Chapter 8: Carbohydrates

Carbohydrates are polyhydroxy aldehydes or ketones or compounds that yield polyhydroxy aldehydes or ketones on hydrolysis

Carbohydrates are very important to plants and animals

Simple carbohydrates are formed by chlorophyll containing plants

$$6CO_2 + 6H_2O \xrightarrow[\text{chlorophyll}]{\text{light}} C_6H_{12}O_6 + 6O_2$$

carbohydrate, glucose

Plants use carbohydrates

To store energy

To provide supporting structures

Animals get their carbohydrates by consuming plants

Humans use carbohydrates for FOOD!!!

energy

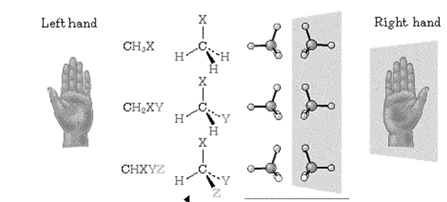
Provide a source of carbon atoms for synthesis of other compounds

In order to understand the structure of carbohydrates, we have to consider some new form of stereoisomerism

What are stereoisomers?

Enantiomers

<u>Enantiomers</u> are mirror image isomers that cannot be superimposed on one another



enantiomer

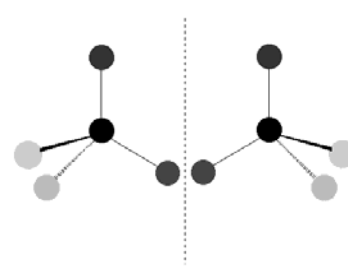
Not all mirror images are going to be enantiomers

So, what makes a pair of molecules an enantiomer?

Whether there is a chiral carbon!

Chiral Carbons

A chiral carbon (or asymmetric carbon) is a carbon that is connected to four different groups

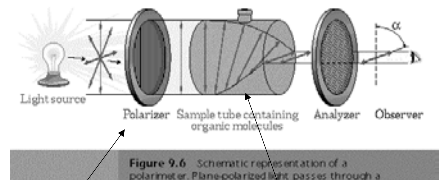


So, if a compound has more than one chiral carbon, how do you know how many stereoisomers it has?

$$\mathbf{2^{\textit{n}}}$$

Where *n* is the number of chiral carbons

What is Polarized Light and How Do Enantiomers Rotate it differently?



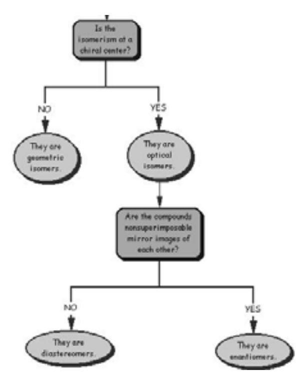
Polarized light vibrates in only one plane

Enantiomers will rotate The polarized light to the left or to the right

The enantiomer that rotates the polarized light clockwise (or to the right) is called <u>dextrorotatory</u> and uses the symbol (+)

The enantiomer that rotates the polarized light counterclockwise (or to the left) is called <u>levorotatory</u> and uses the symbol (-)

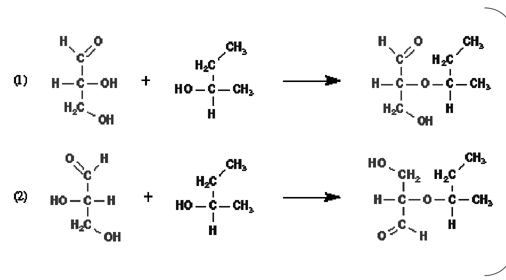
Compounds with More than One Chiral Carbon



<u>All</u> physical properties and chemical properties of enantiomers are identical, except two….

1. **They rotate the plane of polarized light differently.**
2. **When they react with another chiral molecule, the the reaction rates are not the same for the two enantiomers.**

Chemical Reactions with Enantiomers



These two reactions will have very different rates

Racemic mixture – a mixture of equal amounts of enantiomers that does not rotate polarized light

Carbohydrates may be broken into classes based on the size of the molecules

Monosaccharides – basic unit of carbohydrates and have the Formula of $C_nH_{2n}O_n$ where *n* can vary from three to nine.

