

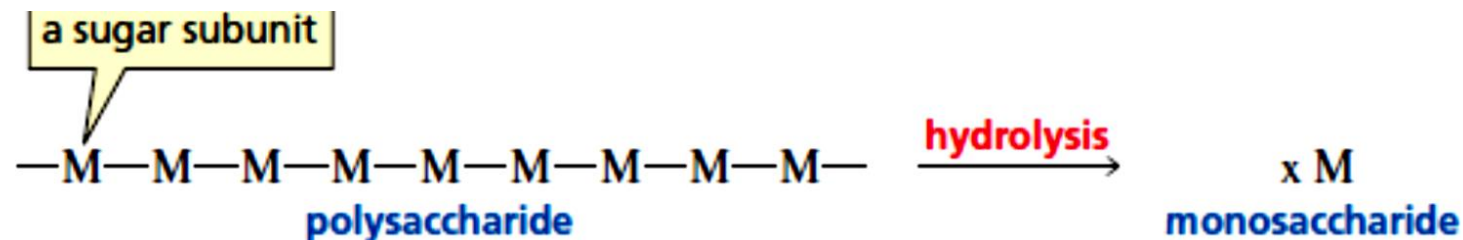
**COURSE CODE:** SC202(CHEMISTRY)  
**COURSE INSTRUCTOR:** DR. DEBARATI MITRA &  
DR. SANGITA TALUKDAR

**CARBOHYDRATES**

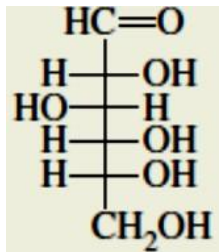
**DEPT. OF SCIENCE AND MATHEMATICS**  
**IITG, GUWAHATI**  
**LECTURE DATES:** 07.02.2023 & 08.02.2023

# Carbohydrates

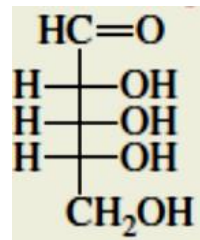
- **Carbohydrates** are polyhydroxy aldehydes such as D-glucose, polyhydroxy ketones such as D-fructose and compounds such as sucrose, which can be hydrolyzed to polyhydroxy aldehydes or polyhydroxy ketones.
- Most sugars have molecular formulas  $C_n(H_2O)_m$ , suggesting that carbon atoms are combined in some way with water. In fact, the empirical formula of most simple sugars is  $C(H_2O)$ .
- There are two classes of carbohydrates: *simple carbohydrates* and *complex carbohydrates*.
- **Simple carbohydrates** are **monosaccharides** (single sugars), whereas **complex carbohydrates** contain two or more sugar subunits linked together.
- **Disaccharides** have two sugar subunits linked together, **oligosaccharides** have 3 to 10 sugar subunits (*oligos* is Greek for “few”) linked together and **polysaccharides** have more than 10 sugar subunits linked together.



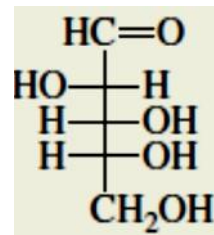
- A *monosaccharide* can be a polyhydroxy aldehyde such as D-glucose or a polyhydroxy ketone such as D-fructose. Polyhydroxy aldehydes are called **aldoses** (“ald” is for aldehyde; “ose” is the suffix for a sugar), whereas polyhydroxy ketones are called **ketoses**.
- Monosaccharides are also classified according to the number of carbons they contain:  
Monosaccharides with three carbons are **trioses**, those with four carbons are **tetroses**, those with five carbons are **pentoses** and those with six and seven carbons are **hexoses** and **heptoses**, respectively.



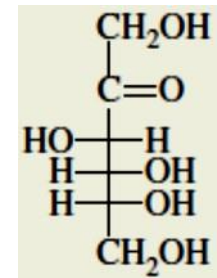
Glucose



Ribose



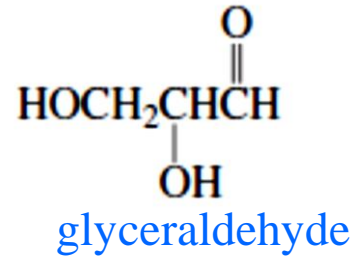
Arabinose



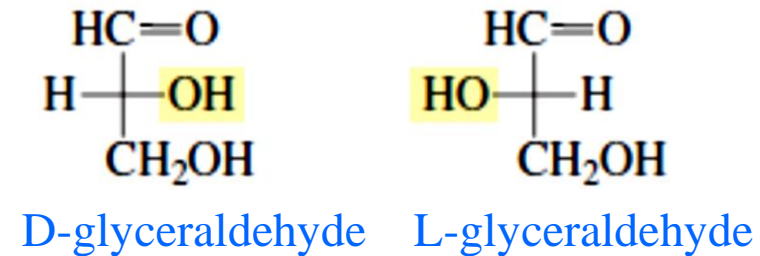
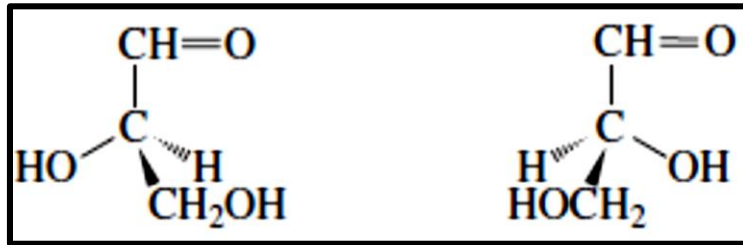
Fructose

## The D and L Notation

The smallest aldose is glyceraldehyde which is an aldotriose.

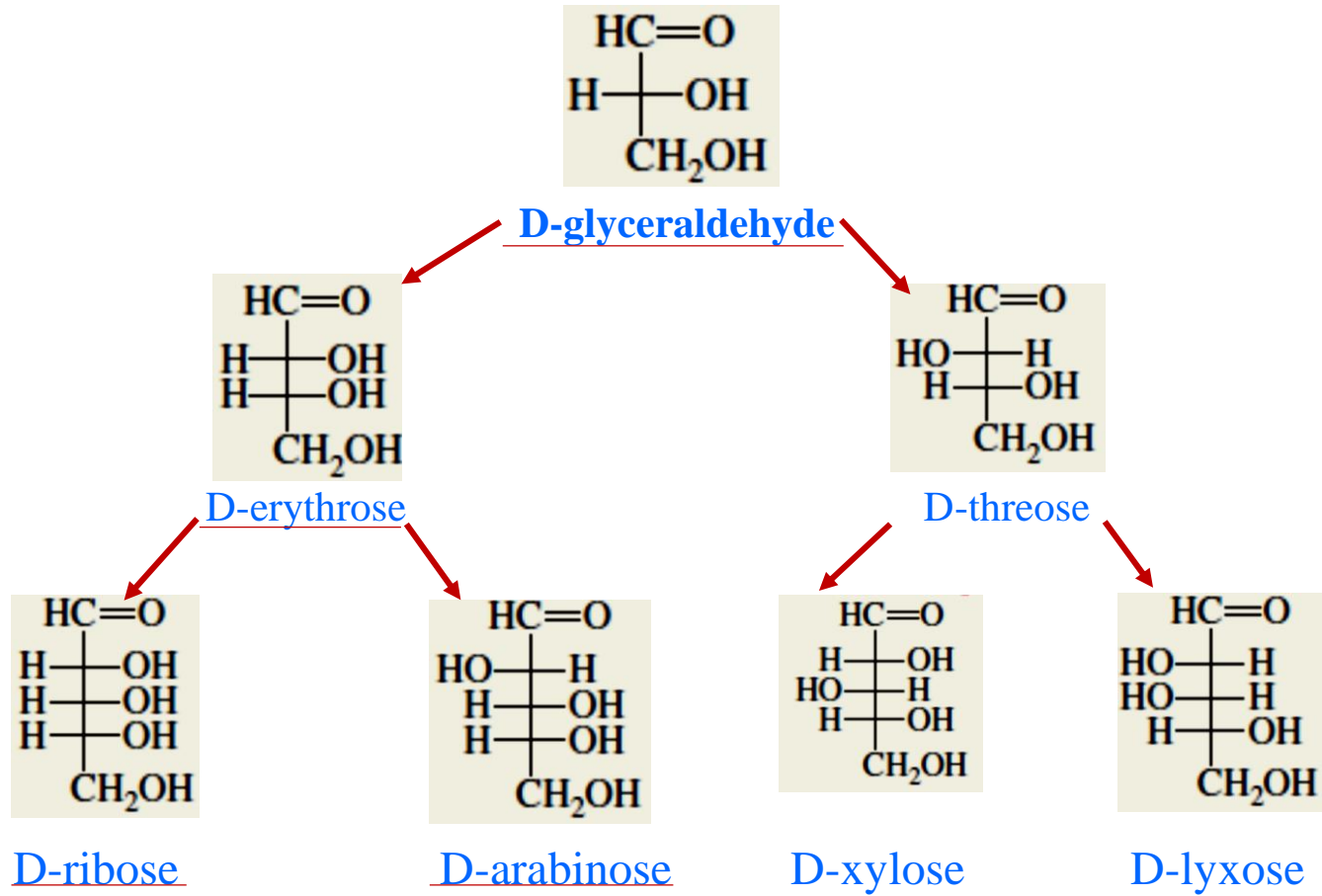


Because glyceraldehyde has an asymmetric carbon, it can exist as a pair of enantiomers.

