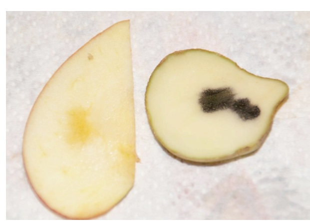


Figure 8-22b Principles of Biochemistry, 4/e

Iodine can insert into the middle of the helix giving starch a **blue** colour in a potato (right). Apples (left) contain very little starch.





http://www.webexhibits.org/causesofcolor/images/content/emerald/DSC03426Z.jpg

II Amylopectin: Up to 200 amylose chains linked α1→6 at "*Branch Points*".
So just like iso-maltose.

This cannot form the helical structure.

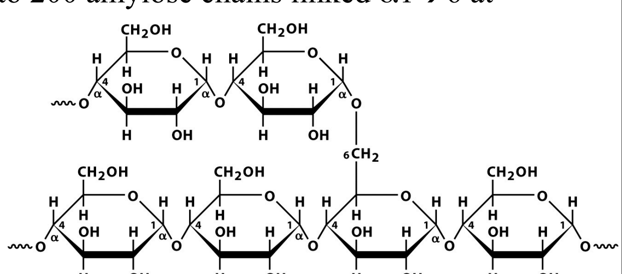


Figure 8-23 Principles of Biochemistry, 4/e

So starch has Maltose and isomaltose units with one reducing end and many non-reducing ends.

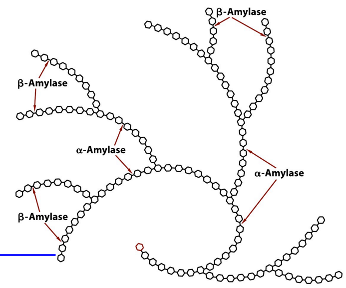


Figure 8-24 Principles of Biochemistry, 4/e
© 2006 Pearson Prentice Hall, Inc.

Saliva and pancreas secrete α-amylase that randomly cleaves α-1,4 bonds. Plants and bacteria secrete β-amylase that removes maltose units starting at the non-reducing end. Debranching enzymes hydrolyse the α-1,6 bonds.

Glycogen: Animal cell storage of Glc.

Similar to amylopectin but more branched. ~15-30 sugars per branch.

Dextrans: Bacterial polysaccharides with α1→6 links and some α1→2 and α1→4 glucose links.

Fructans or **Levans** are fructose storage forms found in plants.

These are all used for reversible energy storage.

Cellulose: (Glc β1→4 Glc)$_n$

Linear chain of 10,000 - 15,000 Glc. See cellobiose.

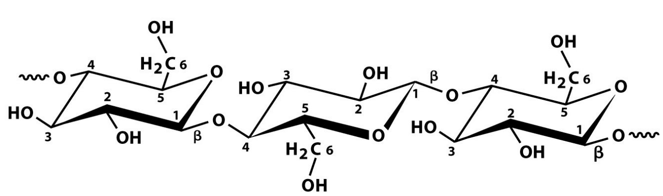


Figure 8-25a Principles of Biochemistry, 4/e
© 2006 Pearson Prentice Hall, Inc.

This is a structural polysaccharide. A strong rod-like structure of parallel chains packed side-by-side is formed.

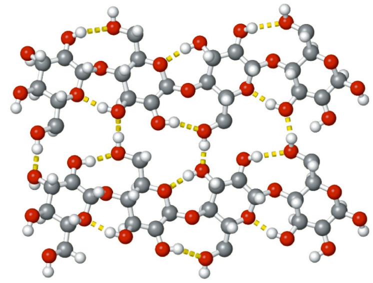
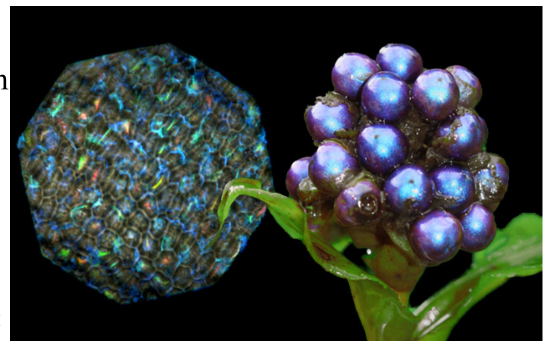


Figure 8-26 Principles of Biochemistry, 4/e
© 2006 Pearson Prentice Hall, Inc.

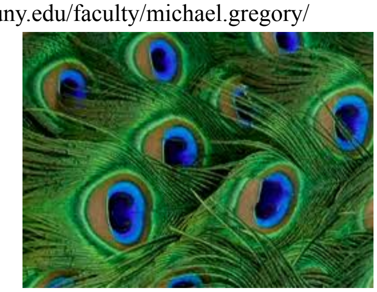
In *Pollia condensata* the irridescent blue color comes from the interaction of light with the helical rods of cellulose in the outer skin. There is no pigment.