Disaccharides – consist of two monosaccharides linked together

Oligosaccharides – consist of three to twenty monosaccharides linked together

Polysaccharide- made up of many monosaccharides

Most Monosaccharides are Chiral Compounds

- Aldoses - polyhydroxy aldehydes
- Ketoses - polyhydroxy ketones
- Most oxidized carbon: aldoses C-1, ketoses usually C-2
- Trioses (3 carbon sugars) are the smallest monsaccharides

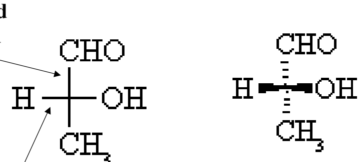
Aldoses and ketoses

- Aldehyde C-1 is drawn at the top of a Fischer projection
- Glyceraldehyde (aldotriose) is chiral (C-2 carbon has 4 different groups attached to it)
- Dihydroxyacetone (ketotriose) does not have an asymmetric or chiral carbon and is not a chiral compound

Fischer Projections

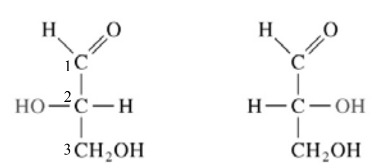
A systematic way to draw 3D structures

Vertical bond going behind the plane



Horizontal bond coming out of the plane

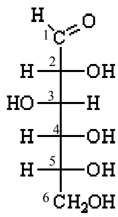
(a)



L-Glyceraldehyde D-Glyceraldehyde

Find the highest number of chiral carbon.
If the OH group is on the left, is a classified as a L enantiomer.
If the OH group is on the right, it is a D enantiomer.

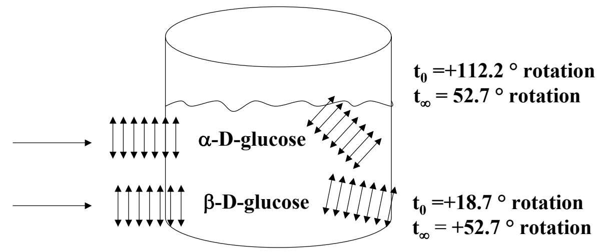
The Most Common Monosaccharide is D-glucose



D-glucose

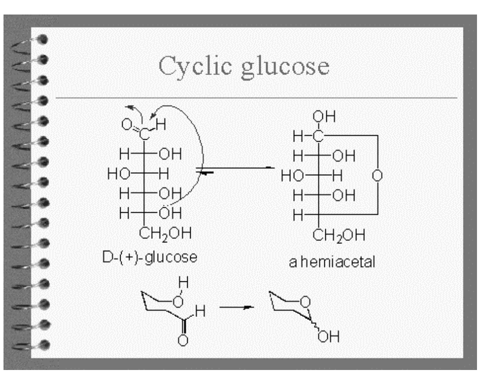
This is the least stable form of glucose.
The aldehyde form cannot be obtained in the solid state

Mutarotation – change of rotation



Result: Optical rotation of both mixtures ends up being the same.
Explanation: Monosaccharides form some other structure in aqueous solution.

That structure is a Hemiacetal

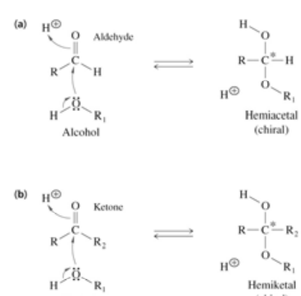


Cyclization of Aldoses and Ketoses

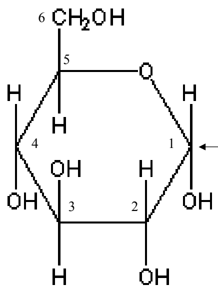
Reaction of an alcohol with:

(a) An aldehyde to form a hemiacetal

(b) A ketone to form a hemiketal



The Solid form of D- Glucose



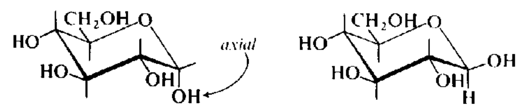
This type of drawing is known as a <u>Haworth</u> formula

Hemiacetal group

$C_6H_{12}O_6$

When solid D-glucose is dissolved in water, the instability of the hemiacetal shows itself and the ring opens allowing possibility for both anonmers of glucose.

Anomers of Glucose



α-D-glucose β-D-glucose

These are not enantiomers!!! They are diastereomers.

Anomers are two stereoisomers of a monosaccharide that differ only at the configuration at C-1 for aldoses and C-2 for ketoses

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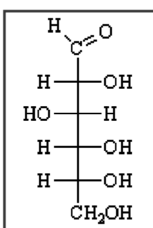
Monosaccharides



D-glucose

How many chiral carbons are there in D-glucose?

4

How many stereoisomers does D-glucose have?

