5.2: Carbohydrate Structures

Learning Outcomes

- Describe the structure and function of carbohydrates.
- Identify functional groups of carbohydrates.
- Give general name for a carbohydrate molecule (i.e. aldotetrose, ketopentose, etc)
- Label carbohydrates as either D- or L-enantiomers.
- Draw the mirror image of a carbohydrate molecule.
- Distinguish between monosaccharides, disaccharides, and polysaccharides.
- Describe the structure of complex carbohydrates.
- Recognize how carbohydrates determine blood type.

The brain is a marvelous organ. And it's a hungry one, too. The major fuel for the brain is the carbohydrate glucose. The average adult brain represents about 2% of our body's weight, but uses 25% of the glucose in the body. Moreover, specific areas of the brain use glucose at different rates. If you are concentrating hard, (taking a test, for example) certain parts of the brain need a lot of extra glucose while other parts of the brain only use their normal amount. Something to think about.

As a child, you may have been told that sugar is bad for you. Well, that's not exactly true. Essentially, carbohydrates are made of sugar, from a single sugar molecule to thousands of sugar molecules all attached together. Why? One reason is to store energy. But that does not mean you should eat it by the spoonful.

Carbohydrates

Carbohydrates are organic compounds that contain only carbon (C), hydrogen (H), and oxygen (O). They contain a chain of carbons, an aldehyde or a ketone, and hydroxyl groups. Every carbon atom is attached to one oxygen atom. There are thousands of different carbohydrates, but they all consist of one or more smaller units called monosaccharides.

Monosaccharides

The general formula for a **monosaccharide** is $(\mathrm{CH_2O})_n$, where n can be any number greater than two. For example, if n is 6, then the formula can be written $\mathrm{C_6H_{12}O_6}$. This is the formula for the monosaccharide glucose. Another monosaccharide, fructose, has the same chemical formula as glucose, but the atoms are arranged differently. Carbohydrates have many isomers because of the arrangement of the $-\mathrm{OH}$ groups in their structures. Compare the glucose and fructose molecules in the figure below. Can you identify their differences? The only differences are the positions of some of the atoms. These differences affect the properties of the two monosaccharides.

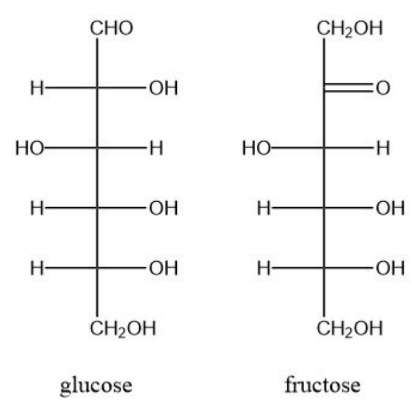


Figure 5.2.1: Structures of glucose and fructose.

Monosaccharides can be classified by the number of carbon atoms they contain: diose (2), triose (3), tetrose (4), pentose (5), hexose (6), heptose (7), and so on. They can also be classified based on whether or not they contain an aldehyde (aldose) or ketone (ketose). We can also combine these two designations to refer to classes of carbohydrates. For example, an aldohexose is a carbohydrate (indicated by the *-ose* ending) with six carbons (*hex*) and an aldehyde group (*aldo*). A ketopentose is a carbohydrate with a ketone and 5 carbons. Both glucose and fructose are hexoses because they contain six carbons but glucose is an aldohexose while fructose (also known as "fruit sugar") is a ketohexose. Other common monosaccharides include galactose (part of lactose), xylose ("wood sugar"), ribose (in RNA), and deoxyribose (in DNA).

Fischer Projections

There are several ways to draw the structure of carbohydrate molecules. The Fischer projection (straight chain) makes it appear that the molecule is flat but it is a three-dimensional molecule. Although we will not be concerned with the 3D orientation, know that the arrangement in the Fischer projection does provide information about the orientation of atoms around each carbon atom.

These projections simplify the drawing of molecules yet retain important information about the arrangement of atoms within the structure. The figure below shows the Fischer projections for the enantiomers (non-superimposable mirror images) of ephedrine and pseudoephedrine. While it may appear that the molecules are the same, they are not because the Fischer projection does not explicitly show the three-dimensional geometry of the molecule.

