

UNIT (10) MOLECULES OF LIFE: CARBOHYDRATES

Before studying carbohydrates we will review and examine isomerism.

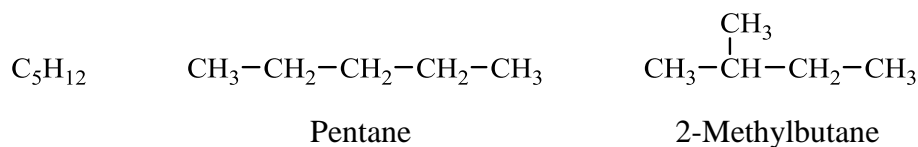
10.1 | Isomerism: Structural Isomers and Stereoisomers

In *unit 7* we defined isomers as compounds with the same molecular formula but different structural formulas.

There are two types of isomerism: structural isomerism and stereoisomerism.

Structural isomerism is defined as isomers having identical molecular formulas but differing in the order in which the individual atoms are connected.

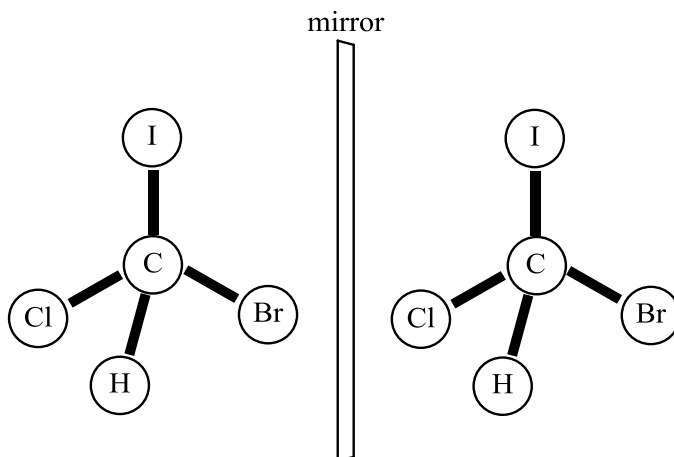
For example, pentane and 2-methylbutane are structural isomers that exhibit structural isomerism. The molecular formula of both isomers is C_5H_{12} .



In **stereoisomerism**, the isomers have the same molecular formula and the same structural formula but differ in the spatial arrangement of the atoms in the molecule.

Suppose you are asked to construct a molecular model of $CHClBrI$ molecule.

Surprisingly, you can make two distinct molecular models (you will make the models in lab 11). You will construct the first model by attaching four different atoms (H, Cl, Br, and I) to the central carbon. The second model will be the “*mirror image*” of the first model. The two models are nonsuperimposable; that is, you can not align all atoms at the same time.



These two models are related to each other in a way similar to your right-hand and left-hand.

A right hand is the nonsuperimposable mirror image of a left hand. If you hold your right hand to a mirror; you see your left hand.

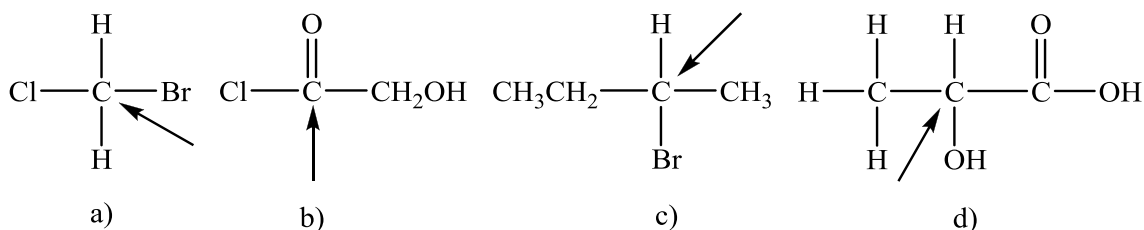
A molecule that is nonsuperimposable on its mirror-image is said to be **chiral** (pronounced “ki-ral”, from Greek word *cheir*, meaning “hand”).

The two stereoisomers that are *nonsuperimposable mirror images* of one another are called a pair of **enantiomers** (Greek: *enantios* + *meros*, opposite + part). If we extend this concept to our hands, we would consider our right and left hands a pair of enantiomers.

Any organic molecule that contains carbon with four different atoms or groups attached is a chiral molecule and the carbon is said to be a chiral carbon.

Worked Example 10-1

Indicate whether the carbon marked with arrow is chiral.

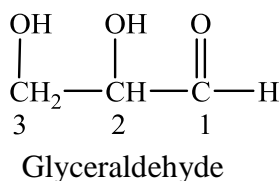


Solution

- a) Not chiral. Two of the groups attached to the carbon atom are identical.
- b) Not chiral. The carbon atom is attached to only *three* groups.
- c) Chiral. The four different groups are -H , -CH_3 , Br , and $\text{-CH}_2\text{CH}_3$.
- d) Chiral. The four different groups are -H , -COOH , OH , and -CH_3 .

Worked Example 10-2

Is glyceraldehyde chiral? Explain.



Solution

A molecule is chiral if it contains at least one C atom bonded to four different groups.

Carbon number one has only *three* different groups attached. The double bond to oxygen is considered two bonds to oxygen, i.e.: two bonds to the same atom.

Carbon number two has four groups attached (-H, -OH, -CH₃, and CHO). The four groups are different.