$2^4 = 16$

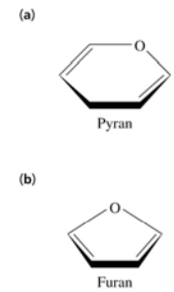
Also known as dextrose

These 16 structures of glucose are called Aldohexoses.

aldo because they have an aldehyde group
hex because there are six carbons
ose because this is an ending used for carbohydrates

(a) Pyran and (b) furan ring systems

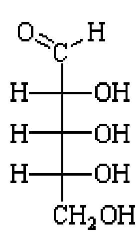
- (a) Six-membered sugar ring is a “pyranose”
- (b) Five-membered sugar ring is a “furanose”



Other Aldoses

You can have other aldoses that don’t have six carbons. There is aldotetroses (4 carbons), aldopentoses (5 carbons) and so on.

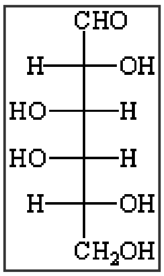
D-Ribose



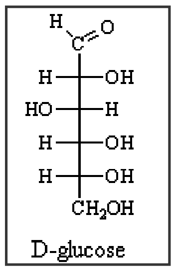
Enantiomers and epimers

- D-Sugars predominate in nature
- **Enantiomers** - pairs of D-sugars and L-sugars
- **Epimers** - sugars that differ at only <u>one</u> of several chiral centers
- Example: D-galactose is an epimer of D-glucose at C-4

Epimers - Different at Carbon Four



D-galactose



D-glucose

Fig. 8.3

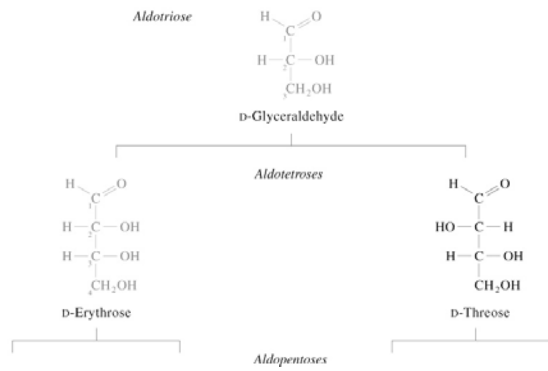


Fig. 8.3

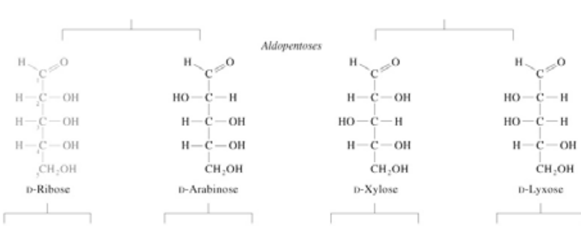
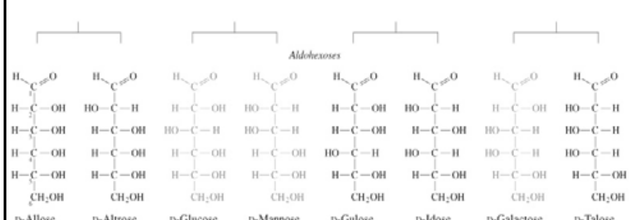
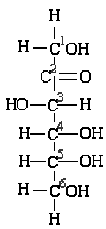