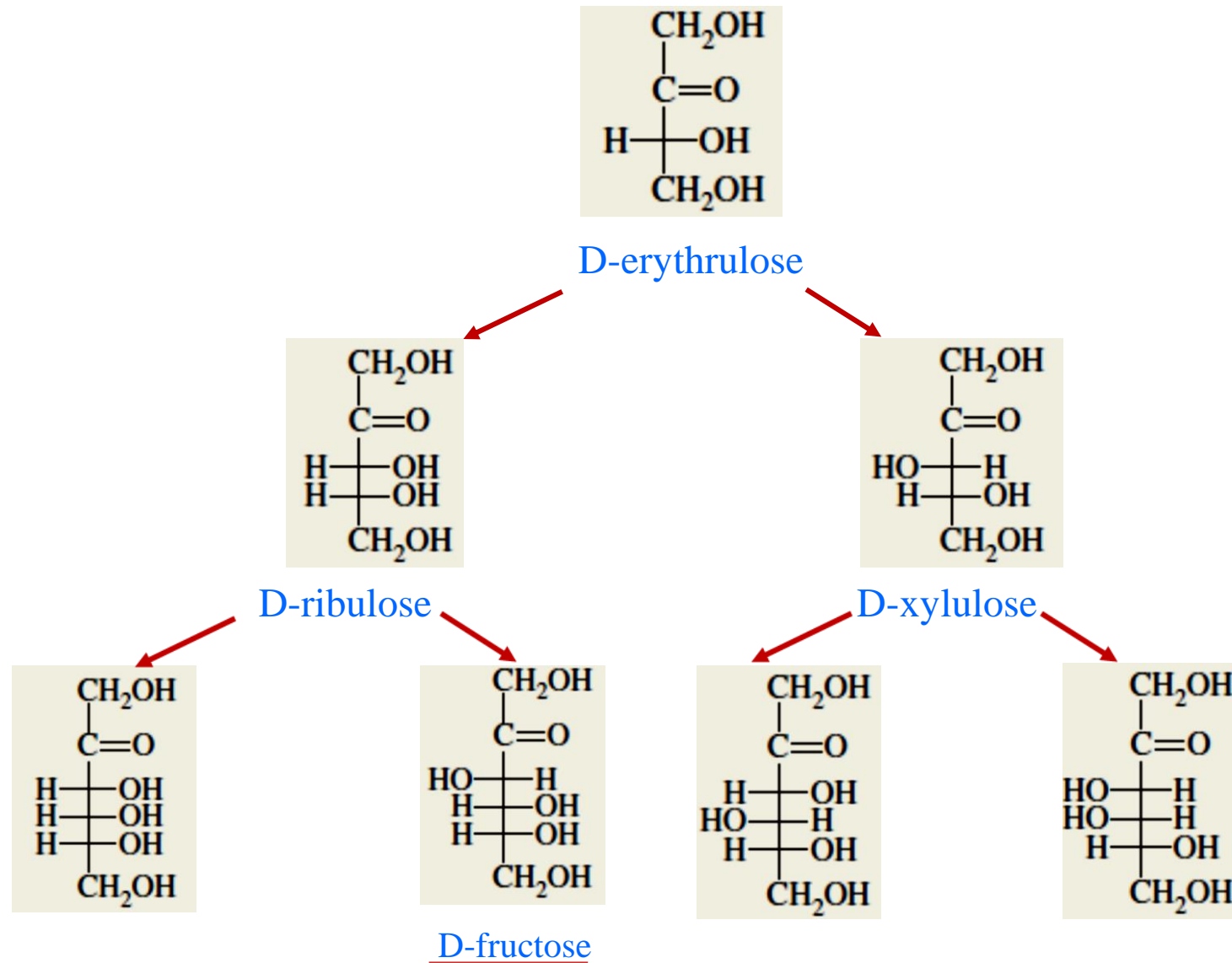


*If the -OH group attached to the **bottom-most asymmetric carbon** (the carbon that is second from the bottom) is on the **right**, then the compound is a D-sugar. If the -OH group is on the **left**, then the compound is an L-sugar.*

## Configurations of the D-Aldoses



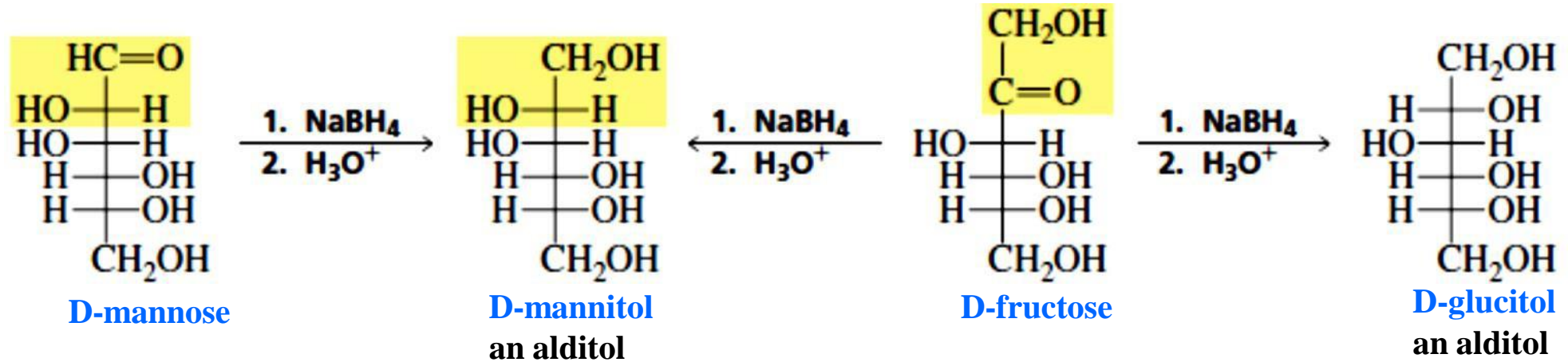
## Configurations of the D-Ketoses



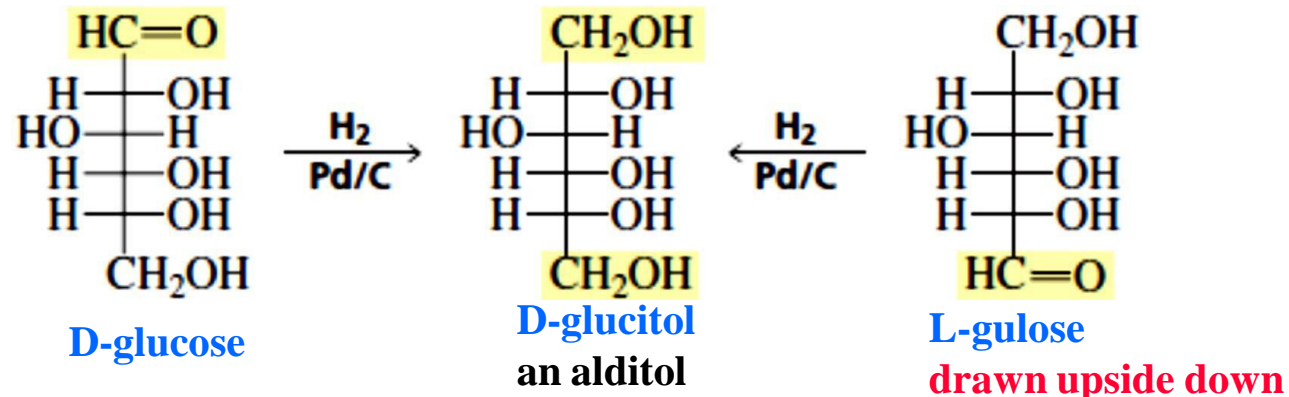
# Redox Reactions of Monosaccharides

## Reduction

The carbonyl group of aldoses and ketoses can be reduced by the usual carbonyl-group reducing agents like  $\text{NaBH}_4$ . The product of the reduction is a polyalcohol, known as an **alditol**. Reduction of an aldose forms one alditol. Reduction of a ketose forms two alditols because the reaction creates a new asymmetric carbon in the product.

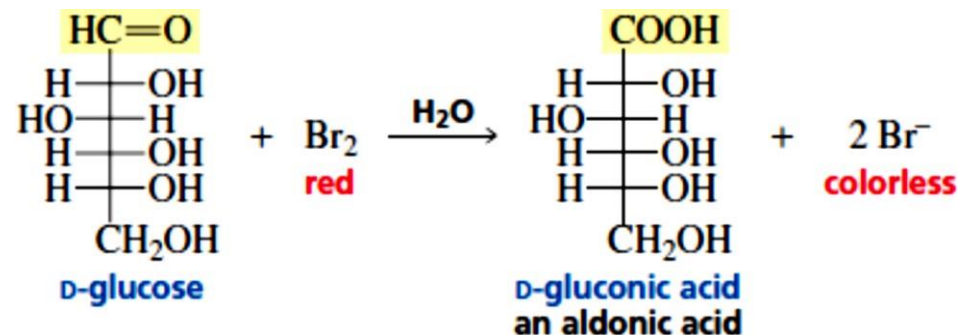


D-Glucitol—also called sorbitol—is about 60% as sweet as sucrose. It is found in plums, pears, cherries, and berries and is used as a sugar substitute in the manufacture of candy. D-Glucitol is also obtained from the reduction of either D-glucose or L-gulose.

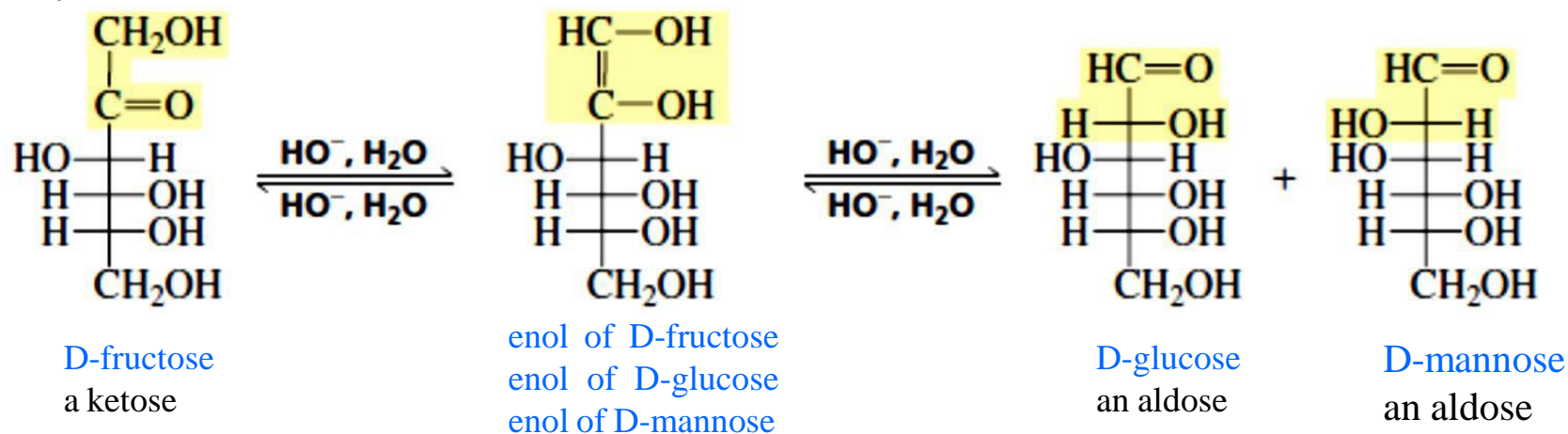


# Oxidation

1.  $\text{Br}_2$  is a mild oxidizing agent and easily oxidizes the aldehyde group, but it cannot oxidize ketones or alcohols. Consequently, if a small amount of an aqueous solution of  $\text{Br}_2$  is added to an unknown monosaccharide, the reddish-brown color will disappear if the monosaccharide is an aldose, but will persist if the monosaccharide is a ketose.