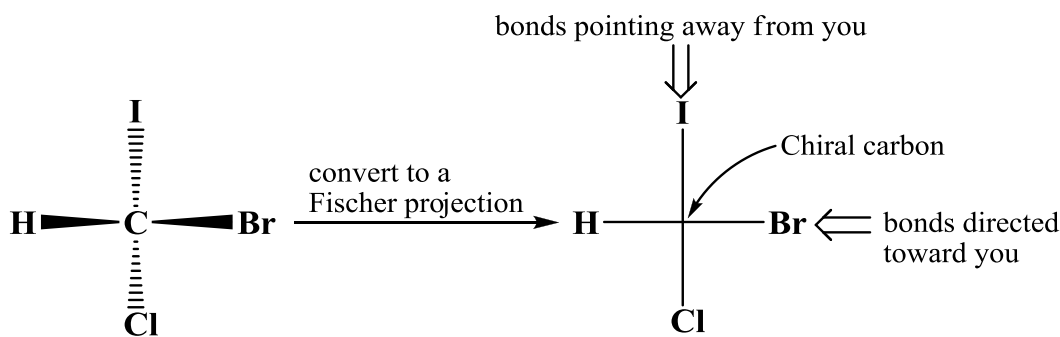
Carbon number three has four groups attached (-OH, -H, -H, and -CHOHCHO). The four different groups are NOT different, two are hydrogen atoms.

Of the three carbons, carbon number 2 has *four different groups*, therefore glyceraldehyde is chiral.

10.2 Drawing Structures for Chiral Molecules: Fischer Projection Formula

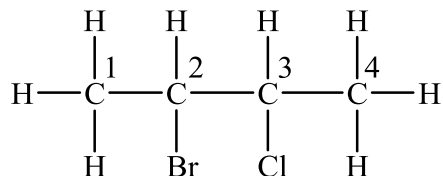
Emil Fischer, a Nobel Prize winning German chemist, devised a simple method to represent a three dimensional molecule using a two dimensional drawing. This representation is called a **Fischer Projection** in honor of its founder. When drawing Fischer projections, the molecule is drawn in the form of a cross with the chiral carbon centered at the point of intersection. The horizontal lines represent bonds directed outward toward the observer and the vertical lines are bonds pointing away.

We can draw Fischer projection for CHClBrI molecule as:

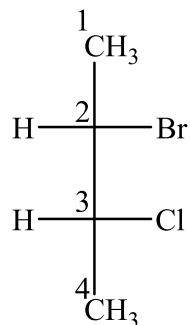


Notice that in a Fischer projection the chiral carbon is not explicitly shown (not written). It is represented as the intersection of vertical and horizontal lines.

Fischer projections can also be written for molecules with more than one chiral carbon. For example, 2-bromo-3-chlorobutane, $\text{CH}_3\text{CHBrCHClCH}_3$ contains two chiral carbons, the second and the third carbon atoms.



The Fischer projection can be drawn as:



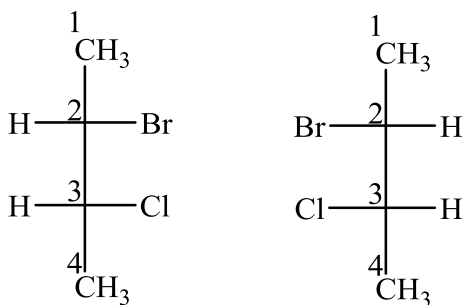
If we examine the two structures above, we notice a distinct difference in the orientation of the carbon chains. In our study of organic chemistry most carbon chains were written horizontally. This practice is universally accepted and quite common indeed. When writing Fischer projections, the carbon chain is *always* written vertically. The above Fischer projection represents only one possible stereoisomer of the molecule. A chiral carbon (by definition) will always have two possible arrangements of the four different groups attached. The molecule above contains two chiral carbons and therefore four possible stereoisomers (two for each chiral carbon). The stereoisomers would represent two pairs of enantiomers. This concept is illustrated in the following worked example.

Worked Example 10-3

Draw ALL possible stereoisomers of $\text{CH}_3\text{CHBrCHClCH}_3$.

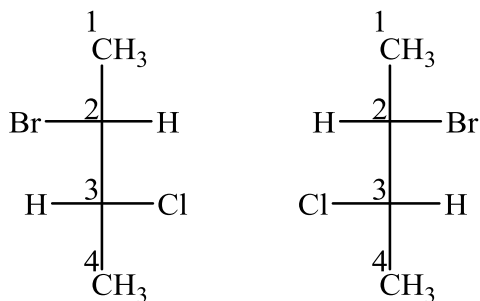
Solution

We draw the carbon chain vertically and place the groups in the first stereoisomer rather arbitrarily. We chose (for no good reason) to put Br and Cl on the same side. The second stereoisomer is simply the mirror image of the first. If you place a mirror on the right of the first molecule, you see the second as the reflected image. Drawing mirror images can be somewhat simplified to basically switching the sides of each group, i.e.: Br on carbon 2 is on the right in the first Fischer projection and on the left in the second. Verify that these two molecules are nonsuperimposable mirror images. You cannot simply flip one onto the other and align all groups. Recall, vertical lines in Fischer projections represent bonds extending away from the viewer, while horizontal lines extend out toward the viewer. Therefore, the Br, Cl, and both hydrogens are extending toward you (CH_3 's are back) in each structure below. Flipping one molecule would change the orientation of one set of atoms....they will not align. These molecules are nonsuperimposable mirror images and therefore a pair of enantiomers. Remember, *only nonsuperimposable mirror images are enantiomers*.



We now draw the third stereoisomer by switching the sides of the two groups on one chiral carbon in one of the stereoisomers above. We have arbitrarily chosen the H and Br on the second carbon in the first molecule (again, for no good reason). The fourth stereoisomer is drawn as discussed above.

These two molecules represent the second pair of enantiomers:



10.3 | Carbohydrates

Carbohydrates, also called **saccharides**, are the most abundant organic compounds in nature. Carbohydrates are molecular compounds containing just three elements: carbon, hydrogen, and oxygen. Glucose (blood sugar), sucrose (table sugar), starch, and cellulose are a few examples of carbohydrates.

Carbohydrates are classified as monosaccharides, disaccharides, oligosaccharides, and polysaccharides based on the overall size of the molecular. Most carbohydrates are easily distinguished from other types of molecules because their names end in “-ose.”