Fig. 8.3

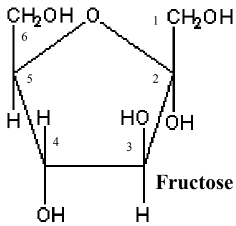


Ketoses

These compounds have a ketone group in the 2 position instead

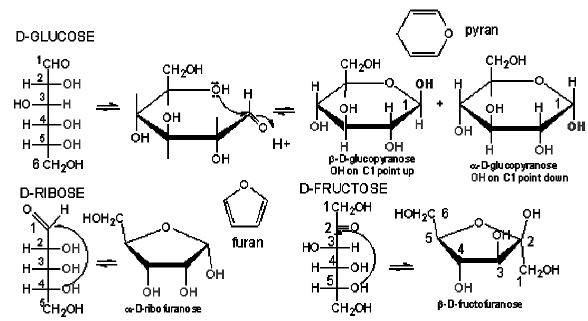


D-FRUCTOSE

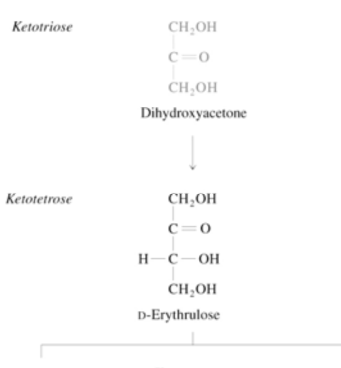


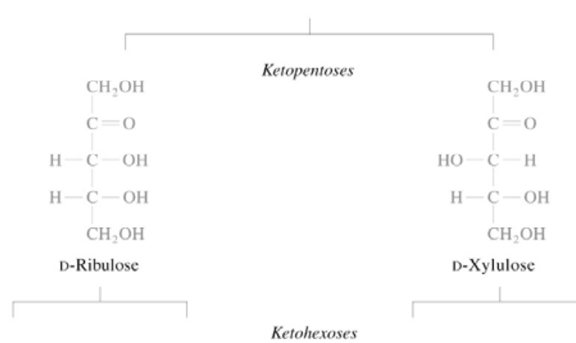
Fructose

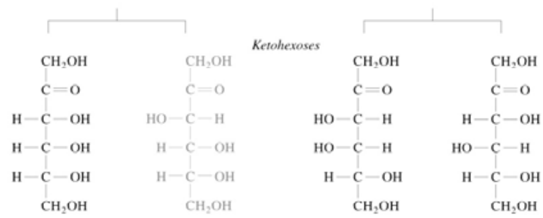
Fruit Sugar



Fisher projections of the 3 to 6 carbon D-ketoses (blue structures are most common)







D-Psicose D-Fructose D-Tagatose D-Sorbose

Physical Properties of Monosaccharides

Sweet → **Therefore called sugars**

Carbohydrates are solid at room temp and soluble in water-

After looking at the structures of glucose and fructose, why would you think that they could dissolve in water?

Optical Activity

There is no simple relationship between conformation and rotation

Chemical Properties of Monosaccharides

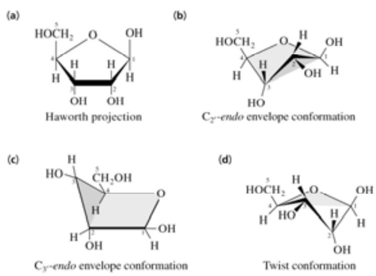
Like D-glucose, all monosaccharides with at least five carbons exist predominately in the cyclic form.

Six member rings are called pyranose rings

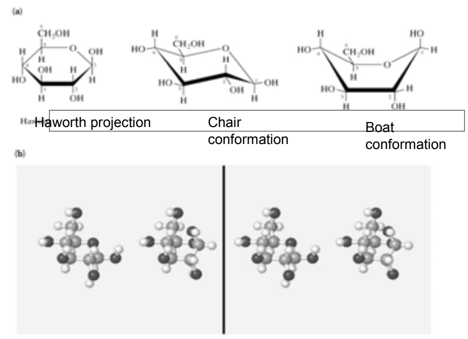
Five member rings are called furanose rings

Conformations of Monosaccharides

Conformations of β-D-ribofuranose

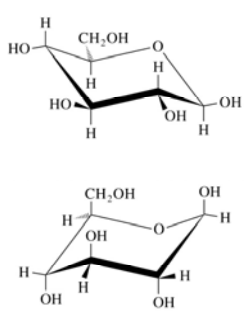


Conformations of β-D-glucopyranose



Conformations of β-D-glucopyranose

- Top conformer is more stable because it has the bulky hydroxyl substituents in <u>equatorial positions</u> (less steric strain)



Reactions of Monosaccharides

A. Oxidation/Reduction

Aldoses in the open chain form have an aldehyde group which is easily oxidized to a carboxylic acid

Regarded as a Reducing Sugar

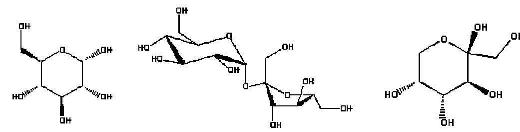
A monosaccharide with a free aldehyde or α-hydroxy ketones (or in equilibrium with) are mild reducing agents

↓

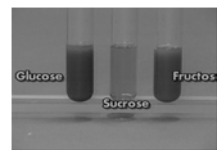
Therefore, these are called reducing sugars

How do you test for oxidation of alehydes or α-hydroxy ketones?

Which one of the following sugars will be positive for the Benedict's test?