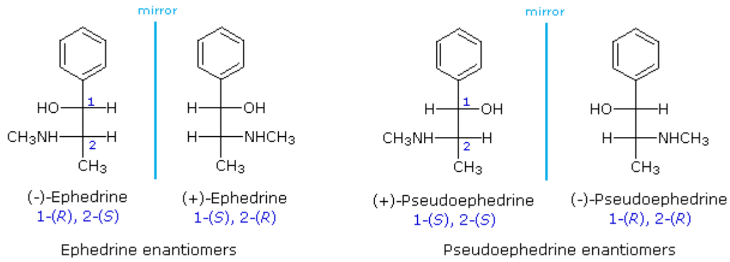


Figure 5.2.2: Fischer projections of ephedrine and pseudoephedrine.

Fischer projections provide an easy way to distinguish among the many, similar carbohydrate molecules that exist. For example, there are sixteen aldohexoses (see figure below). Note the different patterns of the $-\mathrm{OH}$ bonds on the left and right sides of the Fischer projection for each. Changing the orientation of one or more of the $-\mathrm{OH}$ groups changes the identity of the molecule.

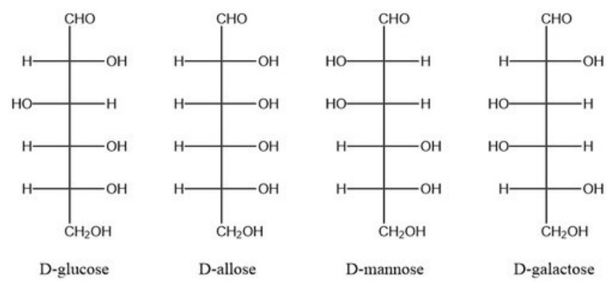


Figure 5.2.3: Four of the sixteen aldohexoses.

Each carbohydrate molecule also has an enantiomer and the two are designated as the D- and L- versions of the compound. The designation is based on the orientation of the $-\mathrm{OH}$ group on the chiral carbon farthest from the aldehyde or ketone. The structures of D-glucose and L-glucose are shown in the figure below. The orientation of all $-\mathrm{OH}$ groups are reversed but only the arrangement of at the carbon indicated by the arrow determines whether the sugar is a D-sugar with the $-\mathrm{OH}$ group on the right or an L-sugar with the $-\mathrm{OH}$ group on the left.

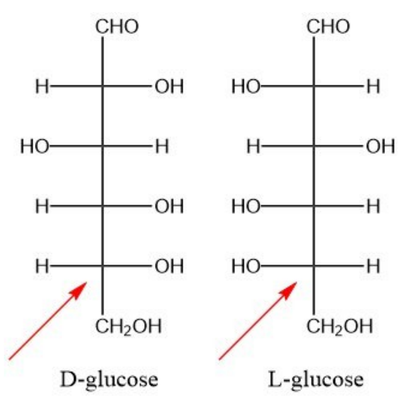


Figure 5.2.4: D-glucose and L-glucose are mirror images of one another.

Haworth Structures

Like Fischer projections, the Haworth structures provide information about a molecule's three-dimensional structure without explicitly showing it in the drawing. Carbohydrates are present in the body in both the chain and ring forms with the latter being more common. Haworth projections provide a simple way to display the ring structures and may or may not show the hydrogen atoms attached to each carbon. Remember, every carbon has four bonds so hydrogens are implied when the structure does not show all four bonds. When the cyclic monosaccharide forms, there are two versions that can form, called α (alpha\) and β (beta) (see figure below). The arrow in the figure indicates the **anomeric** carbon which it the location where the ring forms and where the orientation of the $-\mathrm{OH}$ group can change. The orientation of the other $-\mathrm{OH}$ groups are fixed because they are determined by the orientation of the $-\mathrm{OH}$ groups in the particular monosaccharide (compare to the orientation of the $-\mathrm{OH}$ groups on the left and right sides of the Fischer projections). Each monosaccharide can exist in either α or β form and the two forms will interconvert as the ring opens and closes. The α form occurs when the $-\mathrm{OH}$ group on the anomeric carbon is pointing down and the β version exists when the $-\mathrm{OH}$ group on the anomeric carbon is pointing up.