Monosaccharides: can not be broken down into smaller carbohydrate units.

Disaccharides: contain two monosaccharide units.

***Oligosaccharides:** contain three to ten monosaccharide units.

Polysaccharides: contain more than ten monosaccharide units.

*Oligosaccharides are less common and of minor importance to us.

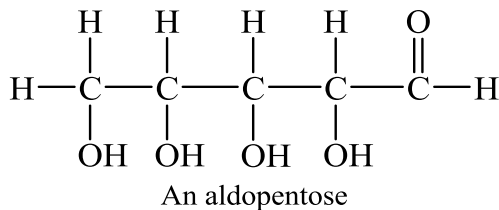
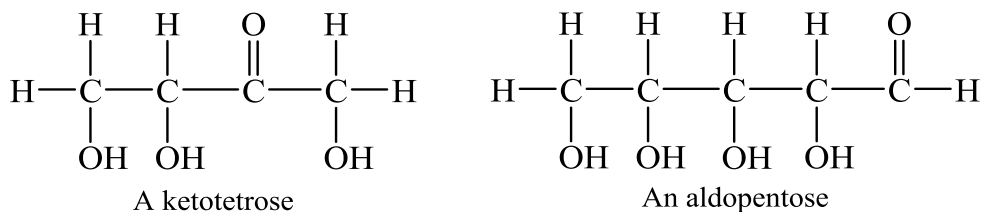
10.4 | Monosaccharides

Monosaccharides (or **simple sugars**) are the fundamental building blocks of all carbohydrates. They can be classified based on *functional group*, the *number of carbon atoms*, or *both*.

Functional group: A monosaccharide may contain an aldehyde or ketone functional group. If an aldehyde is present, the monosaccharide is classified as an *aldose* (note: ald- prefix indicates aldehyde, -ose suffix indicates sugar). A monosaccharide with a ketone group is called a *ketose*.

Number of carbons: A three-carbon monosaccharide is a *triose*, a four-carbon monosaccharide is a *tetrose*, a five-carbon monosaccharide is a *pentose*, and a six-carbon monosaccharide is a *hexose*.

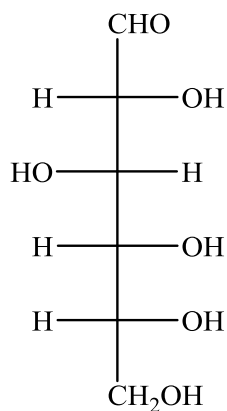
Functional group and number of carbons: A four-carbon monosaccharide with a ketone group is called a ketotetrose. A five-carbon monosaccharide with an aldehyde group is called an aldopentose. Examine the structures below and verify the names.



Monosaccharides are sometimes called *polyhydroxyaldehydes* or *polyhydroxyketones* because generally all carbons except the carbonyl carbon (carbon-oxygen double bond) contain a bound hydroxyl group (-OH).

Worked Example 10-4

The Fischer projection of glucose is given below:



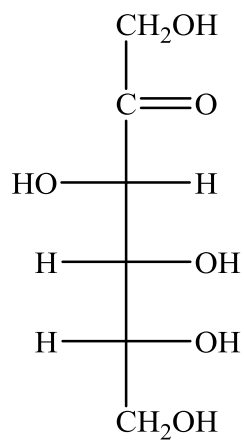
- Write the molecular formula for glucose.
- Classify based on functional group.
- Classify based on the number of carbons.
- Classify based on functional group and the number of carbons.

Solution

- There are six carbon atoms, twelve hydrogen atoms and six oxygen atoms.
The molecular formula is $\text{C}_6\text{H}_{12}\text{O}_6$.
- The functional group is an aldehyde, therefore glucose is an aldose.
- There are six carbon atoms, therefore glucose is a hexose.
- Combining b and c, glucose is an aldohexose.

Practice 10-1

The Fischer projection of fructose is given below:

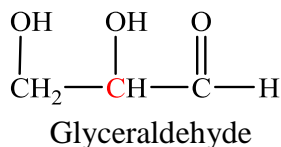


- Write the molecular formula for fructose.
- Classify based on functional group.
- Classify based on the number of carbons.
- Classify based on functional group and the number of carbons.

Answer

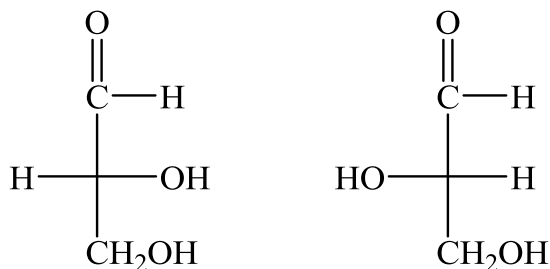
10.5 | Fischer Projections of Monosaccharides: The D- and L- isomers

Glyceraldehyde is the smallest monosaccharide containing a chiral carbon (center carbon).



The two isomers are identified using Fischer projections and differentiated using the prefixes D- and L-. By convention, the carbon chain is written vertically with the carbonyl group (most oxidized carbon) at the top. Identify the carbon containing four different groups (chiral carbon). It is the middle carbon in this case, if the -OH group is on the left, the isomer is assigned "L- (remember L for Left)," if on the right, it is assigned "D-".

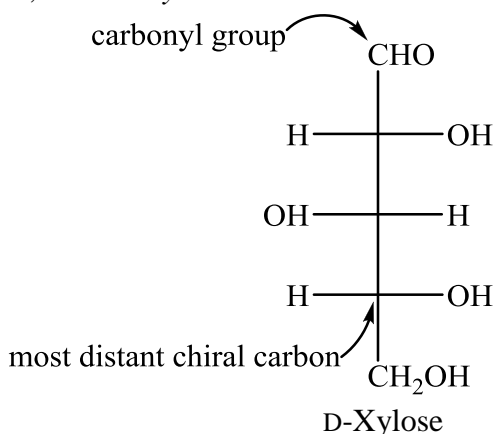
L- is from the Latin *levo* meaning left and D- is from the Latin *dextro* meaning right. The D and L symbols are typically typeset in small caps (D- and L-).