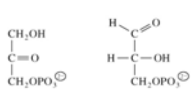
glucose **sucrose** **fructose**



Reactions of Monosaccharides

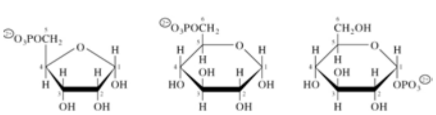
B. Phosphorylation

Phosphorylation occurs by a kinase enzyme



Dihydroxyacetone phosphate

D-Glyceraldehyde 3-phosphate



α-D-Ribose 5-phosphate

α-D-Glucose 6-phosphate

α-D-Glucose 1-phosphate

Reactions of Monosaccharides

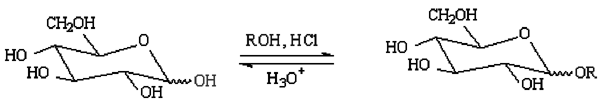
C. Acetal Formation

What happens to hemiacetals in the presence of an alcohol and an acid?

↓

Forms an acetal or a glycoside

Glycoside Formation

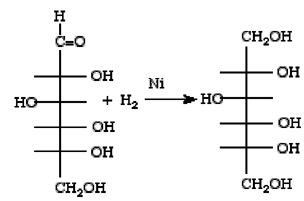


D-glucose

Glycosides (acetals)

Derivatives of Monosaccharides

Monosaccharides in which one or more functional groups have been altered through chemical reactions are monosaccharide derivatives

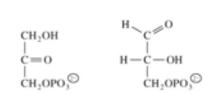


D-Glucose

D-Sorbitol

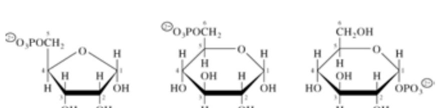
Derivatives of Monosaccharides

A. Phosphate Sugars



Dihydroxyacetone phosphate

D-Glyceraldehyde 3-phosphate



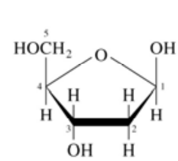
α-D-Ribose 5-phosphate

α-D-Glucose 6-phosphate

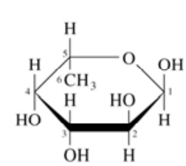
α-D-Glucose 1-phosphate

Derivatives of Monosaccharides

B. Deoxy Sugars



β-2-Deoxy-D-ribose



α-L-Fucose
(6-Deoxy-L-galactose)

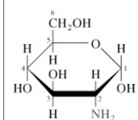
Derivatives of Monosaccharides

C. Amino Sugars

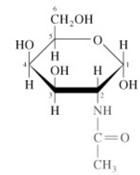
- An amino group replaces a monosaccharide OH
- Amino group is sometimes acetylated
- Amino sugars of glucose and galactose occur commonly in glycoconjugates

Derivatives of Monosaccharides

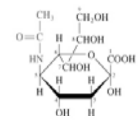
C. Amino Sugars



α-D-Glucosamine



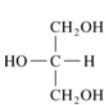
N-Acetyl-α-D-galactosamine



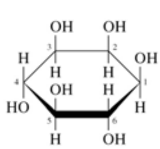
N-Acetyl-α-D-neuraminic acid

Derivatives of Monosaccharides

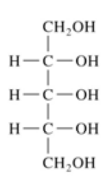
D. Sugar Alcohol



Glycerol



myo-Inositol



D-Ribitol

Derivatives of Monosaccharides

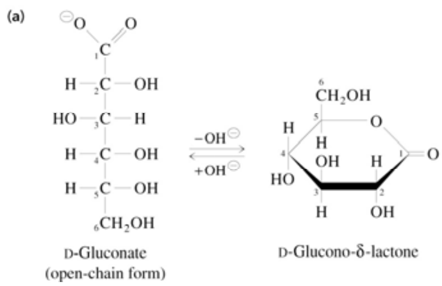
E. Sugar Acids

- Sugar acids are carboxylic acids
- Produced from aldoses by:

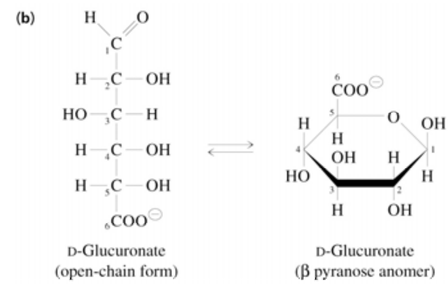
  (1) Oxidation of C-1 to yield an **aldonic acid**