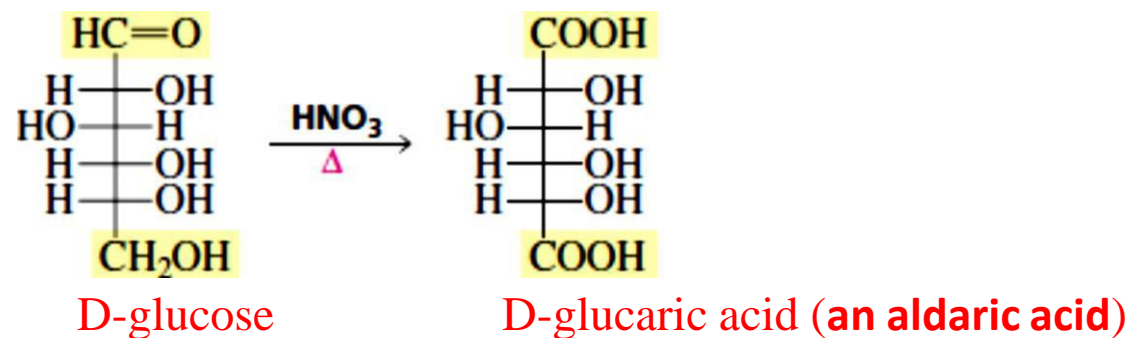


2. Both aldoses and ketoses are oxidized to aldonic acids by Tollens reagent ( $\text{Ag}^+$ ,  $\text{NH}_3$ ,  $\text{OH}^-$ ), silver mirror/black precipitate is formed; so this reagent cannot be used to distinguish between aldoses and ketoses. Ketoses are oxidized because the reaction is carried out under basic conditions, and in a basic solution, ketoses are converted into aldoses by enolization.





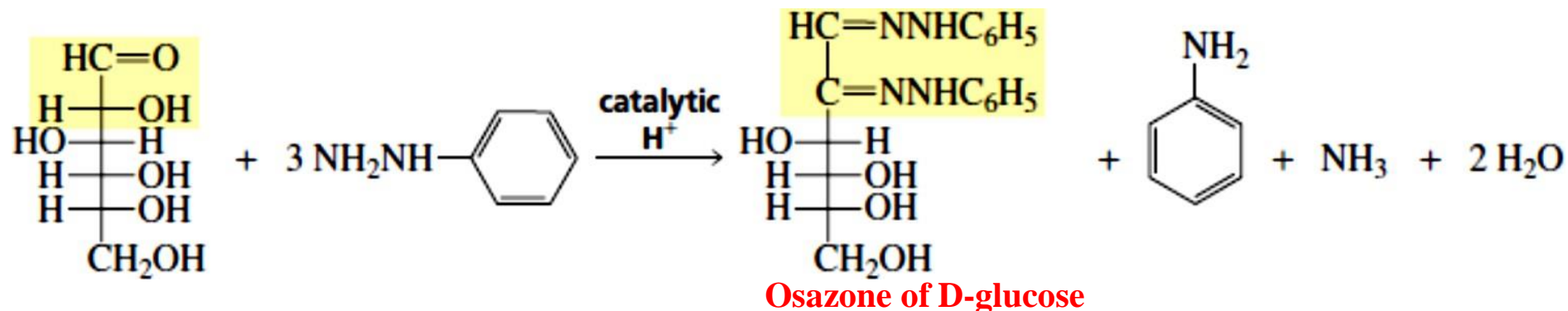
3. If a stronger oxidizing agent is used (such as  $\text{HNO}_3$ ), one or more of the alcohol groups can be oxidized in addition to the aldehyde group. A primary alcohol is the one most easily oxidized. The product that is obtained is called an **aldaric acid**.

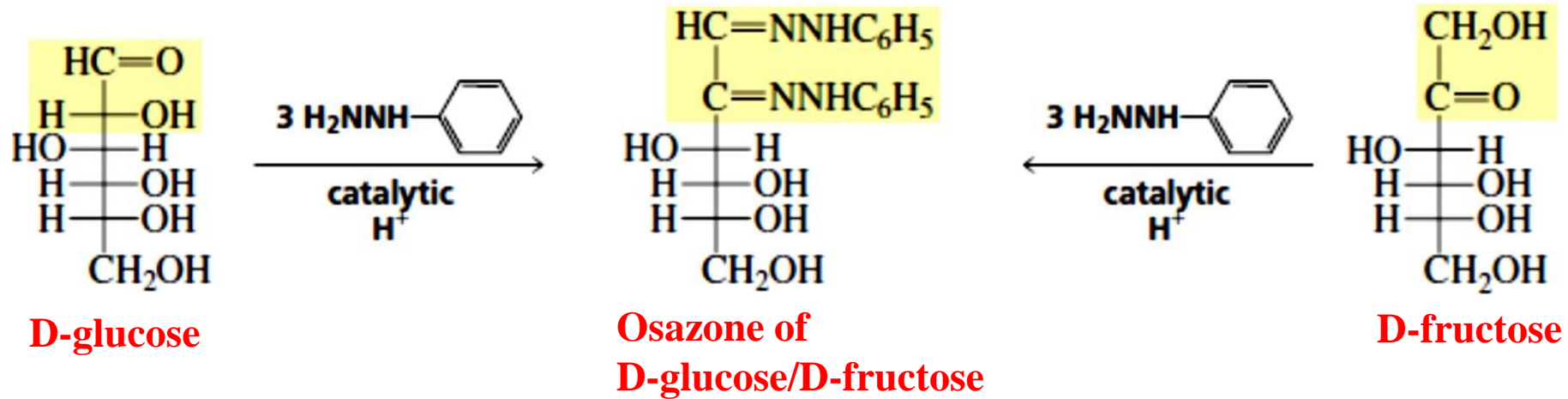


Aldoses reduce Tollens reagent, as we would expect aldehydes to do. They also reduce Fehling's solution, an alkaline solution of cupric ion complexed with tartrate ion (or Benedict's solution, in which complexation is with citrate ion); the deep-blue color of the solution is discharged, and red cuprous oxide precipitates.

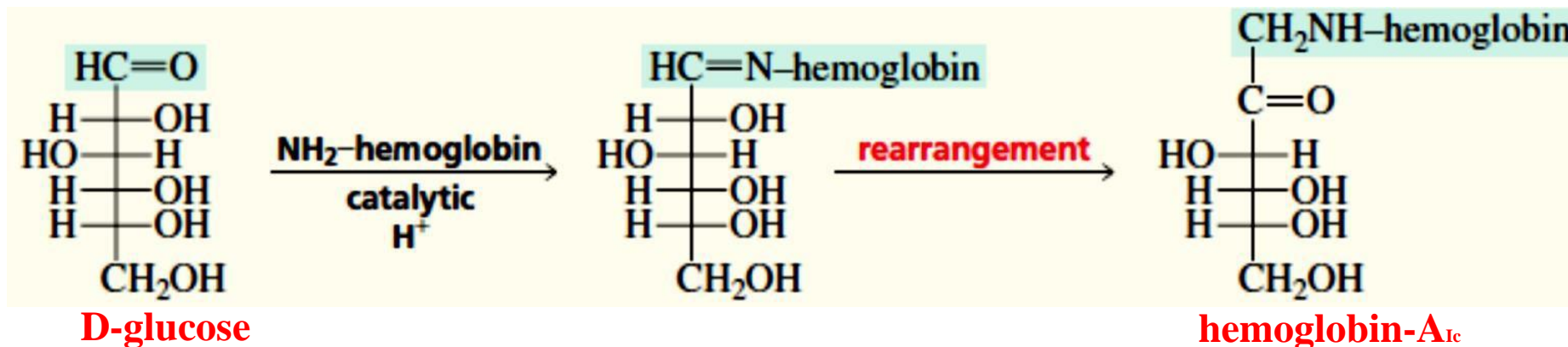
## Osazone Formation

Aldoses and ketoses react with three equivalents of phenylhydrazine, forming osazones. One equivalent functions as an oxidizing agent (to oxidise  $-\text{CHOH}$  at C-2 to  $-\text{CO}$ ) and itself is reduced to aniline and ammonia. The rest two equivalents form imines with carbonyl groups. The reaction stops at this point, regardless of how much phenylhydrazine is present.





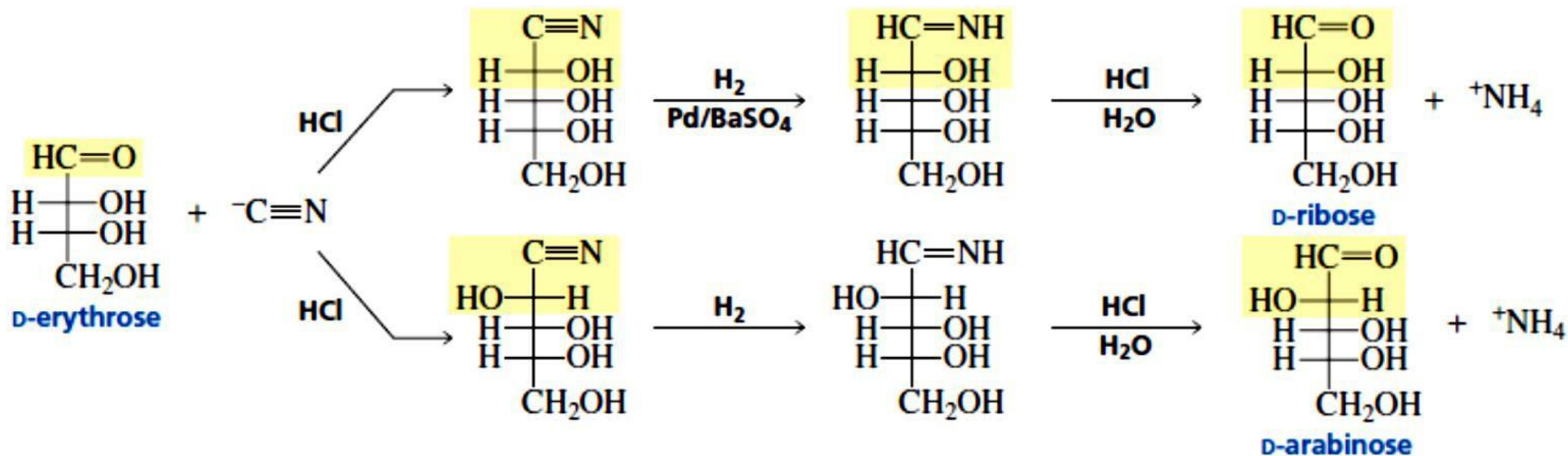
### Measuring The Blood Glucose Levels of Diabetics:



Glucose reacts with an amino group of hemoglobin to form an imine that subsequently undergoes an irreversible rearrangement to a more stable  $\alpha$ -amino ketone known as hemoglobin-A<sub>1c</sub>. Measuring the hemoglobin-A<sub>1c</sub> level is a way to determine whether the blood glucose level of a diabetic person is being controlled. Cataracts, a common complication in diabetics, are caused by the reaction of glucose with the -NH<sub>2</sub> group of proteins in the lens of the eye. The arterial rigidity common in old age may be attributable to a similar reaction of glucose with the -NH<sub>2</sub> group of proteins.