D-glyceraldehyde

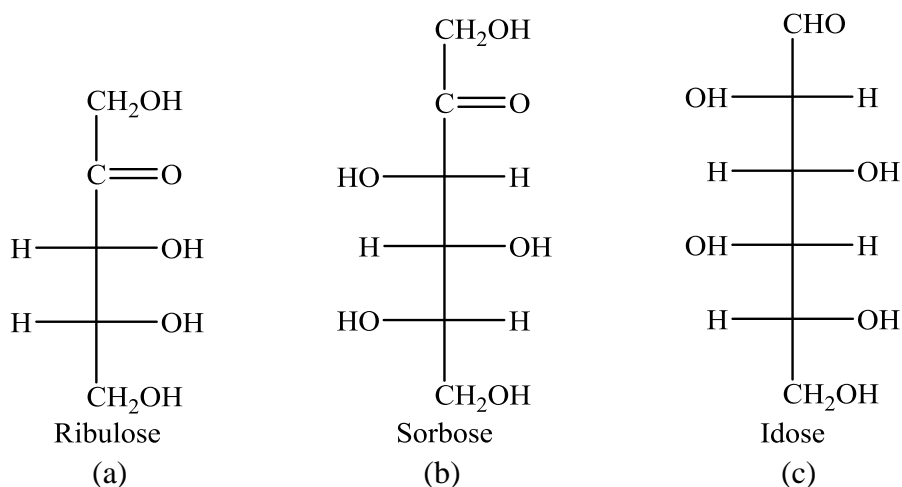
L-glyceraldehyde

If there are two or more chiral carbons in the molecule, the chiral carbon *most distant* from the carbonyl group determines the D- or L- isomers. This will always be the second to the last carbon in the Fischer projection. Therefore, when assigning D- or L- to more complex isomers, focus *only* on the second to the last carbon.



Practice 10-2

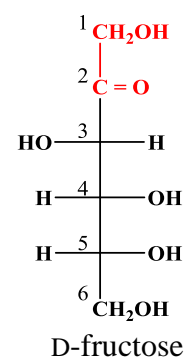
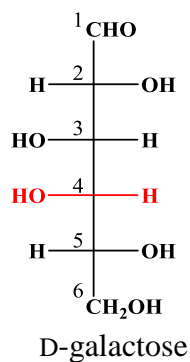
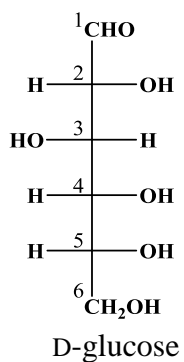
State whether each of the following is the D or L isomer.



Answer

10.6 | Biologically Important Monosaccharides

D-glucose is the most common monosaccharide in biological system. Glucose is also known as **dextrose** or **blood sugar**. Other important monosaccharides are galactose, fructose, ribose, and deoxyribose. The Fischer projections for the D- isomers of glucose, galactose, and fructose are shown below.



Note the structures of galactose and glucose are very similar; they differ only in the orientation of -OH at carbon 4. In contrast, fructose is a ketone and differs from glucose and galactose (aldehydes) at carbons 1 and 2.

Notice that glucose, galactose, and fructose all have the same molecular formula, $C_6H_{12}O_6$. They are *isomers*.

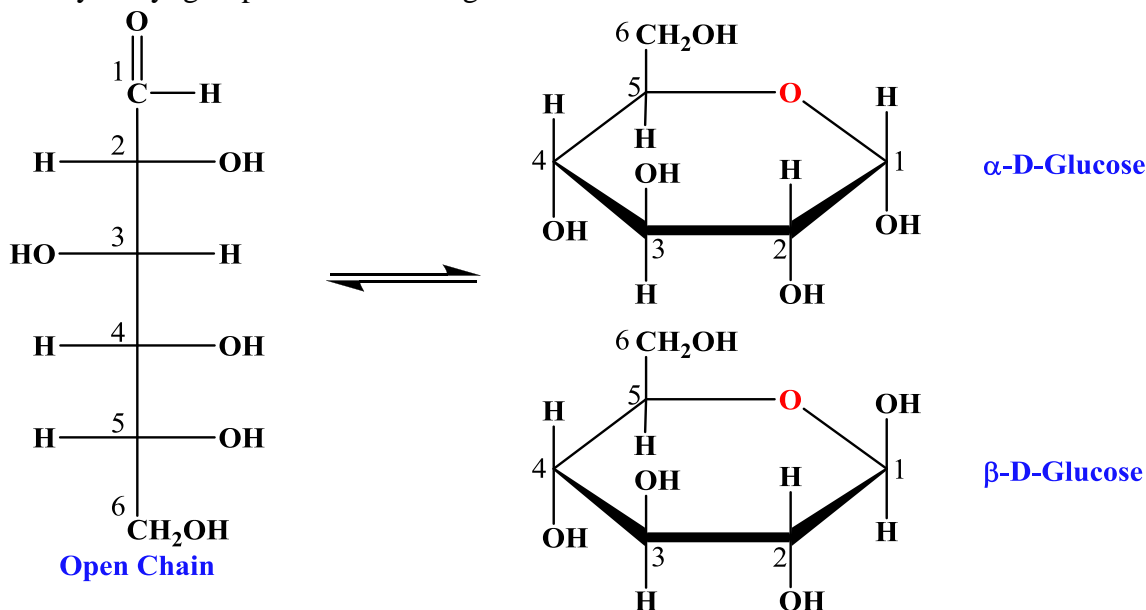
10.7 | The Cyclic Structure of Monosaccharides: Haworth Structures

Experimental studies indicate that the dominant forms of monosaccharides containing five or more carbons are cyclic structures in aqueous solutions.

