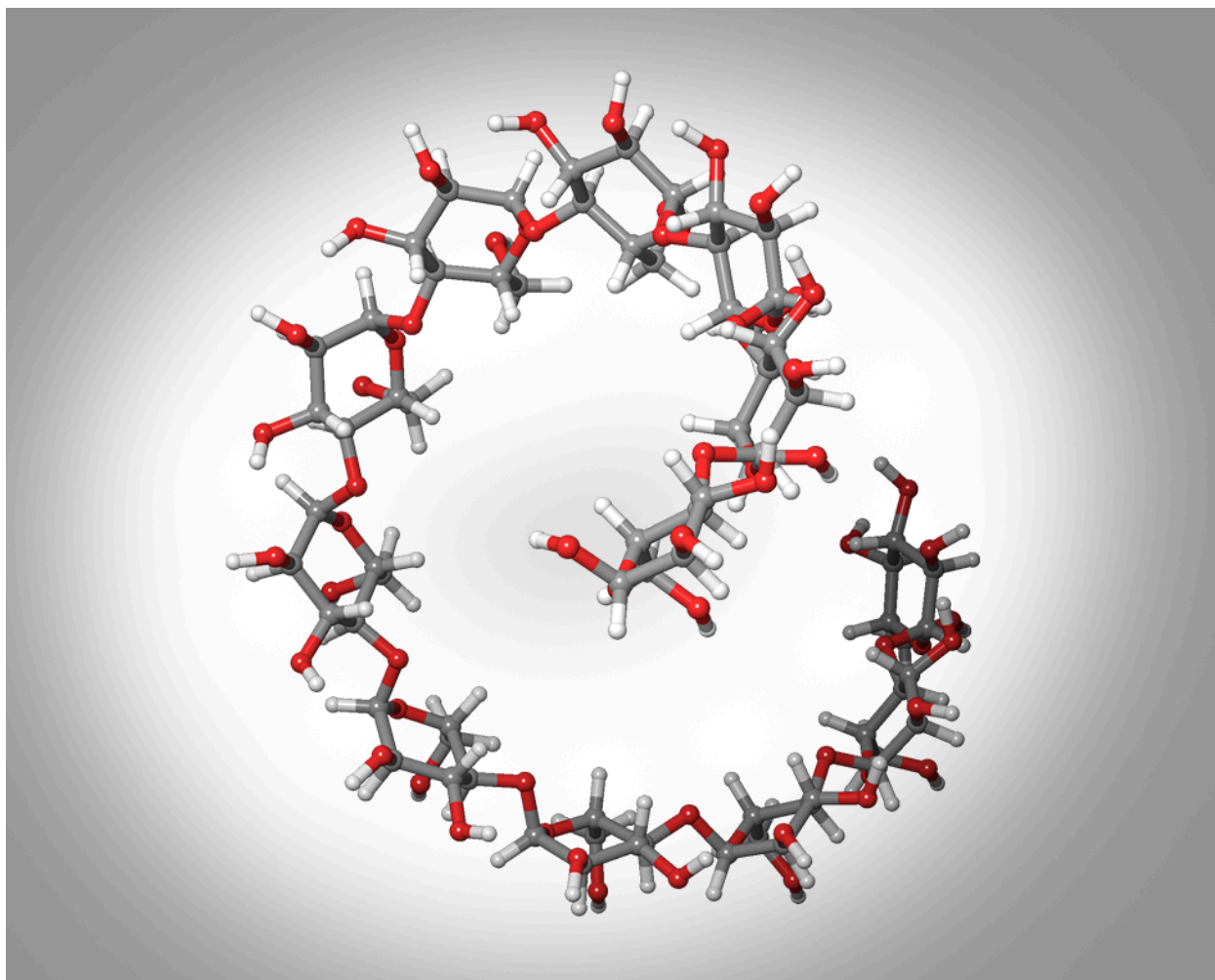


Carbohydrates



Carbohydrates

About this Lesson:

Carbohydrates are one of the most important organic molecules found in living organisms and come in many different forms and sizes. This lesson will introduce the role of carbohydrates in living systems and will cover the carbohydrate taxonomy, including monosaccharides, disaccharides, oligosaccharides, and polysaccharides.