## Chain Elongation: The Kiliani–Fischer Synthesis

The carbon chain of an aldose can be increased by one carbon in a **Kiliani–Fischer synthesis**.

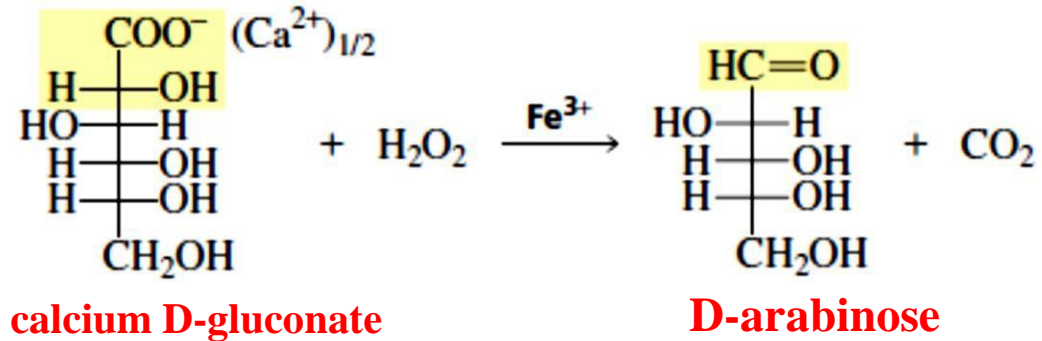


In the first step of the synthesis (the Kiliani portion), the aldose is treated with sodium cyanide and HCl. Addition of cyanide ion to the carbonyl group creates a new asymmetric carbon. Consequently, two cyanohydrins that differ only in configuration at C-2 are formed. The cyanohydrins are reduced to imines, using a partially deactivated palladium (on barium sulfate) catalyst so that the imines would not be further reduced to amines. The imines could then be hydrolyzed to aldoses

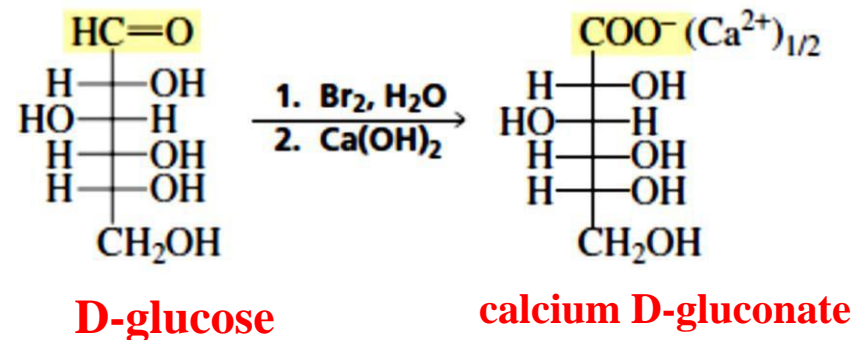
**The Kiliani–Fischer synthesis leads to a pair of C-2 epimers.**

## Chain Shortening: The Ruff Degradation

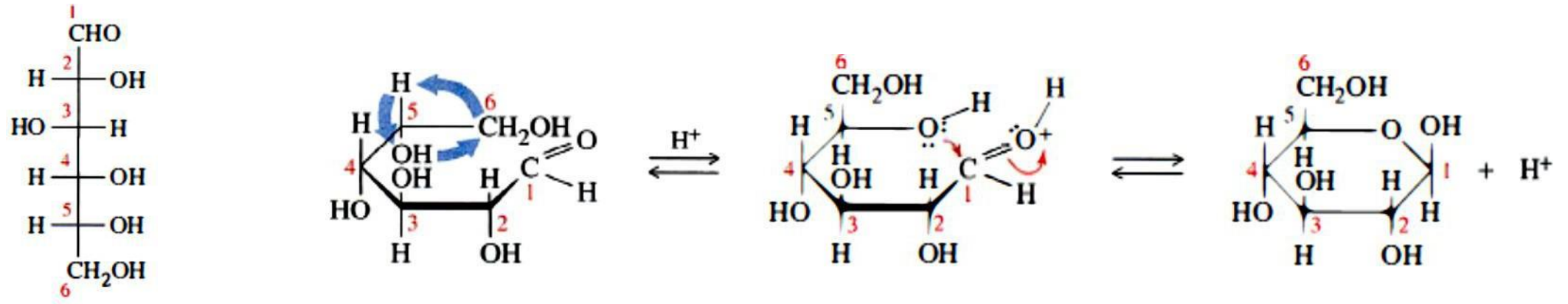
The **Ruff degradation** shortens an aldose chain by one carbon. In the Ruff degradation, the calcium salt of an aldonic acid is oxidized with hydrogen peroxide. Ferric ion catalyzes the oxidation reaction, which cleaves the bond between C-1 and C-2, forming  $\text{CO}_2$  and an aldehyde.



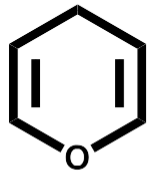
The calcium salt of the aldonic acid, necessary for the Ruff degradation, is easily obtained by oxidizing an aldose with an aqueous solution of bromine and then adding calcium hydroxide to the reaction mixture



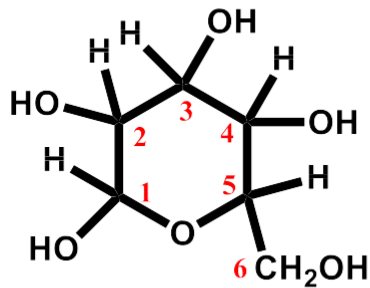
# Pyranose and Furanose Names



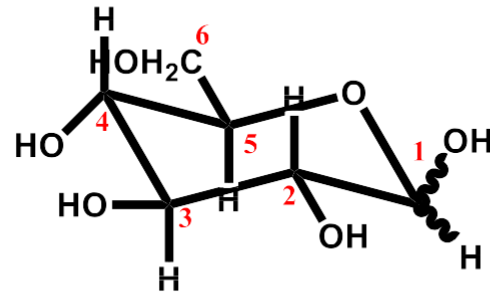
- Cyclic structures of monosaccharides are named according to their five- or six-membered rings.
- A six-membered cyclic hemiacetal is called a **pyranose**, derived from the name of the six-membered cyclic ether pyran.
- A five-membered cyclic hemiacetal is called a **furanose**, derived from the name of the five-membered cyclic ether furan.



Pyran



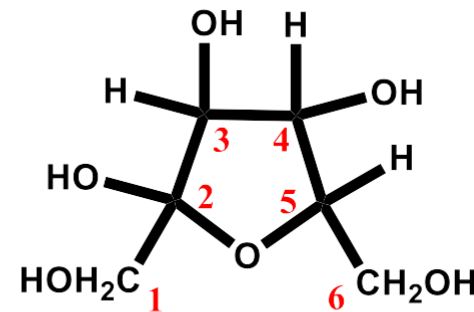
pyranose



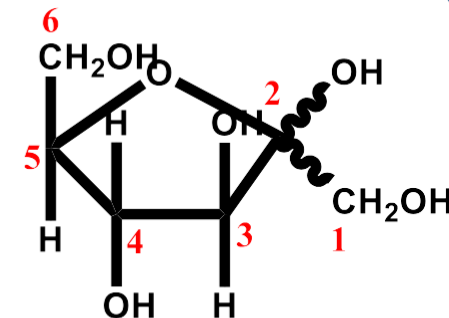
D-glucopyranose



Furan



furanose



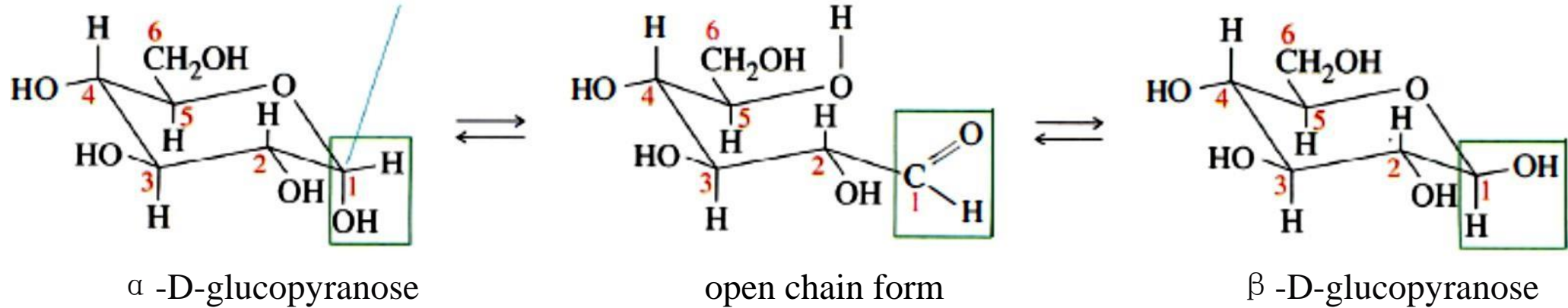
D-fructofuranose



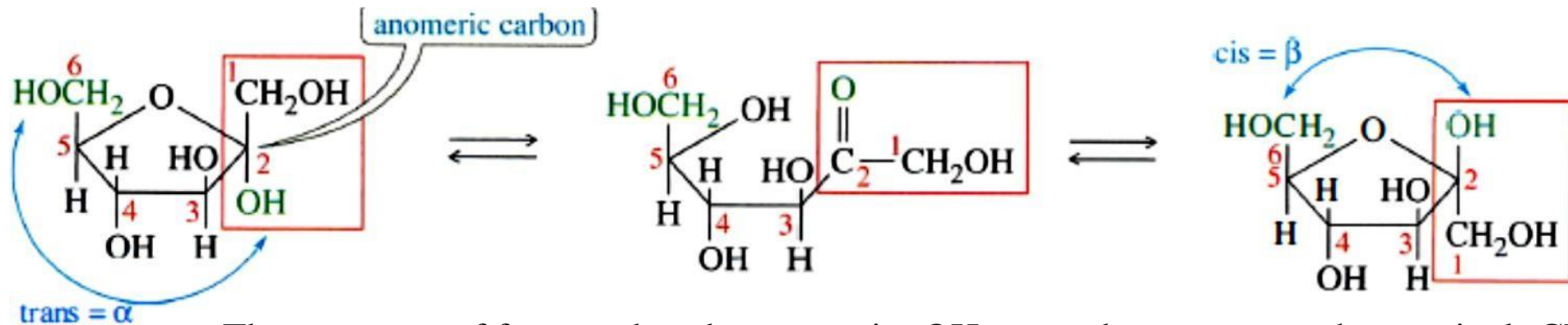
## Cyclic Structure of Monosaccharides

**Anomers** are two sugars that differ in configuration only at the carbon that was the carbonyl carbon in the open-chain form. This carbon is called the **anomeric carbon**. The prefixes  $\alpha$  and  $\beta$  denote the configuration about the anomeric carbon.