PNAS 2012 109 (39) 15712-15715

Chitin: arthropod exoskeleton, shells of crustaceans, & peacock feathers.

www.davidlnelson.md/ Cazadero/Bugs.htm
http://faculty.clintoncc.suny.edu/faculty/michael.gregory/



http://www.photobiology.info/Ball.html

N-acetylglucosamines linked β1→4 in a linear chain.

It is cellulose with a C2 N-acetyl.

Glycoproteins:

Sugars may be O-linked to Ser/Thr/Tyr.

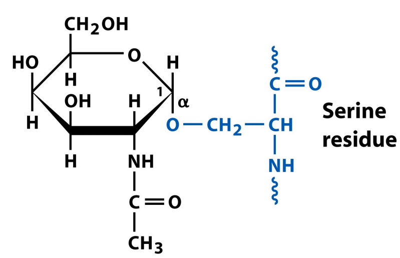


Figure 8-33a Principles of Biochemistry, 4/e
© 2006 Pearson Prentice Hall, Inc.

Or N-linked to Asn/Gln.

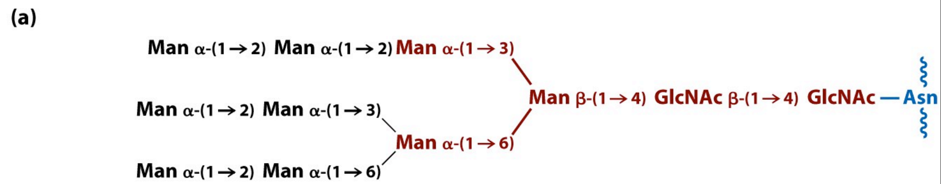


Figure 8-35 Principles of Biochemistry, 4/e

A great variety of sequence, branching, and linkage.

α / β; 1→2, 1→3, 1→4 ...

The cell walls of bacteria contain a cross-linked network of short peptides and sugars called **peptidoglycan**.

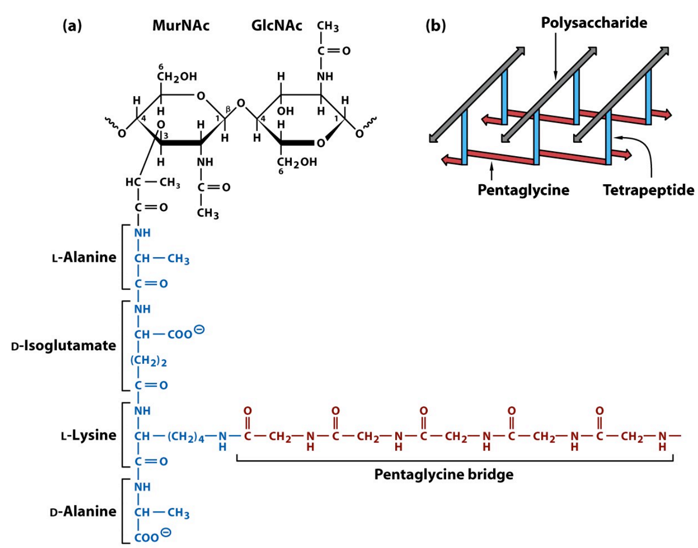


Figure 8-31 Principles of Biochemistry, 4/e

In animals, extracellular matrix, cartilage, tendons, and skin contain **proteoglycans**. Proteins with large amounts of carbohydrate.

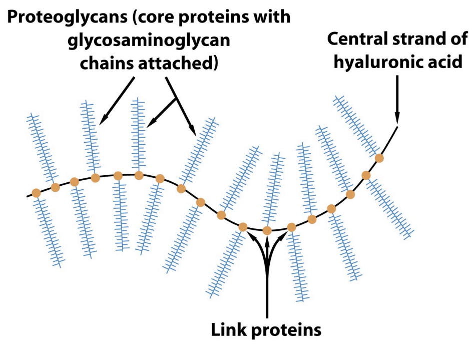


Figure 8-29 Principles of Biochemistry, 4/e

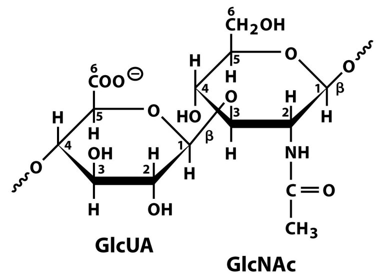


Figure 8-28 Principles of Biochemistry, 4/e