Using Maestro, students will learn how to use the 2D sketcher to build simple carbohydrate molecules, visualize the shapes of simple sugars, and build and compare the structures of cellulose and starch in the Maestro graphical interface.

Learning Objectives:

- Define the term carbohydrate and explain its importance in living organisms
- Describe the carbohydrate taxonomy and identify examples of monosaccharides, disaccharides, and polysaccharides
- Examine simple carbohydrate structures in different 2D and 3D representations
- Build and compare complex carbohydrate structures using the Polymer Builder

Lesson Contents:

1. [Setting Up the Maestro Session](#)
2. [Introduction to Carbohydrates](#)
3. [Carbohydrate Taxonomy](#)
4. [Types and Properties of Polysaccharides](#)
5. [Molecular Visualization of Carbohydrates](#)
6. [Individual Exercise](#)
7. [Summary, Additional Resources, and References](#)
8. [Glossary of Terms](#)

Standards Alignment:

- AAMC MCAT
 - Biological and Biochemical Foundations of Living Systems ([1D](#))
- IBDP Chemistry
 - Biochemistry - Carbohydrates ([B4](#))
- IBDP Biology
 - Carbohydrates and Lipids ([2.3](#))

Assessments for Understanding:

The following types of formative assessments are embedded in this lesson:

- Assessment of student understanding through discussion of warm-up questions and filling in any knowledge gaps about the different types and properties of carbohydrates
- Visual assessment of student-generated simple sugars and complex carbohydrates

Associated Documentation Pages: [Building a Carbohydrate Polymer](#)

Warm-Up Questions:

Read the Khan Academy article on [Carbohydrates](#) and answer the following questions:

1) How does our body get energy from complex carbohydrates?

2) What are the two main functions of polysaccharides?

Need help? Contact us at teaching@schrodinger.com

1. Setting Up the Maestro Session

At the start of the Maestro session, it is essential to 1) check your mouse actions, 2) change the file path to the Working Directory for this lesson, and 3) save your project file. The working directory indicated in this section contains the files necessary to complete this lesson. If you do not set the appropriate working directory, you will be unable to run any calculations.

1. Launch the Virtual Cluster

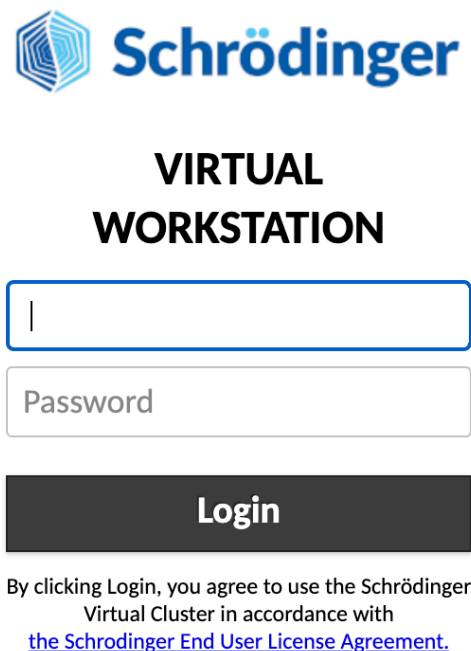
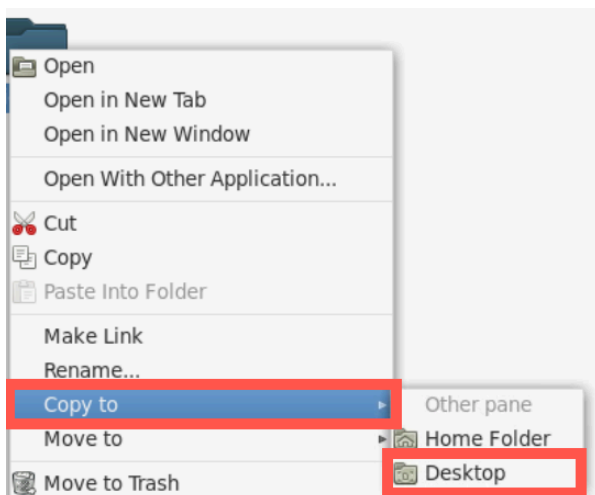