Anomeric carbon



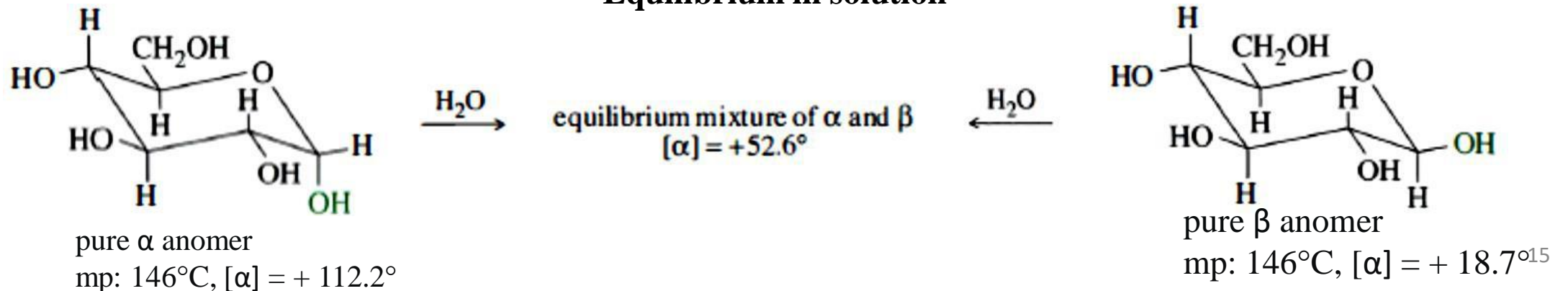
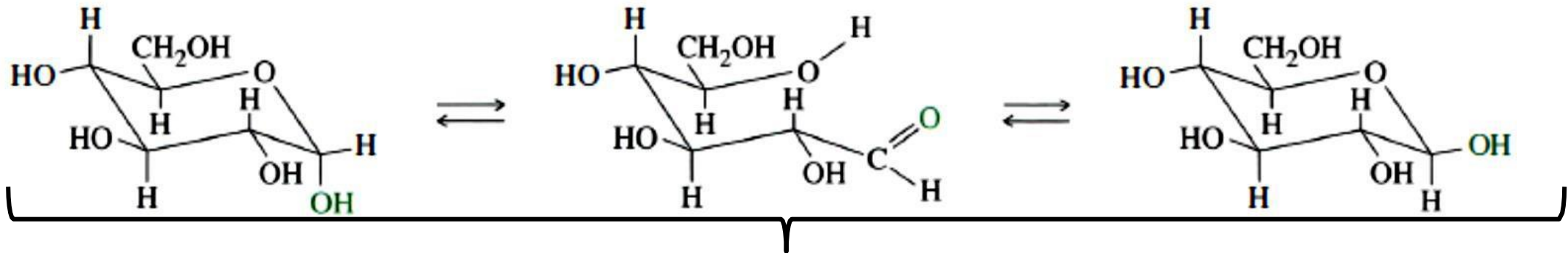
Anomers of glucose: The hydroxyl group on the anomeric (hemiacetal) carbon is down (axial) in the  $\alpha$  anomer and up (equatorial) in the  $\beta$  anomer.



The  $\alpha$  anomer of fructose has the anomeric -OH group down, trans to the terminal -CH<sub>2</sub>OH group. The  $\beta$  anomer has the anomeric hydroxyl group up, cis to the terminal -CH<sub>2</sub>OH group.

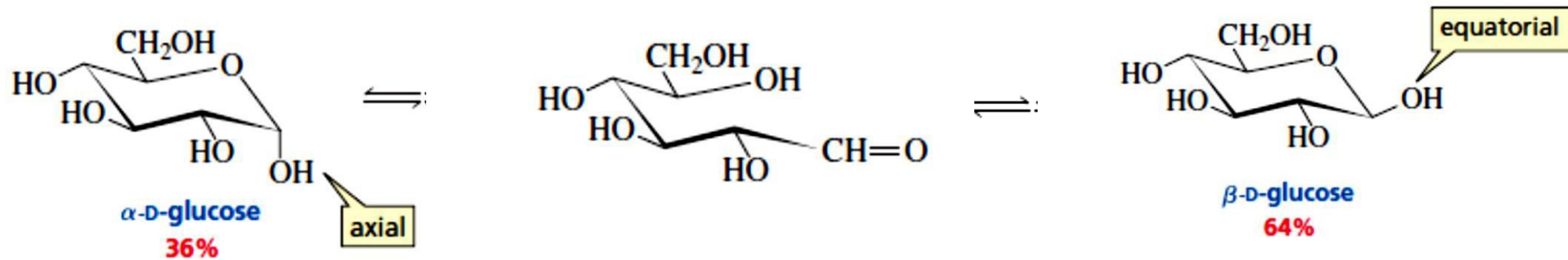
# Mutarotation

When one of the pure glucose anomers dissolves in water, an interesting change in the specific rotation is observed. When the  $\alpha$  anomer dissolves, its specific rotation gradually decreases from an initial value of  $+112.2^\circ$  to  $+52.6^\circ$ . When the pure  $\beta$  anomer dissolves, its specific rotation gradually increases from  $+18.7^\circ$  to the same value of  $+52.6^\circ$ . This change in rotation occurs because, in water, the hemiacetal opens to form the aldehyde and when the aldehyde recyclizes, both  $\alpha$ -D-glucose and  $\beta$ -D-glucose can be formed. Eventually, the three forms of glucose reach to an equilibrium. The specific rotation of the equilibrium mixture is  $+52.6^\circ$ . A slow change in optical rotation to an equilibrium value is known as **mutarotation**.



Q. Why is there more  $\beta$ -D-glucose than  $\alpha$ -D-glucose in an aqueous solution at equilibrium?

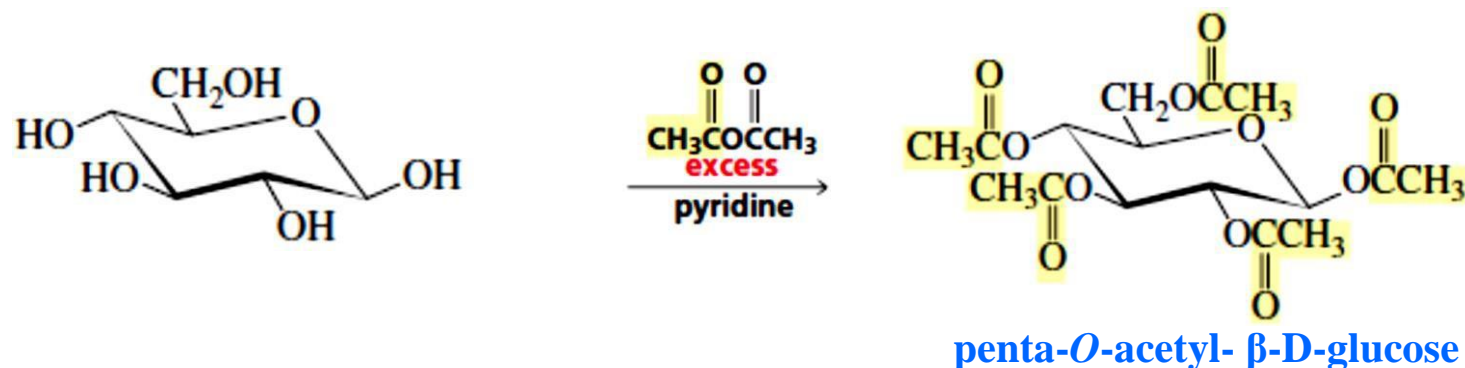
The -OH group bonded to the anomeric carbon is in the equatorial position in  $\beta$ -D-glucose, whereas it is in the axial position in  $\alpha$ -D-glucose causing steric crowding. Therefore,  $\beta$ -D-glucose is more stable than  $\alpha$ -D-glucose, so  $\beta$ -D-glucose predominates at equilibrium in an aqueous solution.



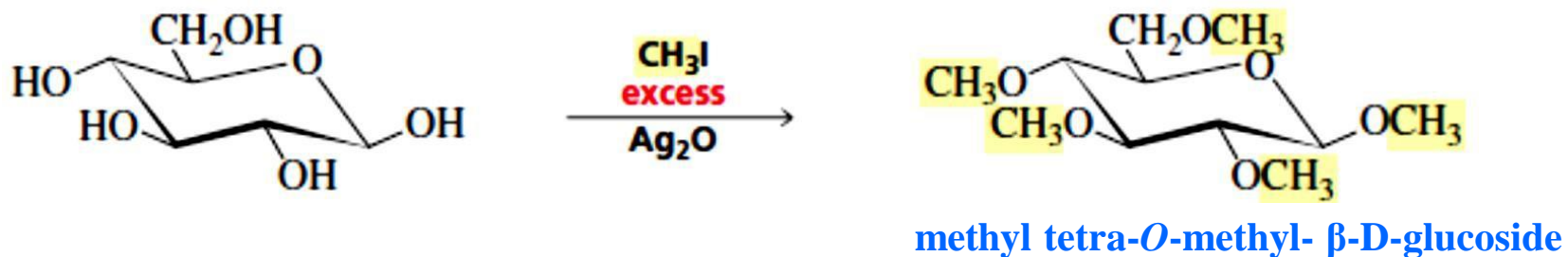


## Acylation and Alkylation of Monosaccharides

The -OH groups of monosaccharides show the chemistry typical of alcohols. For example, they react with acetyl chloride or acetic anhydride to form esters.

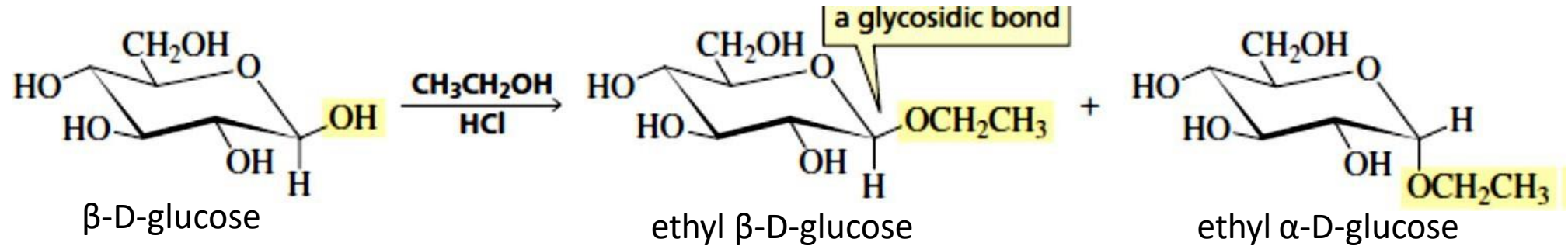


The -OH groups also react with methyl iodide/silver oxide to form ethers. The -OH group is a relatively poor nucleophile, so silver oxide is used to increase the leaving tendency of the iodide ion in the  $\text{S}_{\text{N}}2$  reaction.