The cyclic structure of monosaccharides is commonly represented using **Haworth projections**, named after the English chemist Sir Walter N. Haworth.

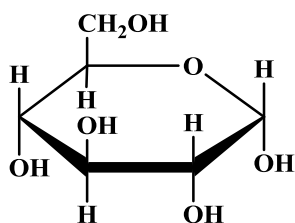
The open-chain form of D-glucose is converted to a cyclic form through a ring closure reaction involving the -OH group on carbon five and the C-1 carbonyl carbon.

The carbonyl group at C-1 reacts with the hydroxyl group at C-5 to give a six-membered ring containing oxygen. The newly formed ring is a rigid structure that has two planes, one above the ring, the other below. When the ring closes, the C-5 -OH loses the hydrogen and the oxygen is incorporated into the ring. The C-1 carbonyl carbon loses its double bond to oxygen and becomes a single bond to -OH. The newly formed -OH at C-1 (formerly the carbonyl carbon) can be drawn above or below the ring producing two different isomers. These two isomers are called **anomers** named α (alpha) and β (beta) anomers. In the α anomer, the C-1 hydroxyl group is below the ring, in the β anomer, the C-1 hydroxyl group is above the ring.

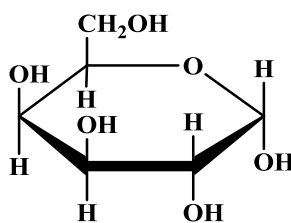


Worked Example 10-5

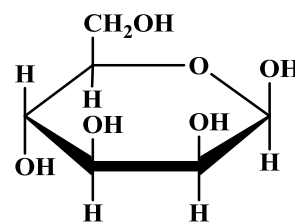
Identify each of the following as an α or a β form.



α



α



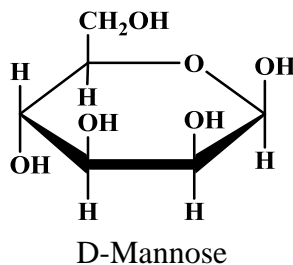
β

Solution

α : When the hydroxyl group on carbon 1 is written below the ring
 β : When the hydroxyl group on carbon 1 is written above the ring

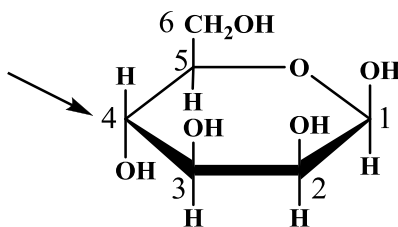
Worked Example 10-6

Identify the #4 carbon atom in mannose and classify the mannose as a pentose or a hexose.



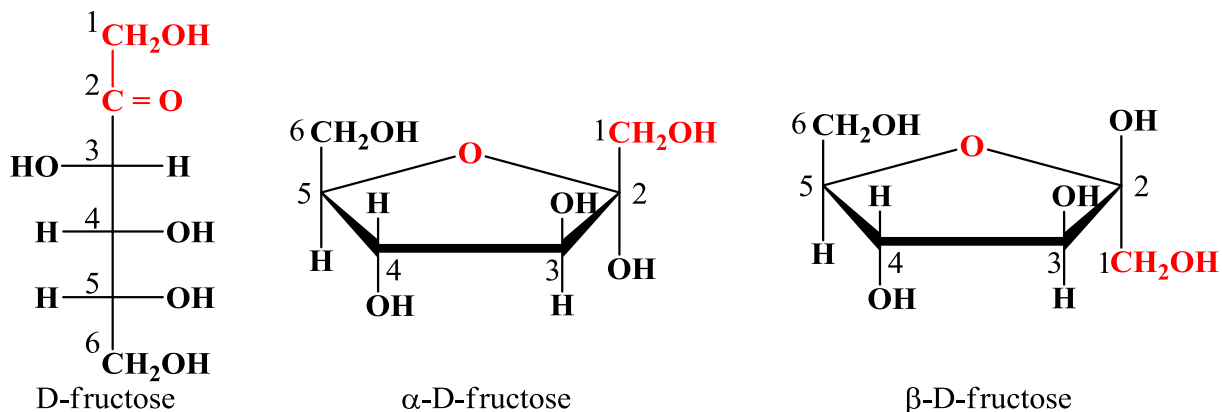
Solution

To identify the #4 carbon atom, we number the carbons starting from the right side of the ring:



Mannose has six carbon atoms, so it is a hexose.

Haworth Structure of Fructose



Note the carbonyl carbon is carbon #2 in fructose. In the Haworth, the (former) carbonyl carbon will always be the carbon to the right of the oxygen in the ring.

10.8 | Reducing Sugars

Recall from *unit 8* that aldehydes can be oxidized to carboxylic acids using very mild oxidizing reagents such as **Benedict's reagent**.

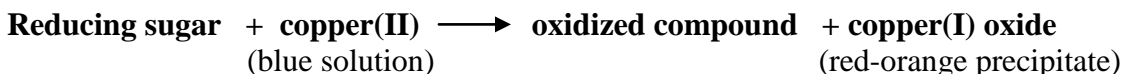
Ketoses do not easily oxidize, however some can rearrange to aldoses which do oxidize. For example; fructose (ketose) will rearrange into an aldose when treated with a basic Benedict's solution.

As Benedict's reagent oxidizes a carbohydrate, the Cu^{2+} ion in the Benedict's solution is reduced to Cu^+ . Any carbohydrate (sugar) that can reduce the Benedict's reagent is called the **reducing sugar**.