Figure 1-1. Virtual workstation login page.



2. Double-click the **course-data** folder on the desktop

Figure 1-2. Course-data folder on the desktop.



3. Right-click the Carbohydrates folder and select **Copy to > Desktop**

Figure 1-3. Copy the lesson folder to the Desktop.



4. Double-click the Maestro icon on the desktop

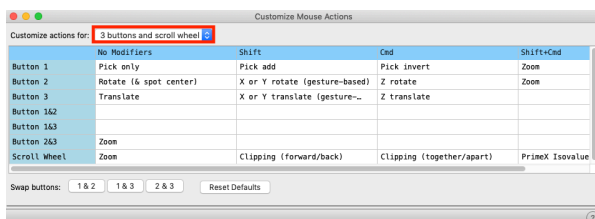
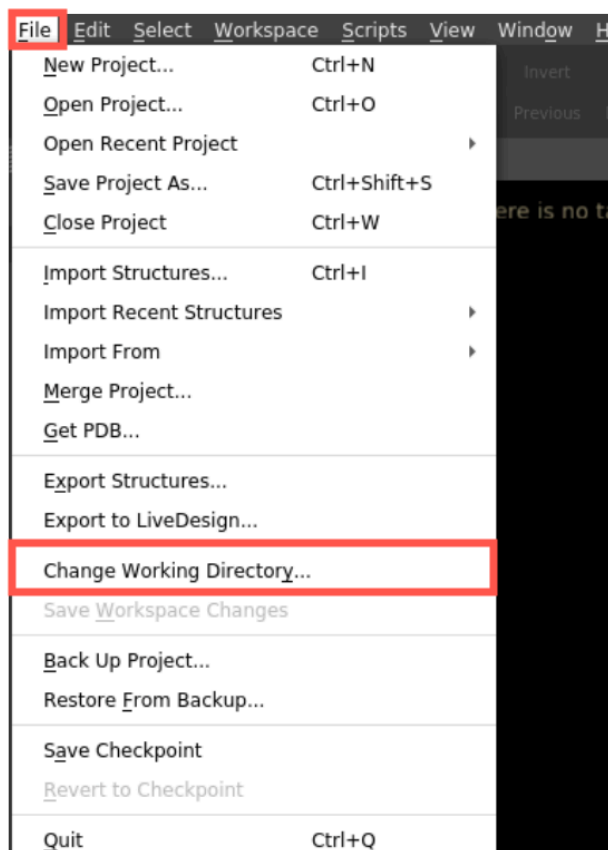


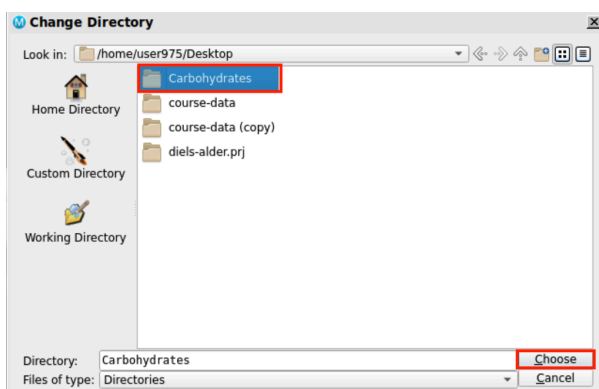
Figure 1-4. Change the mouse actions.