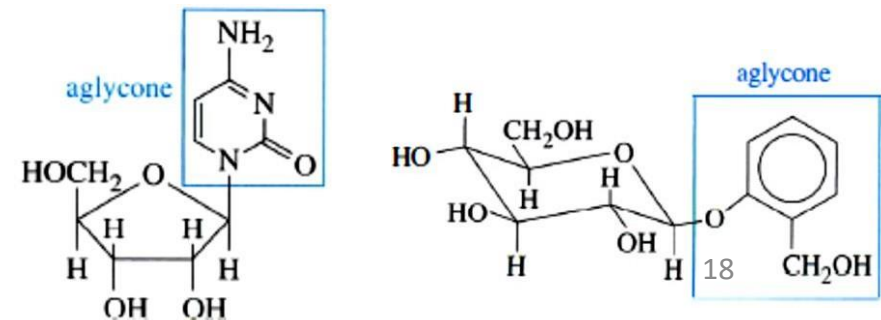
## Formation of Glycosides

The cyclic hemiacetal (or hemiketal) formed by a monosaccharide, can react with an alcohol to form an acetal (or ketal). The acetal (or ketal) of a sugar is called a **glycoside**, and the bond between the anomeric carbon and the alkoxy oxygen is called a **glycosidic bond**. Glycosides are named by replacing the “e” ending of the sugar’s name with “ide.” Thus, a glycoside of glucose is a glucoside, a glycoside of galactose is a galactoside, etc.



The  $-\text{OH}$  group bonded to the anomeric carbon becomes protonated in the acidic solution, and a lone pair on the ring oxygen helps to expel a molecule of water. The anomeric carbon in the resulting oxocarbenium ion is  $\text{sp}^2$  hybridized, so that part of the molecule is planar. An **oxocarbenium ion** has a positive charge that is shared by a carbon and an oxygen. When the alcohol comes in from the **top** of the plane, the  **$\beta$ -glycoside** is formed; when the alcohol comes in from the **bottom** of the plane, the  **$\alpha$ -glycoside** is formed.

An **aglycone** is the group bonded to the anomeric carbon atom of a glycoside

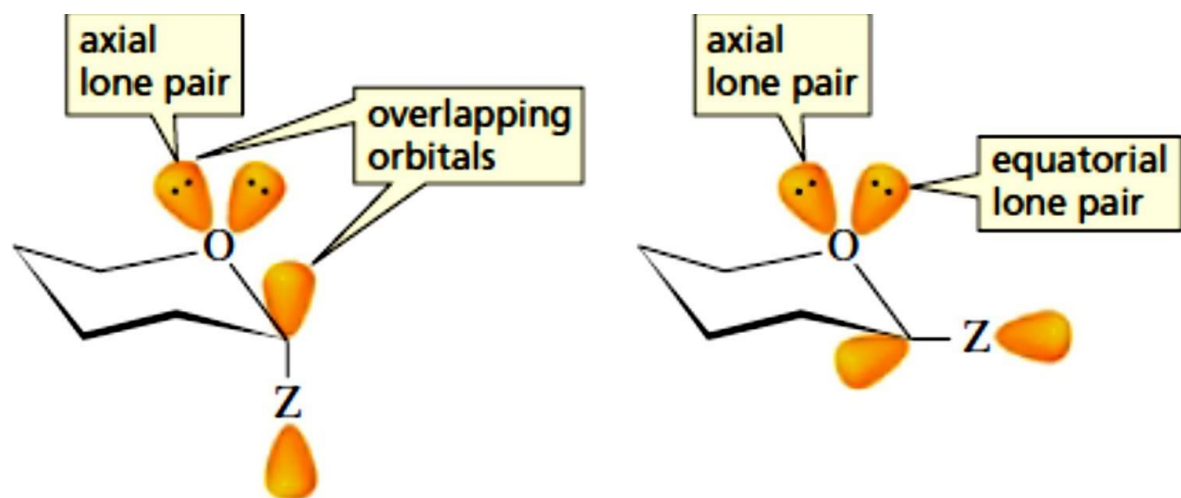


## The Anomeric Effect

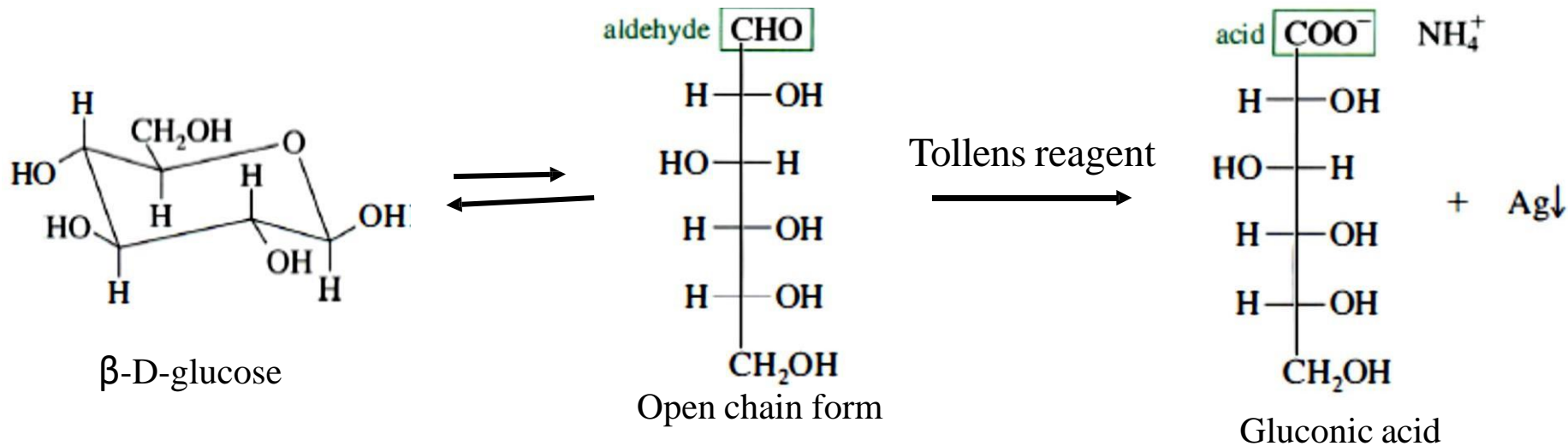
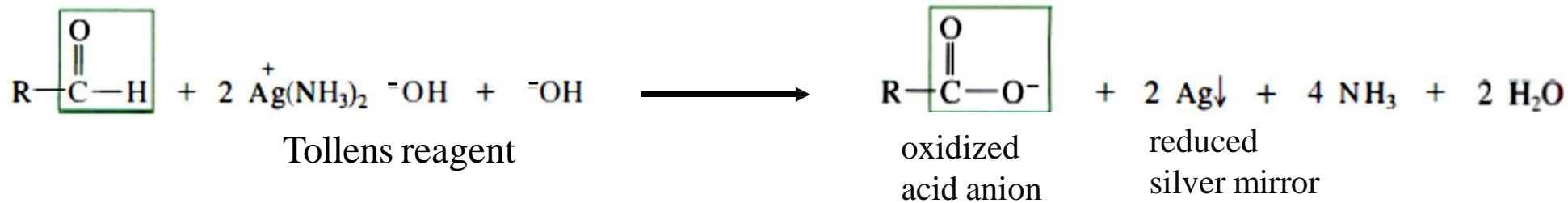
When glucose reacts with an alcohol to form a glucoside, the major product becomes the  $\alpha$ -glucoside. Since acetal formation is reversible, the  $\alpha$ -glucoside must be more stable than the  $\beta$ -glucoside. The preference of certain substituents bonded to the anomeric carbon for the axial position is called the **anomeric effect**.

### What is responsible for the anomeric effect?

The C-Z bond has a  $\sigma^*$  antibonding orbital. If one of the ring oxygen's lone pairs is in an orbital that is parallel to the  $\sigma^*$  antibonding orbital, the molecule can be stabilized by electron density from oxygen moving into the  $\sigma^*$  orbital. The orbital containing the axial lone pair of the ring oxygen can overlap the  $\sigma^*$  orbital only if the substituent is axial. If the substituent is equatorial, neither of the orbitals that contain a lone pair is aligned correctly for overlap. As a result of overlap between the lone pair and the  $\sigma^*$  orbital, the C-Z bond is longer and weaker and the C-O bond within the ring is shorter and stronger than normal.

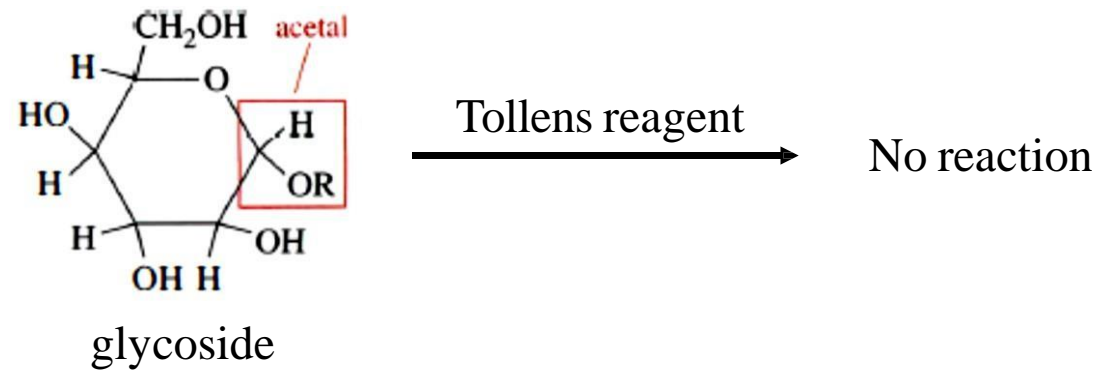


## Reducing and Nonreducing Sugars

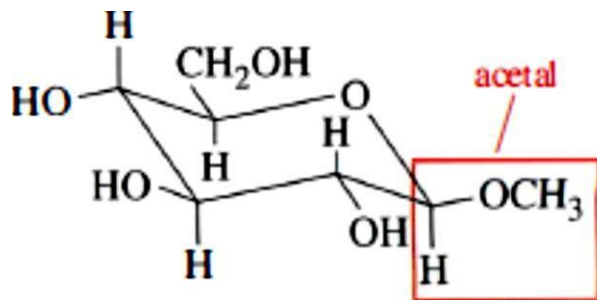


Hemiacetals (or hemiketals) are in equilibrium with the open-chain sugars in aqueous solution. So as long as a sugar has an aldehyde, a ketone, a hemiacetal or a hemiketal group; it is able to reduce an oxidizing agent and therefore is classified as a **reducing sugar**.