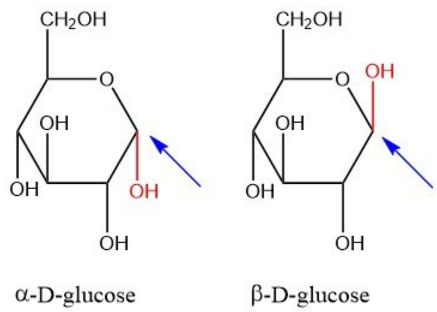


Figure 5.2.5: The cyclic forms of carbohydrates can interconvert between the alpha and beta forms.

As a result of these different orientations, we can have four forms of each monosaccharide. For example, glucose can exist as α-D-glucose, α-L-glucose, β-D-glucose, or β-L-glucose. While the α and β forms can interconvert, the same cannot be said for D and L versions. Naturally occurring monosaccharides are in the D version, called "D sugars". The arrangement within the D or L form is fixed and they cannot interconvert.

Disaccharides

If two monosaccharides bond together, they form a carbohydrate called a **disaccharide**. Two monosaccharides will bond together through a dehydration reaction, in which a water molecule is lost. A dehydration reaction is a **condensation reaction**, a chemical reaction in which two molecules combine to form one single molecule, losing a small molecule in the process. In the dehydration reaction, this small molecule is water. The bond between two monosaccharides is known as a **glycosidic bond**.

An example of a disaccharide is sucrose (table sugar), which consists of the monosaccharides glucose and fructose (see figure below). Other common disaccharides include lactose ("milk sugar") and maltose. Monosaccharides and disaccharides are also called *simple sugars*. They provide the major source of energy to living cells.

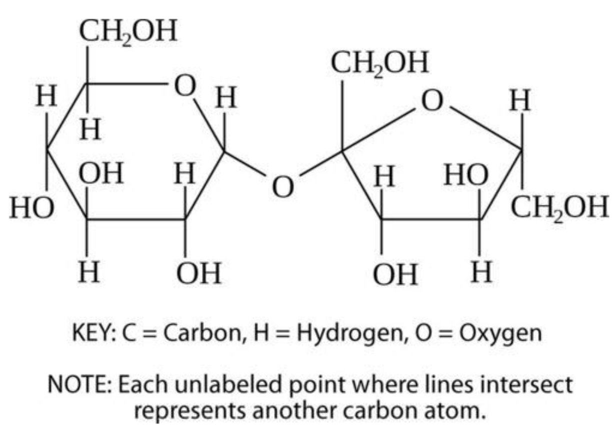
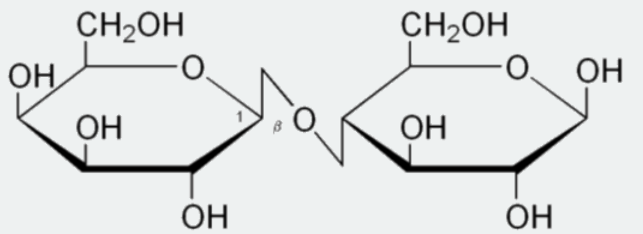


Figure 5.2.6: Sucrose molecule. This sucrose molecule is a disaccharide. It is made up of two monosaccharides: glucose on the left and fructose on the right.

Got milk?

Milk is one of the basic foods needed for good nutrition, especially for growing children. It contains vitamins and minerals necessary for healthy development. Unfortunately, milk and other dairy products also contain lactose, a carbohydrate that can make some people very ill. Lactose intolerance is a condition in which the lactose in milk cannot be digested well in the small intestine. The undigested lactose then moves into the large intestine where bacteria attack it, forming large amounts of gas. Symptoms of lactose intolerance include bloating, cramps, nausea, and vomiting. Avoidance of foods containing lactose is recommended for people who show signs of lactose intolerance. Since dairy products can provide many vital nutrients, tablets can be taken that provide the needed digestive materials in the small intestine. Lactose-free milk is also readily available.

Lactose



Oligosaccharides

An **oligosaccharide** is a saccharide polymer containing a small number (typically two to ten) of monosaccharides. Oligosaccharides can have many functions; for example, they are commonly found on the plasma membrane of animal cells where they can play a role in cell-cell recognition. In general, they are found attached to compatible amino acid side-chains in proteins or to lipids.

Oligosaccharides are often found as a component of **glycoproteins** or **glycolipids**. They are often used as chemical markers on the outside of cells, often for cell recognition. Oligosaccharides are also responsible for determining blood type.