5. Check your mouse actions.
 - o Go to **Workspace > Customize Mouse Actions**
 - o *Note:* This lesson was made with a three-button mouse with a scroll wheel, but a trackpad can still be used
 - o **Trackpad keys:**
 - **Up/Down trackpad** = Zoom In/Out
 - **Option** = Rotate
 - **Control** = Translate



6. Go to File > Change Working Directory

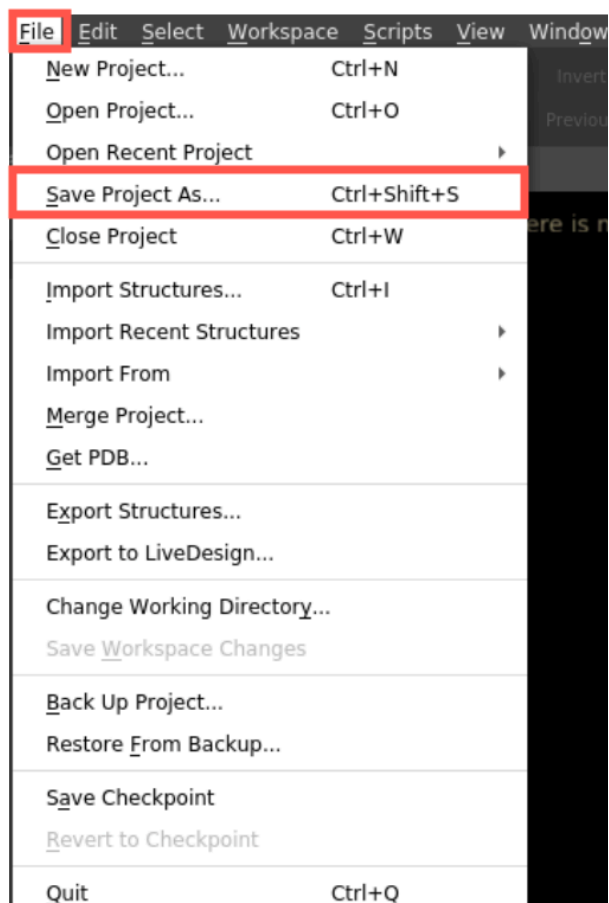
Figure 1-5. Change Working Directory option.



7. Navigate to Desktop > Carbohydrates folder and click **Choose**

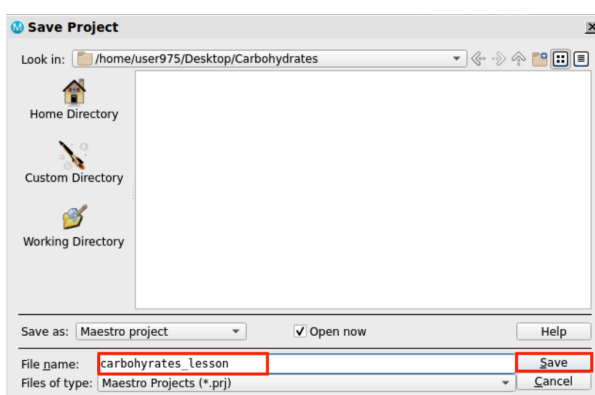
Pre-generated input and results files are included for running jobs or examining output

Figure 1-6. Change Working Directory panel.



8. Go to File > Save Project As

Figure 1-7. Save Project option.



9. Change the *File name* to carbohydrates_lesson, click Save

- The project is now named carbohydrates_lesson.prj

Figure 1-8. Save Project panel.

2. Introduction to Carbohydrates

When you first think of the word carbohydrates, chances are you thought of food! Potatoes, rice, and pasta are all rich sources of carbohydrates and happen to be a part of our daily diet. Along with proteins and fats, carbohydrates are one of three main nutrients found in our food and drinks and they play a vital role in the human body. Carbohydrates provide the body with **glucose**, a source of quick, short-term energy that is used to support various bodily functions and physical activity. Glucose can be used immediately by the body or it can be stored in the liver and muscles for later use.