  (2) Oxidation of the highest-numbered carbon to an **alduronic acid**

E. Sugar Acids



E. Sugar Acids

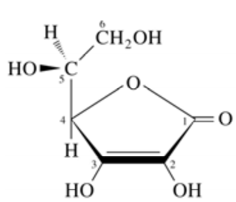


Derivatives of Monosaccharides

F. Ascorbic Acid (Vitamin C)

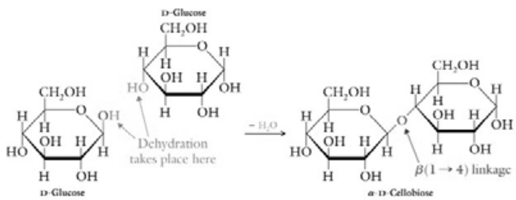
- L-Ascorbic acid is derived from D-glucuronate

L-Ascorbic acid

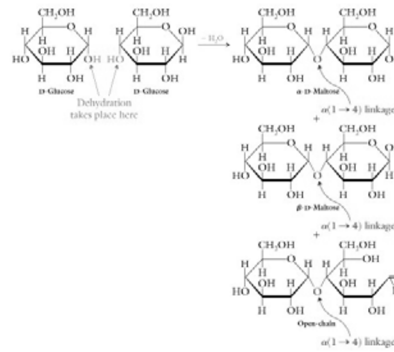


Disaccharides and Other Glycosides

- **Glycosidic bond** - primary structural linkage in <u>all polymers</u> of monosaccharides
- An acetal linkage - the anomeric sugar carbon is condensed with an alcohol, amine or thiol
- **Glucosides** - glucose provides the anomeric carbon



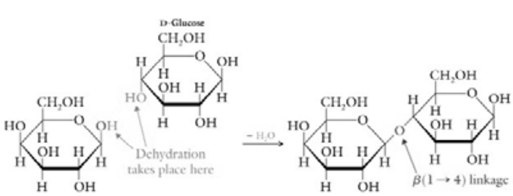
Glucose (β (1→4)) glucose linkage



Glucose (α (1→4)) glucose linkage

Maltose is the ingredient in most syrups

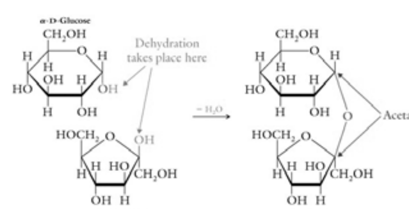
β-D-Lactose



Galactose (β (1→4)) glucose linkage

Lactose occurs in mammalian milk.

Sucrose



Glucose (α1→β2) fructose linkage

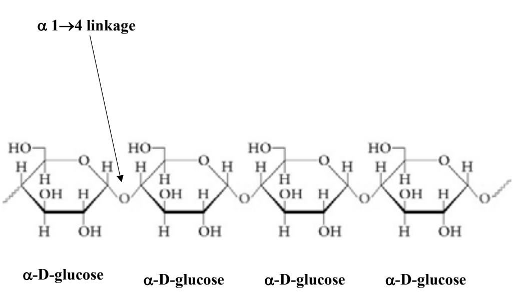
Polysaccharides

- **Homoglycans** - homopolysaccharides containing only one type of monosaccharide
- **Heteroglycans** - heteropolysaccharides containing residues of more than one type of monosaccharide
- Lengths and compositions of a polysaccharide may vary within a population of these molecules

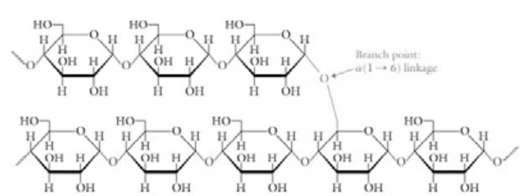
A. Starch and Glycogen

- D-Glucose is stored intracellularly in polymeric forms
- Plants and fungi - starch
- Animals - glycogen
- Starch is a mixture of amylose (unbranched) and amylopectin (branched)

Amylose



Amylopectin

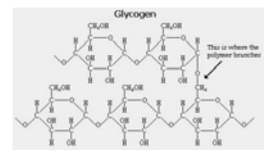


Both amylose and amylopectin make up starch in plants.

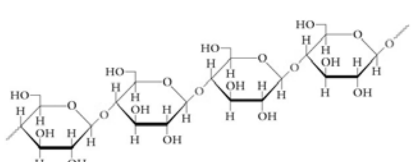
Amylopectin

Glycogen is animal starch.

Similar to amylopectin in the branching, but has more branching sites per molecule than amylopectin.