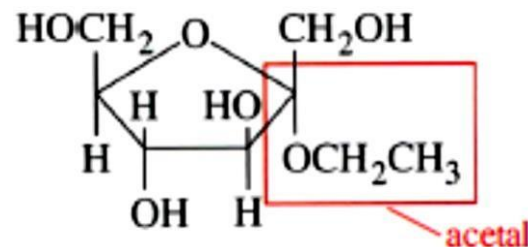
Glycosides are acetals (or ketals), they are not in equilibrium with the openchain aldehyde (or ketone) in neutral or basic aqueous solutions. Because they are not in equilibrium with a compound with a carbonyl group, they cannot be oxidized by reagents such as  $\text{Ag}^+$  or  $\text{Br}_2$ . Glycosides, therefore, are nonreducing sugars—they cannot reduce  $\text{Ag}^+$  or  $\text{Br}_2$ .



Examples of nonreducing sugars:



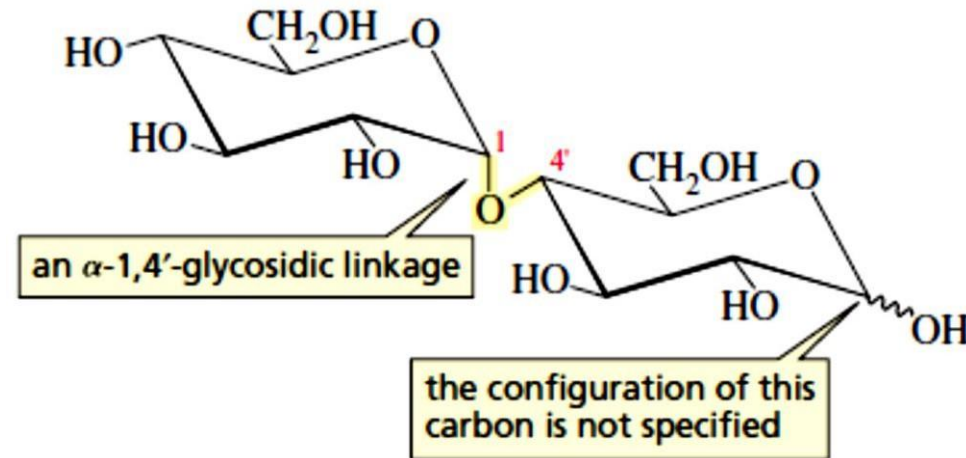
Methyl  $\beta$ -D-glucopyranoside



Ethyl  $\alpha$ -D-fructofuranoside

## Disaccharides

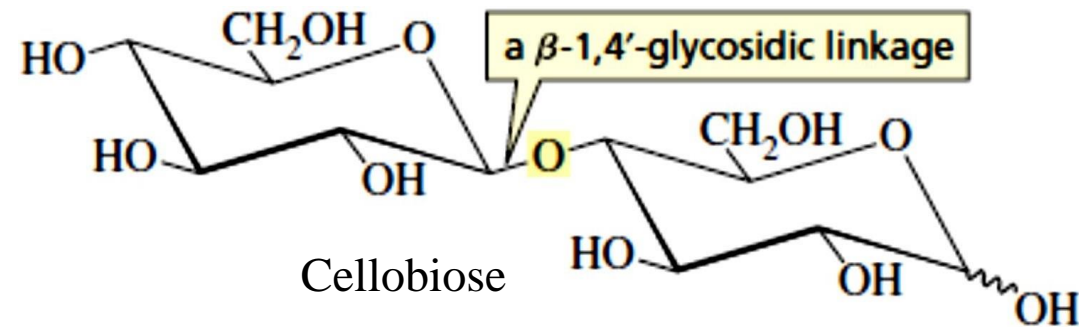
**Disaccharides** are compounds consisting of two monosaccharide subunits hooked together by an acetal linkage. For example, maltose is a disaccharide obtained from the hydrolysis of starch. It contains two D-glucose subunits linked together by an acetal linkage. This particular acetal linkage is called an  **$\alpha$ -1,4'-glycosidic linkage**. The linkage is between C-1 of one sugar subunit and C-4 of the other. The “prime” superscript indicates that C-4 is not in the same ring as C-1. The linkage is an  **$\alpha$ -1,4'-glycosidic linkage** because the oxygen atom involved in the glycosidic linkage is in the  **$\alpha$ -position**.



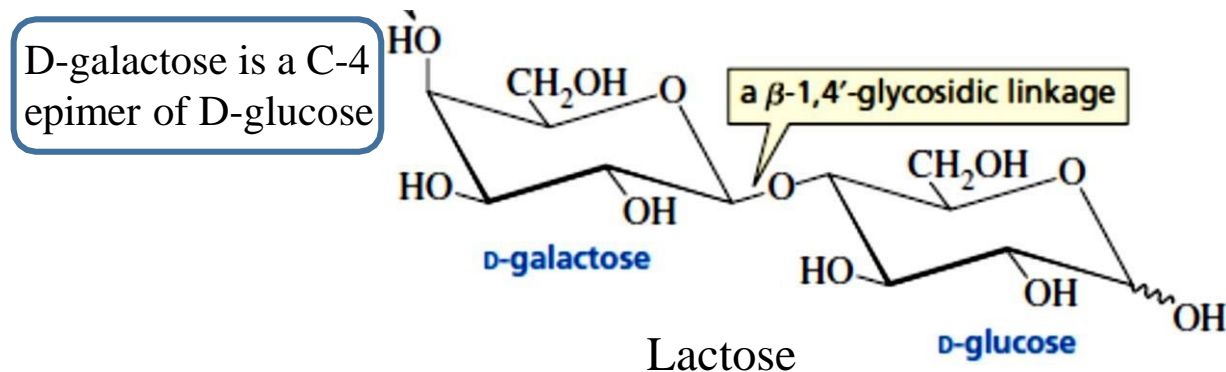
In  $\alpha$ -maltose, the -OH group bonded to this anomeric carbon is in the axial position. In  $\beta$ -maltose, the -OH group is in the equatorial position. Because maltose can exist in both  $\alpha$  and  $\beta$  forms, mutarotation occurs when crystals of one form are dissolved in a solvent. **Maltose is a reducing sugar because the right-hand subunit is a hemiacetal and therefore is in equilibrium with the open-chain aldehyde that is easily oxidized.**



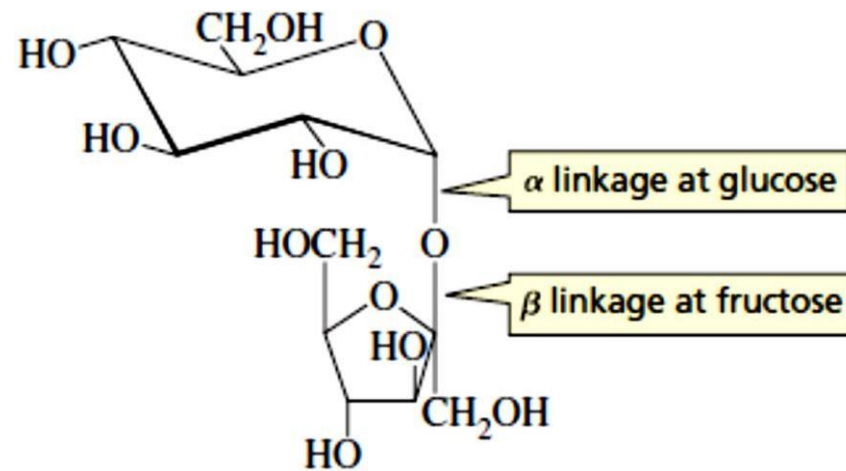
- **Cellobiose**, a disaccharide obtained from the hydrolysis of cellulose, also contains two D-glucose subunits. Cellobiose differs from maltose in that the two glucose subunits are hooked together by a  **$\beta$ -1,4'-glycosidic linkage**.
- Like maltose, cellobiose exists in both  $\alpha$  and  $\beta$  forms because the -OH group bonded to the anomeric carbon not involved in acetal formation, can be in either the axial position (in  $\alpha$  cellobiose ) or the equatorial position (in  $\beta$  cellobiose ).
- Cellobiose is a reducing sugar because the subunit on the right is a hemiacetal.



- **Lactose** is a disaccharide found in milk. One of the subunits of lactose is D-galactose, and the other is D-glucose.
- The D-galactose subunit is an acetal, and the D-glucose subunit is a hemiacetal. The subunits are joined through a  **$\beta$ -1,4'-glycosidic linkage**.
- Because one of the subunits is a hemiacetal, lactose is a reducing sugar and undergoes mutarotation.



- Sucrose consists of a D-glucose subunit and a D-fructose subunit linked by a glycosidic bond between C-1 of glucose (in the  $\alpha$ -position) and C-2 of fructose (in the  $\beta$ -position ).
- Sucrose is not a reducing sugar and does not exhibit mutarotation because the glycosidic bond is between the anomeric carbon of glucose and the anomeric carbon of fructose. Sucrose, therefore, does not have a hemiacetal or hemiketal group, so it is not in equilibrium with the readily oxidized open-chain aldehyde or ketone form in aqueous solution.