Let's begin our discussion of carbohydrates by examining the elements from which carbohydrates are built. If we look at the name, carbohydrate, we can break it down to two parts: carbo- and hydrate-. The carbo- part tells us that the element carbon is a main component in the structure of carbohydrates. The hydrate- part means water and originates from the Greek language. Water, as we all know, is composed of hydrogen and oxygen atoms. Hence, carbohydrates are composed of carbon, hydrogen, and oxygen atoms, and are what we call, **biological macromolecules**. While there are many different types of carbohydrates, they all have the generic formula $C_n(H_2O)_n$.

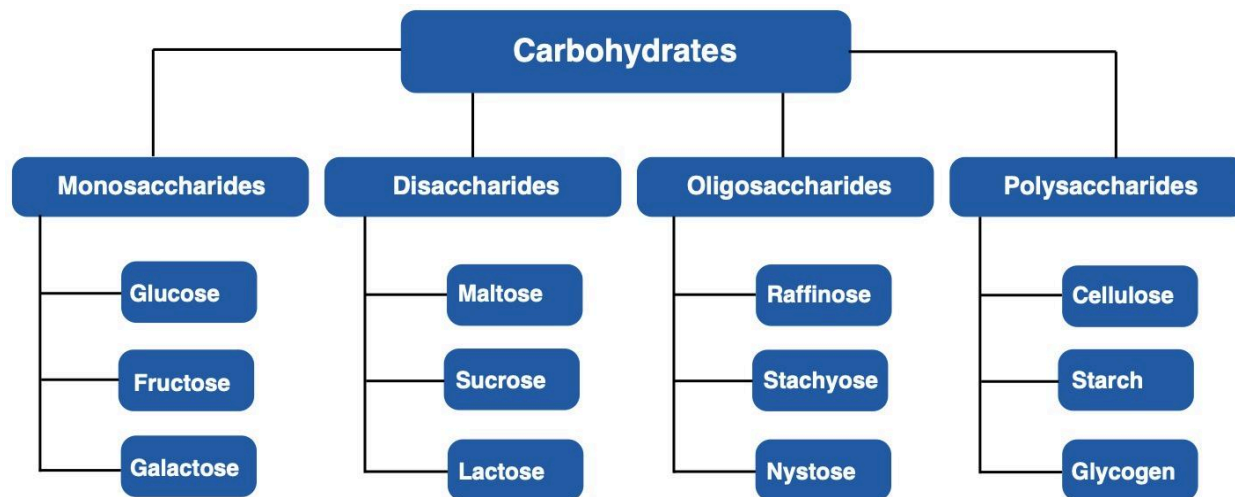


Figure 2-1. Carbohydrate taxonomy chart

3. Carbohydrate Taxonomy

Let's continue our exploration of carbohydrates. As you can see from **Figure 2-1**, carbohydrates exist in many different shapes and sizes. They can exist as simple sugars, such as **monosaccharides** and **disaccharides**, or they can exist in more complex forms, like **oligosaccharides** and **polysaccharides**.

3.1. Monosaccharides

Monosaccharides are carbohydrates composed of one type of sugar. Monosaccharides have a formula of $(\text{CH}_2\text{O})_n$ and typically contain three to seven carbon atoms. Most of the oxygen atoms found in monosaccharides are in hydroxyl (OH) groups, but one of them is part of a carbonyl group (C=O). The position of the carbonyl group can be used to categorize the monosaccharides: if the monosaccharide has an aldehyde group (R-CH=O), the sugar is known as an **aldose**; if the monosaccharide has a ketone (R-C=O-R), the sugar is known as a **ketose**.