Cellulose



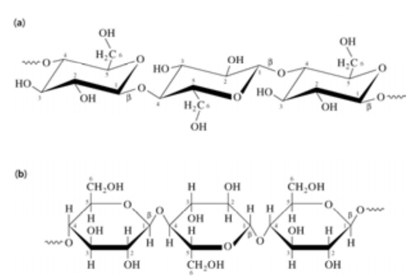
Most abundant molecule in living tissue.

Cellulose and Chitin

Structure of cellulose

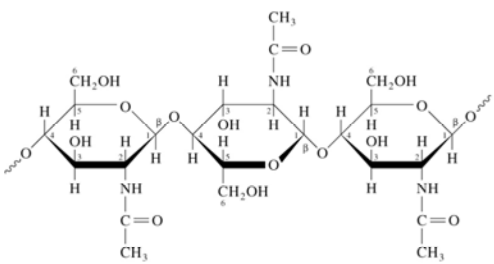
(a) Chair conformation

(b) Haworth projection



Structure of chitin

- Repeating units of β-(1-4)GlcNAc residues



Glycoconjugates

- Heteroglycans appear in three types of glycoconjugates:

  Proteoglycans

  Peptidoglycans

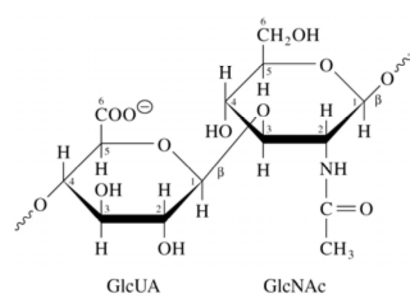
  Glycoproteins

A. Proteoglycans

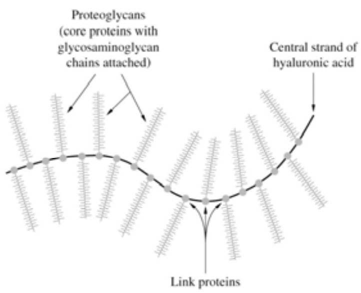
- **Proteoglycans** - glycosaminoglycan-protein complexes
- **Glycosaminoglycans** - unbranched heteroglycans of repeating disaccharides (many <u>sulfated</u> hydroxyl and amino groups)
- Disaccharide components include: (1) amino sugar (D-galactosamine or D-glucosamine), (2) an alduronic acid

Repeating disaccharide of hyaluronic acid

- GlcUA = D-glucuronate
- GlcNAc= N-acetylglucosamine



Proteoglycan aggregate of cartilage



B. Peptidoglycans

- **Peptidoglycans** - heteroglycan chains linked to peptides
- Major component of bacterial cell walls
- Heteroglycan composed of alternating GlcNAc and N-acetylmuramic acid (MurNAc)
- β-(1 $\rightarrow$4) linkages connect the units

Glycan moiety of peptidoglycan

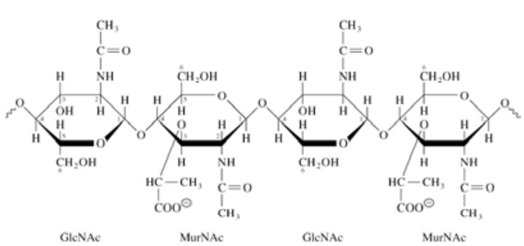
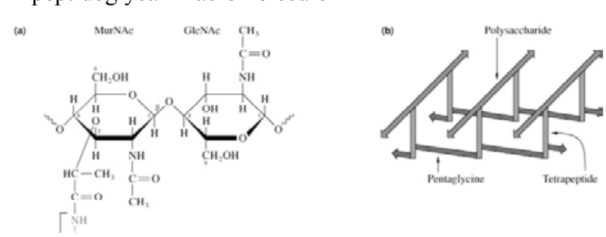


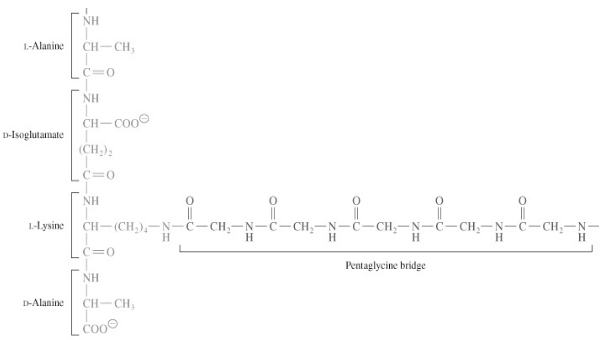
Fig 8.31 Structure of the peptidoglycan of *S. aureus*