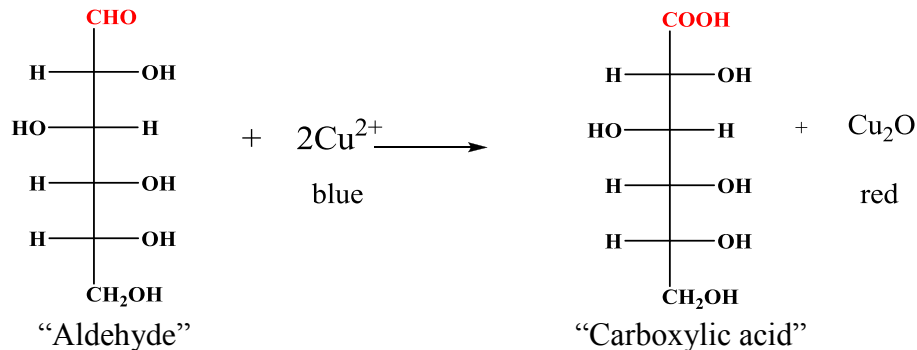
All monosaccharides and all common disaccharides (except sucrose) are reducing sugars.

In a positive Benedict's test, the blue color of the solutions turns greenish, and a dark red, orange, brown, or yellow **precipitate** forms. Benedict's test requires heating the test solutions in boiling water for several minutes.

General reaction:

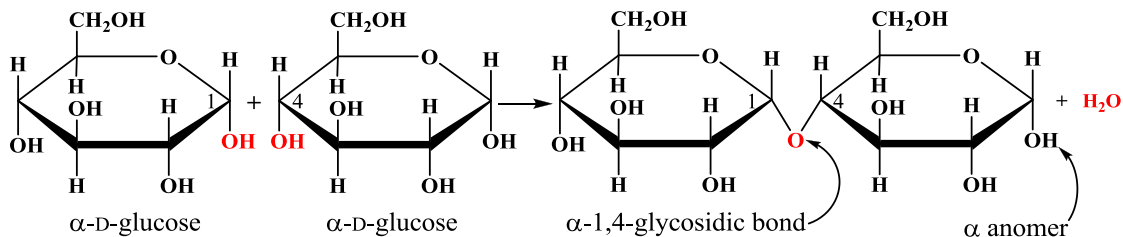


Specific example:



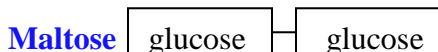
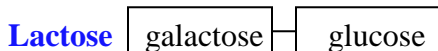
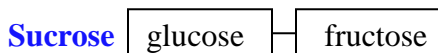
10.9 | Biologically Important Disaccharides

Two monosaccharides can react to form a **disaccharide** molecule in a dehydration reaction (loss of water).



Disaccharides are joined through an “oxygen bridge”. The carbon-oxygen bonds are called *glycosidic* bonds.

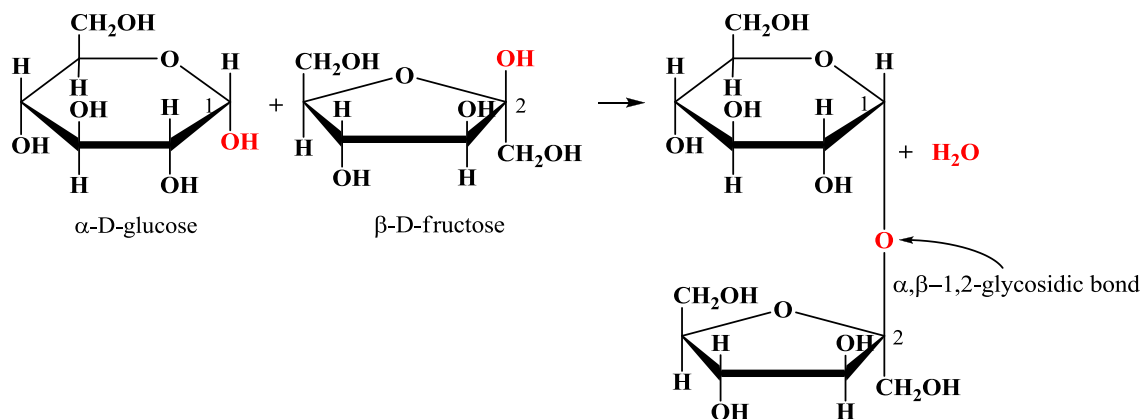
The most common disaccharides are sucrose, lactose, and maltose.



Sucrose

Sucrose (*table sugar*) is the most abundant disaccharide in the biological world. Sucrose contains an α -D-glucose unit and a β -D-fructose unit joined by a α, β (1 \rightarrow 2) glycosidic linkage.

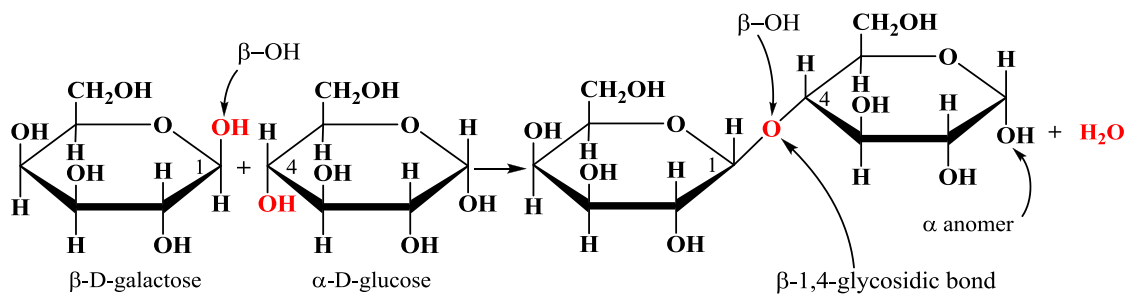
Sucrose is a non-reducing sugar because the glycosidic bond involves both anomeric carbons; therefore there is no free aldehyde group.



Lactose

Lactose (*milk sugar*) is made up of a $\beta\text{-D-galactose}$ unit and a D-glucose unit joined by a $\beta(1 \rightarrow 4)$ glycosidic linkage.