Apart from glucose, other monosaccharides include **fructose** and **galactose**. Fructose is the natural sugar found in fruits, while galactose can be found in abundance in dairy products. What's interesting is that glucose, fructose, and galactose are all **isomers**. This means that they all have the same chemical formula, but the way the atoms are arranged in each carbohydrate differ. **Figure 3-1** illustrates the structures of glucose, fructose, and galactose in a side-by-side comparison.

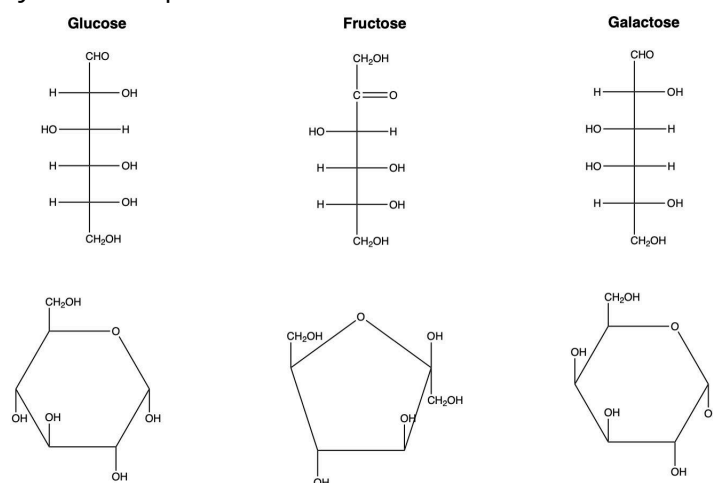


Figure 3-1. Structures of glucose, fructose and galactose



Practice #1. Look closely at **Figure 3-1**. Circle the aldehyde and ketone groups in each carbohydrate. Categorize glucose, fructose, and galactose as an aldose or ketose.

Figure 3-1 does not paint a complete picture. This is because glucose is a monosaccharide that can exist in two main forms: **D-glucose** (or dextrose) and **L-glucose**. D-glucose and L-glucose are **enantiomers**, which means that their molecular structures are mirror images of each other. The key difference is that in D-glucose, three hydroxyl groups and one hydrogen group are on the right side whereas in L-glucose, the three hydroxyl groups and one hydrogen group are on the left side.



Practice #2. Is the glucose structure in **Figure 3-1** in D- form or L-form?

Unlike L-glucose, D-glucose occurs more widely in nature and is thus one of the most important aldohexose sugars found in living organisms. D-glucose contains two further isomers: **alpha-D-glucose** and **beta-D-glucose**. The key difference between alpha (α) and beta (β) D-glucose is the orientation of the hydroxyl groups attached to the first and fourth carbon atoms. Alpha-D-glucose has hydroxyl groups in the 1 and 4 positions on the same side. Beta-D-glucose has hydroxyl groups in the 1 and 4 positions on opposite sides. **Figure 3-2** demonstrates this configuration.