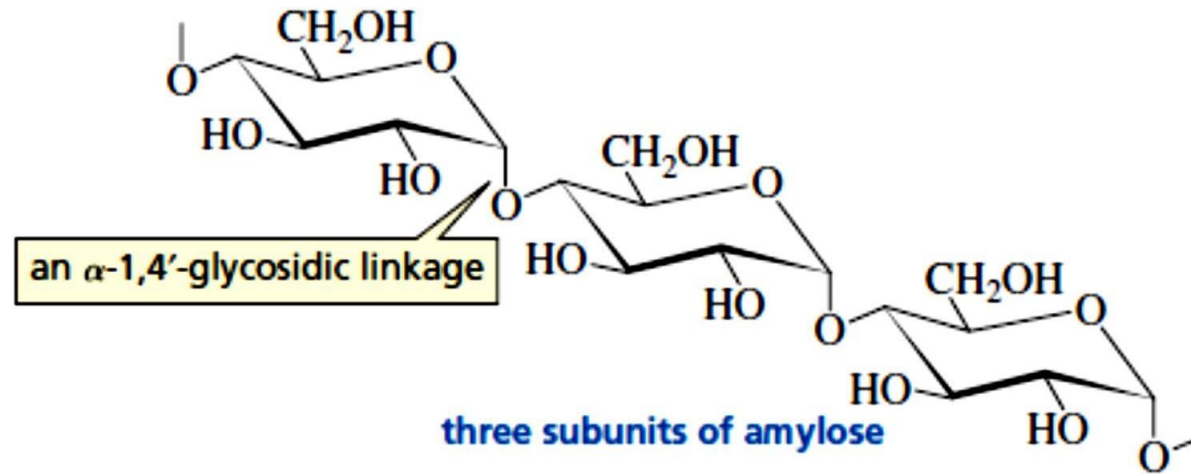
Sucrose has a specific rotation of  $+66.5^\circ$ . When it is hydrolyzed, the resulting equimolar mixture of glucose and fructose possess a specific rotation of  $-22.0^\circ$ . Because the sign of the rotation changes when sucrose is hydrolyzed, a (1:1) mixture of glucose and fructose is called *invert sugar*. The enzyme that catalyzes the hydrolysis of sucrose is called *invertase*.



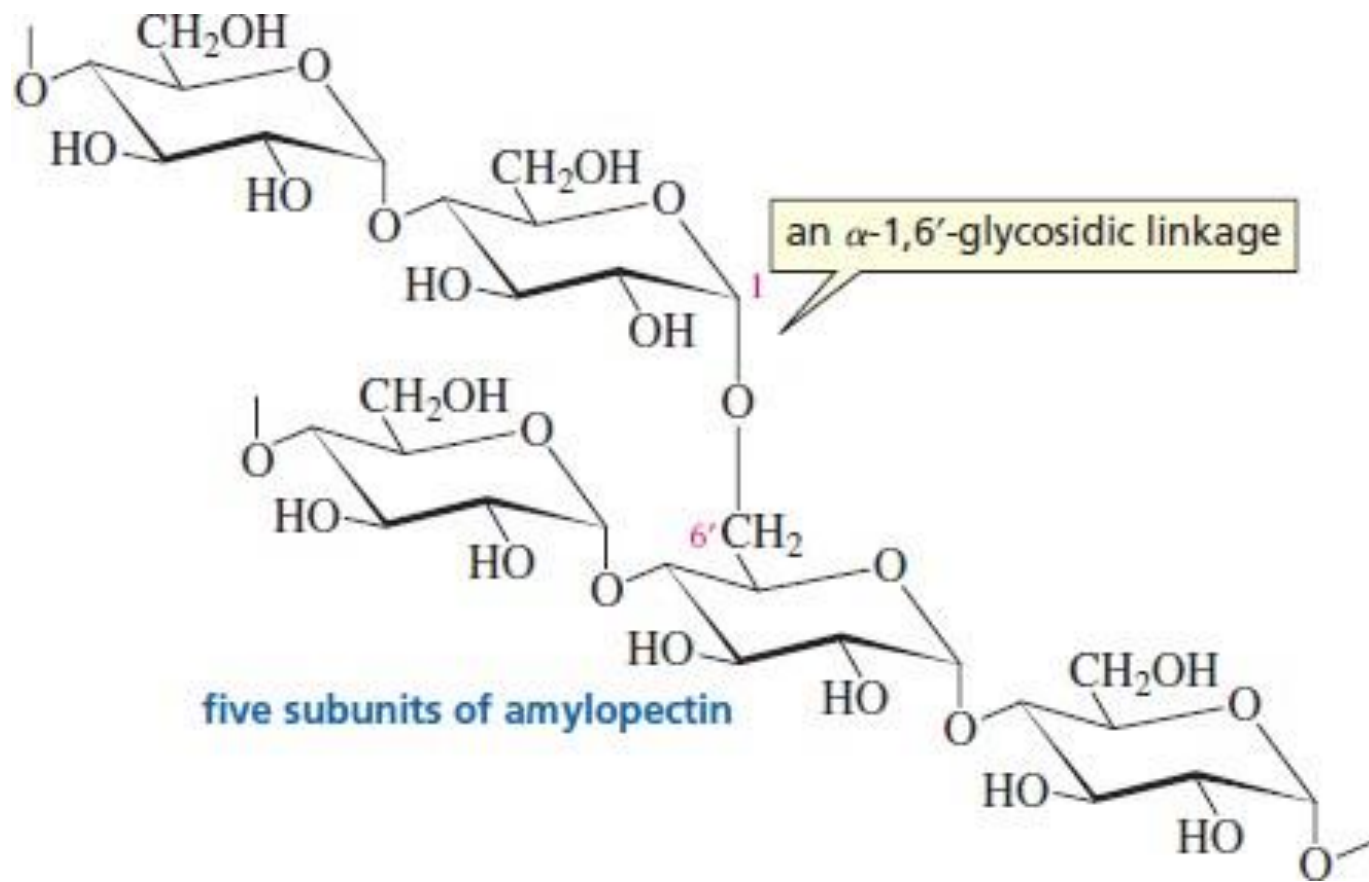
# Polysaccharides

Polysaccharides contain as few as 10 or as many as several thousand monosaccharide units joined together by glycosidic linkages. The most common polysaccharides are **starch and cellulose**.

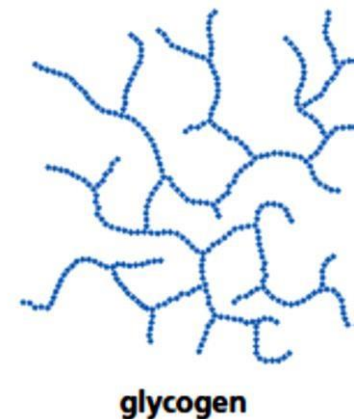
Starch is a mixture of two different polysaccharides: amylose (about 20%) and amylopectin (about 80%). Amylose is composed of unbranched chains of D-glucose units joined by  $\alpha$ -1,4' - glycosidic linkages.



Amylopectin is a branched polysaccharide. Like amylose, it is composed of chains of D-glucose units joined by  $\alpha$ -1,4'-glycosidic linkages. **Unlike amylose, however, amylopectin also contains  $\alpha$ -1,6'- glycosidic linkages. These linkages create the branches in the polysaccharide.**

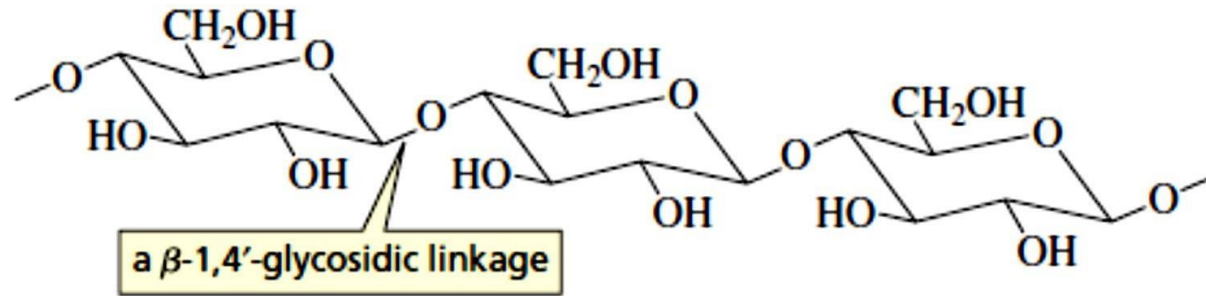


Animals store their excess glucose in a polysaccharide known as glycogen. Glycogen has a structure similar to that of amylopectin, but glycogen has more branches. The branch points in glycogen occur in about every 10 residues, whereas those in amylopectin occur in about every 25 residues. The high degree of branching in glycogen has important physiological effects. When the body needs energy, many individual glucose units can be simultaneously removed from the ends of many branches.



Cellulose is the structural material of higher plants. Cotton, for example, is composed of about 90% cellulose and wood is about 50% cellulose.

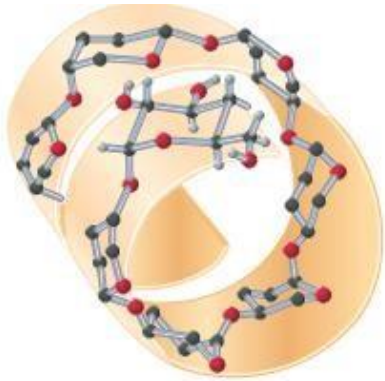
Like amylose, cellulose is composed of unbranched chains of D-glucose units. Unlike amylose, however, the glucose units in cellulose are joined by  $\beta$ -1,4'- glycosidic linkages rather than by  $\alpha$ -1,4'- glycosidic linkages.



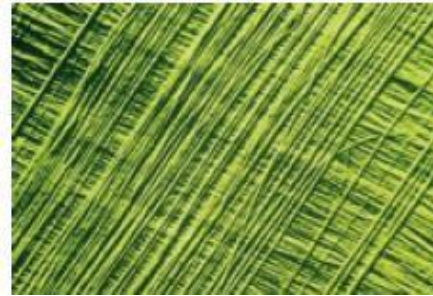
$\alpha$ -1,4'- glycosidic linkages are **easier** to hydrolyze than  $\beta$ -1,4'- glycosidic linkages because of the **anomeric effect** that weakens the bond to the anomeric carbon.

All mammals have the enzyme ( $\alpha$ -glucosidase) that hydrolyzes the  $\alpha$ -1,4'- glycosidic linkages that join glucose units, **but they do not have the enzyme ( $\beta$ -glucosidase) that hydrolyzes  $\beta$ -1,4'- glycosidic linkages.** As a result, mammals *cannot* obtain the glucose they need by eating cellulose **as cellulose has  $\beta$ -1,4'- glycosidic linkages.** However, bacteria that possess  $\beta$ -glucosidase, inhabit the digestive tracts of grazing animals - so cows can eat grass and horses can eat hay - to meet their nutritional requirements for glucose.

- The  $\alpha$ -linkages in starch cause amylose to form a helix that promotes **hydrogen bonding** of its -OH groups to water molecules. As a result, starch is **soluble** in water.
- On the other hand, the  $\beta$ -linkages in cellulose promote the formation of intramolecular hydrogen bonds. Consequently, these molecules line up in linear arrays and intermolecular hydrogen bonds form between adjacent chains. These large aggregates cause cellulose to be **insoluble** in water.



The  $\alpha$ -1,4'-glycosidic linkages in amylose cause it to form a left handed helix. Many of its -OH groups form hydrogen bonds with water molecules



Strands of cellulose in a plant fiber

The different glycosidic linkages in starch and cellulose give these compounds very different physical properties.

- Reference

- 1) Organic Chemistry by Solomon
- 2) Organic chemistry by Morrison & Boyd
- 3) [www.google.com](http://www.google.com)