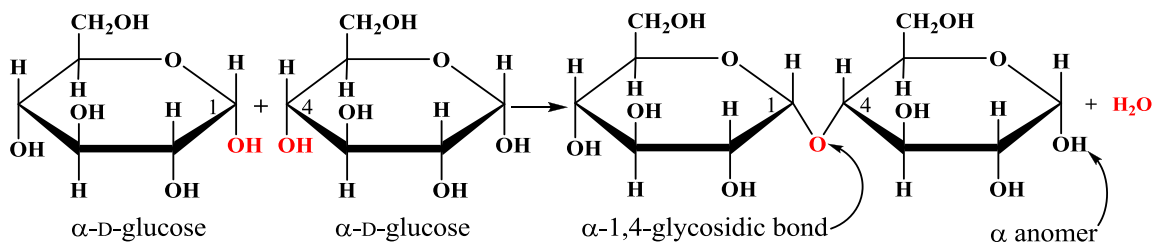
Lactose is a reducing sugar (glucose ring on the right has a free anomeric carbon that can open to give an aldehyde).



Maltose

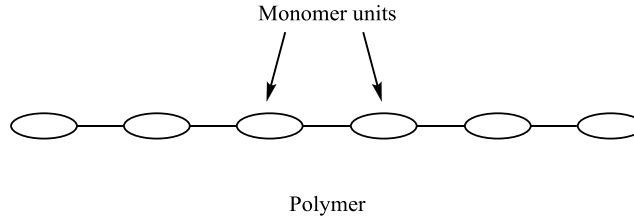
Maltose (*malt sugar*) is made up of two D-glucose units. The glycosidic linkage between two glucose units is an $\alpha(1 \rightarrow 4)$ linkage.

Maltose is a reducing sugar (glucose ring on the right can open to give an aldehyde).



10.10 | Polysaccharides

A **polymer** is a very large molecule composed of many small, repeating structural units that are identical. The repeating structural units are called *monomers*.



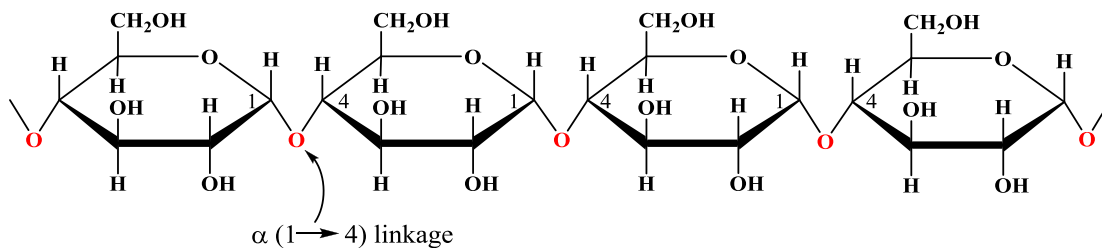
Polysaccharides consist of a large number of bound monosaccharide units.

Three very important polysaccharides are **starch**, **glycogen**, and **cellulose**. They all contain only glucose units and are differentiated by the type of *glycosidic bonds* and the degree of branching in the molecule.

Starch

Starch is the primary storage polysaccharide in plants. The most common forms of starch are *amylose* and *amylopectin*. Most starches contain 20 to 25% amylose and 75 to 80% amylopectin. Complete hydrolysis (breakdown) of both amylose and amylopectin produces only D-glucose.

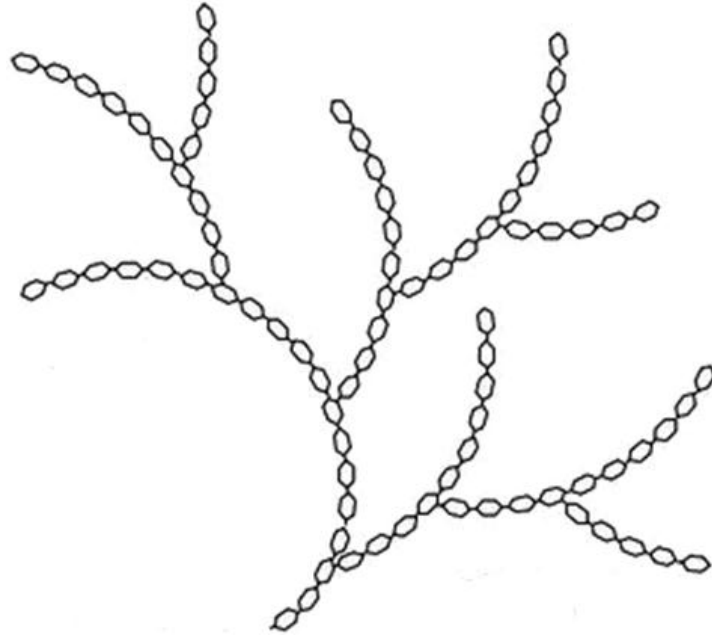
Amylose molecules are continuous chains of D-glucose units joined by α -1,4-glycosidic linkage. There are no branch points in the molecule which may contain of as many as 4,000 D-glucose units.



Amylopectin is a branched-chain polysaccharide much larger than amylose.

Amylopectin molecules, on the average, consist of several thousand α -D-glucose units joined by α -1,4-glycosidic linkage. The molecular masses routinely approach 1 million or more.