(a) Repeating disaccharide unit, (b) Cross-linking of the peptidoglycan macromolecule



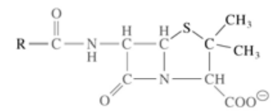
(to tetrapeptide, next slide)

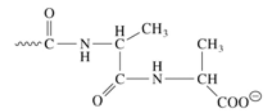
(to disaccharide, previous slide)



Penicillin inhibits a transpeptidase involved in bacterial cell wall formation

- Structures of penicillin and -D-Ala-D-Ala
- Penicillin structure resembling -D-Ala-D-Ala is shown in pink





~D-Ala – D-Ala

C. Glycoproteins

- Proteins that contain covalently-bound oligosaccharides
- O-Glycosidic and N-glycosidic linkages
- Oligosaccharide chains exhibit great variability in sugar sequence and composition
- **Glycoforms** - proteins with identical amino acid sequences but different oligosaccharide chain composition

Four subclasses of O-glycosidic linkages

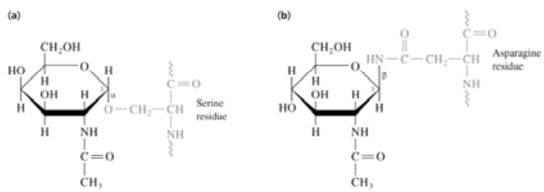
(1) GalNAc-Ser/Thr (most common)

(2) 5-Hydroxylysine (Hyl) to D-galactose (unique to collagen)

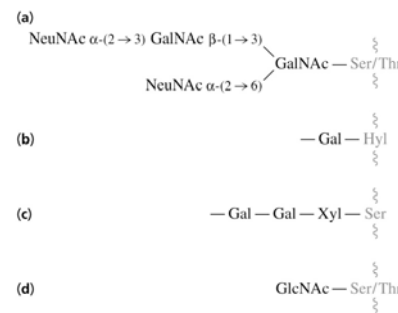
(3) Gal-Gal-Xyl-Ser-core protein

(4) GlcNAc to a single serine or threonine

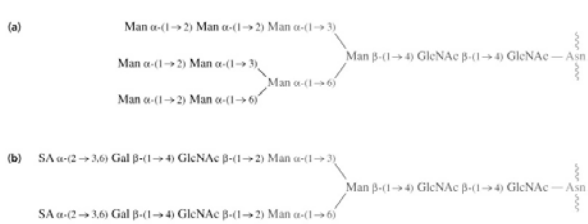
O-Glycosidic and N-glycosidic linkages



Four subclasses of O-glycosidic linkages



Structures of N-linked oligosaccharides



Structures of N-linked oligosaccharides

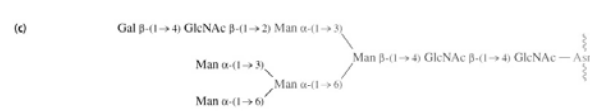


TABLE 8.2 Structures of some common polysaccharides

Polysaccharide[a]	Component(s)[b]	Linkage(s)
Storage homoglycans		
Starch		
Amylose	Glc	α-(1→4)
Amylopectin	Glc	α-(1→4), α-(1→6) (branches)
Glycogen	Glc	α-(1→4), α-(1→6) (branches)
Structural homoglycans		
Cellulose	Glc	β(1→4)
Chitin	GlcNAc	β(1→4)
Heteroglycans		
Glycosaminoglycans	Disaccharides (amino sugars, sugar acids)	Various
Hyaluronic acid	GlcUA and GlcNAc	β(1→3), β(1→4)

[a] Polysaccharides are unbranched unless otherwise indicated
[b] Glc, Glucose; GlcNAc, *N*-acetylglucosamine; GlcUA, D-glucuronate.

Table 8.1

TABLE 8.1 Abbreviations for some monosaccharides and their derivatives

Monosaccharide or derivative	Abbreviation
Pentoses	
Ribose	Rib
Xylose	Xyl
Hexoses	
Fructose	Fru
Galactose	Gal
Glucose	Glc
Mannose	Man
Deoxy sugars	
Abequose	Abe
Fucose	Fuc
Amino sugars	
Glucosamine	GlcN
Galactosamine	GalN
N-Acetylglucosamine	GlcNAc
N-Acetylgalactosamine	GalNAc
N-Acetylneuraminic acid	NeuNAc
N-Acetylmuramic acid	MurNAc
Sugar acids	
Glucuronic acid	GlcUA
Iduronic acid	IdoA