Blood Type

Carbohydrates attached to red blood cells also determine blood type (see figure below). Of the four blood types, type O has the fewest types of saccharides attached to it while type AB has the most. As a result, type O blood is considered the universal donor because it doesn't have any saccharides present that will appear as foreign when transfused into blood of another type. The reverse is not true. For example, if type A blood is given to a patient with type O blood, it will be rejected by the body because there is an unknown species being introduced to the body. Type A blood cells contain N-acetyl-galactosamine which is not present in type O blood. A person with type O blood would undergo rejection upon receiving type A blood. The Rhesus factor (Rh) in blood also affects donor and acceptor properties but it does not depend on carbohydrates. The Rh factor is determined by the presence (Rh+) or absence (Rh-) of a specific protein on the surface of red blood cells.

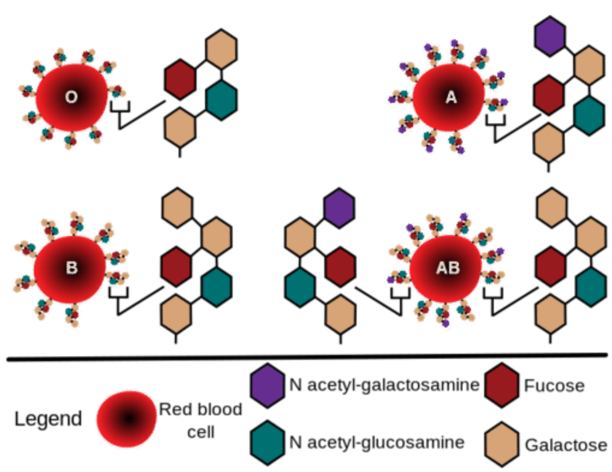


Figure 5.2.7: ABO blood types.

Polysaccharides

Polysaccharides are long carbohydrate molecules of repeated monomer units joined together by glycosidic bonds. A polysaccharide may contain anywhere from a few monosaccharides to several thousand monosaccharides. Polysaccharides are also called **complex carbohydrates**. Polysaccharides have a general formula of $\mathrm{Cx(H_2O)y}$, where x is usually a large number between 200 and 2500.

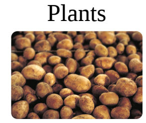
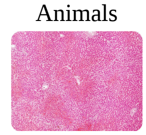
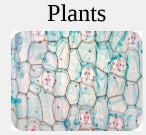
Starches are one of the more common polysaccharides. Starch is made up of a mixture of amylose (15-20%) and amylopectin (80-85%). Amylose consists of a linear chain of several hundred glucose molecules and amylopectin is a branched molecules made of several thousand glucose units. Starches can be digested by **hydrolysis reactions**, catalyzed by enzymes called **amylases**, which can break the glycosidic bonds. Humans and other animals have amylases, so they can digest starches. Potato, rice, wheat, and maize are major sources of starch in the human diet. The formations of starches are the ways that plants store glucose. **Glycogen** is sometimes referred to as *animal starch*. Glycogen is used for long-term energy storage in animal cells. Glycogen is made primarily by the liver and the muscles.

Are we there yet?

As the weather warms up, the runners come out. Not just the casual joggers, but those really serious ones who actually enjoy running all 26.2 miles of a marathon. Prior to these races (and a lot of shorter ones), you hear a lot about carbo-loading. This practice involves eating a lot of starch in the days prior to the race. The starch is converted to glucose, which is normally used for biochemical energy. Excess glucose is stored as glycogen in liver and muscle tissue to be used when needed. If there is a lot of glycogen available, the muscles will have more biochemical energy to draw on when needed for the long run. The rest of us will just sit at the sidewalk restaurant eating our spaghetti and enjoying watching other people work hard.

The main functions of polysaccharides are to store energy and form structural tissues. Examples of several other polysaccharides and their roles are listed in the table below. These complex carbohydrates play important roles in living organisms.

Table 5.2.1: Complex Carbohydrates

Complex Carbohydrate	Function	Organism
Starch	Stores energy	Plants 
Amylose	Stores energy	Plants
Glycogen	Stores energy	Animals 
Cellulose	Forms cell walls	Plants 
Chitin	Forms an exoskeleton	Some animals 

Contributors and Attributions

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- Allison Soult, Ph.D. (Department of Chemistry, University of Kentucky)

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