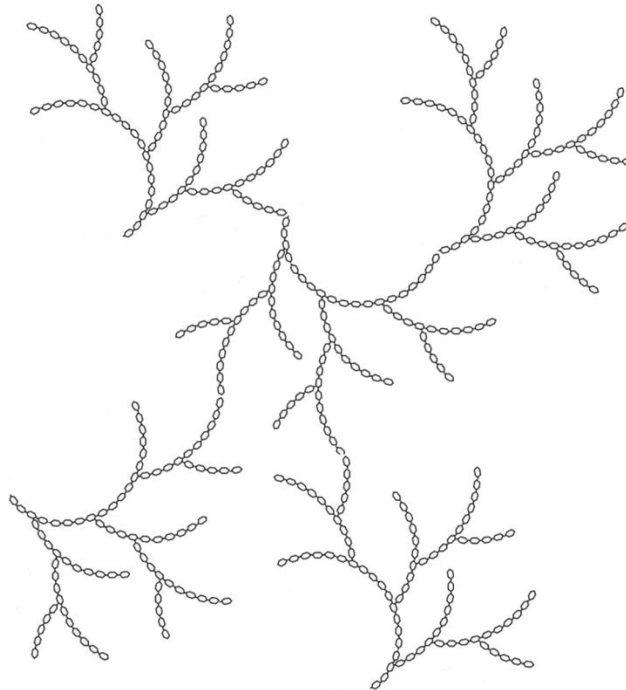
Major sources of starch are rice, corn, potatoes, and wheat.



A representation of the branched-chain structure of amylopectin
(each small unit represents a single glucose molecule)

Glycogen

Glycogen is the major glucose storage molecule in animals. Structurally, glycogen is very similar to amylopectin (α -D-glucose units joined by α -1,4-glycosidic linkages), but glycogen is more highly branched.

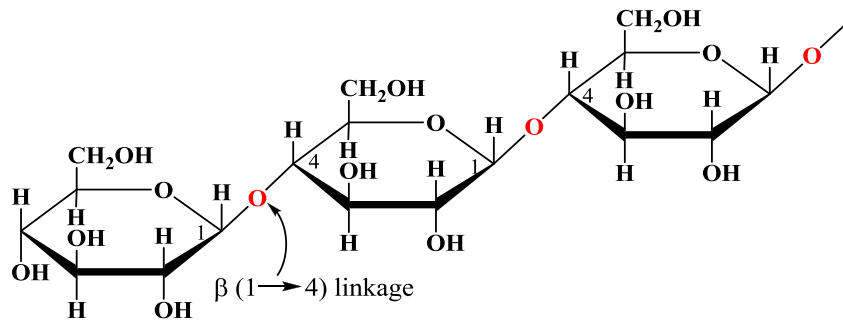


A representation of the branched-chain structure of glycogen

Cellulose

Cellulose is the most abundant organic molecule found in nature. Structurally, cellulose is a long, unbranched, D-glucose polymer in which the glucose units are linked by β (1 \rightarrow 4) glycosidic bonds. In the structure below, note the carbon-1 oxygens are above the ring, therefore β (1 \rightarrow 4).

Cellulose in our diet is referred to as **fiber** and, in contrast to glycogen, amylose, and amylopectin, it cannot be digested. This is because our digestive system does not have the enzymes to catalyze the hydrolysis of β -glycosidic bonds.

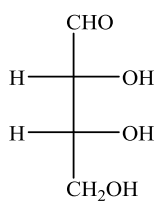


Homework Problems

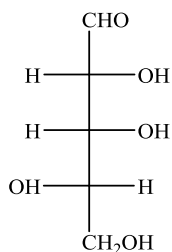
10.1 Draw Fisher projection formulas for each of the following and indicate each chiral carbon with asterisks (*).

- an aldotetrose
- a ketotetrose
- an aldohexose
- a ketohexose

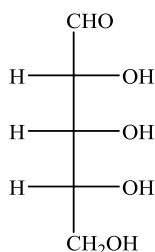
10.2 Determine whether each of the following is a D- or L- sugar. Explain your answer.



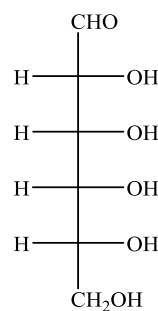
a.



b.

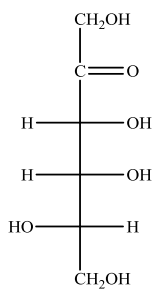


c.

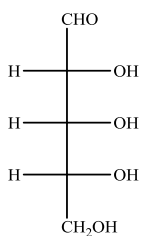


d.

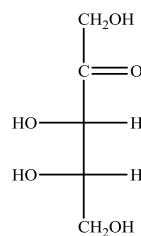
10.3 Draw a Fisher projection for the mirror image of each of the following monosaccharides.



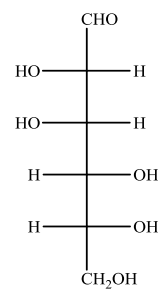
a.



b.

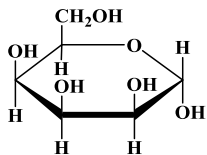


c.

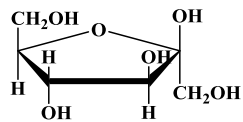


d.

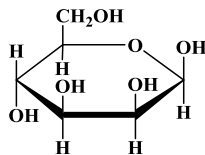
10.4 Identify each of the following as an α or a β form and draw the structural formula of the other anomer:



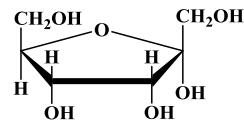
a.



b.

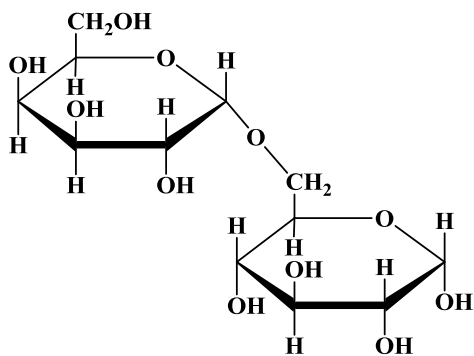


c.



d.

10.5 Consider the following disaccharide:



- Name the two monosaccharides that are formed on hydrolysis of the disaccharide?
- Describe the glycosidic linkage between the two monosaccharide units.

10.6 Describe the structural similarities and differences between the following pairs of polysaccharides:

- Glycogen and amylopectin
- Amylose and cellulose