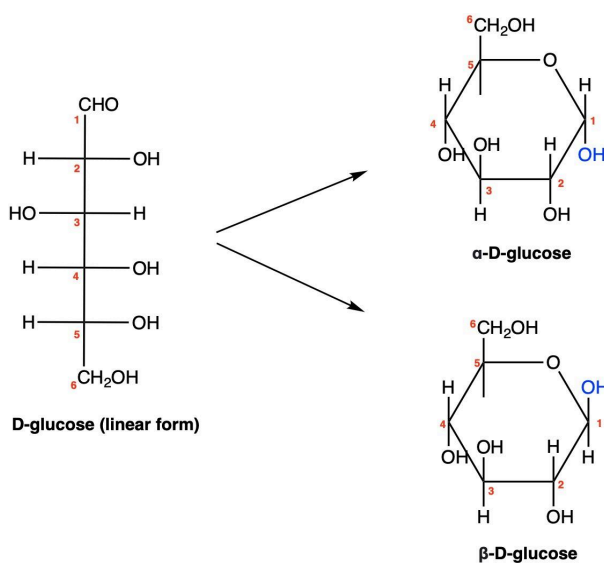


Figure 3. Molecular structures of alpha-D-glucose and beta-D-glucose

3.2. Disaccharides

A disaccharide is a carbohydrate formed when two monosaccharides are joined together via a condensation reaction (also known as a dehydration reaction). In this process, the hydroxyl group of one monosaccharide combines with the hydrogen of another, releasing a water molecule in the process and forming a covalent bond called a **glycosidic linkage**. The reaction that takes place between two monosaccharides is demonstrated in **Figure 3-3**.

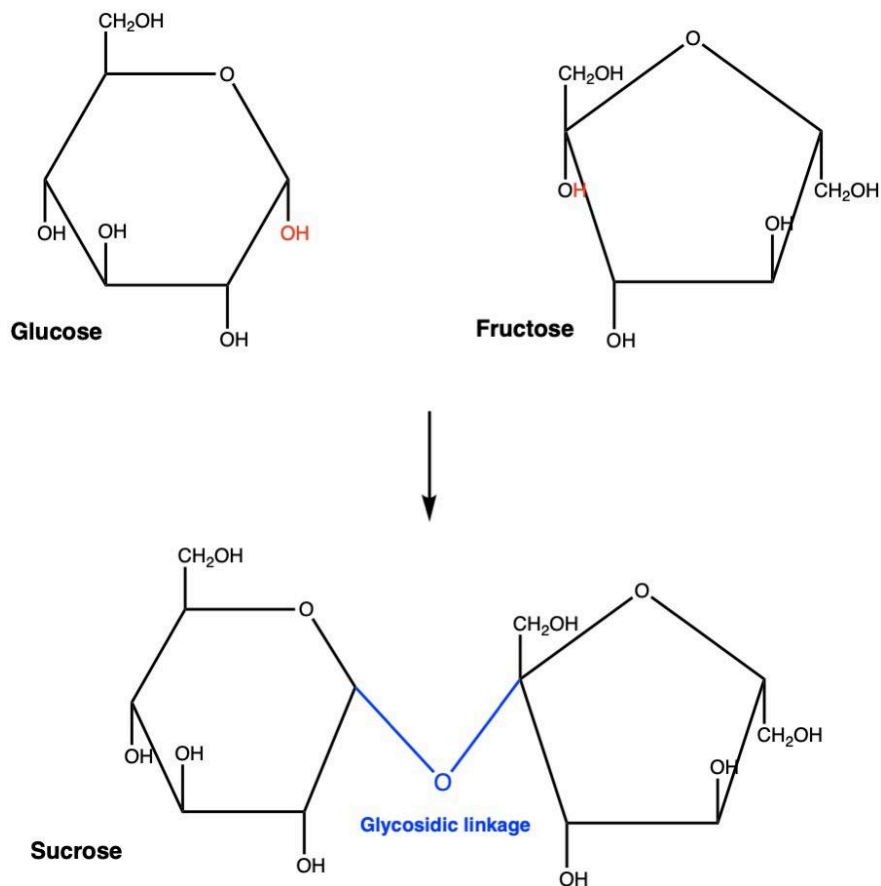


Figure 3-3. Condensation reaction between glucose and fructose to form sucrose.

3.3. Oligosaccharides

Oligosaccharides and polysaccharides are both made up of monosaccharides. The main difference between the two is that **oligosaccharides** are made out of a fewer number of monosaccharides whereas **polysaccharides** are made out of a larger number of monosaccharides. A number of oligosaccharides can also form multiple linkages to produce a polysaccharide. **Cellulose**, **starch**, and **glycogen** are well-known examples of polysaccharides. These complex macromolecules are an important source of energy in animal cells, and form a structural component of a plant cell.

Polysaccharides can either be a straight chain of monosaccharides known as **linear polysaccharides**, or they can also form branches known as a **branched polysaccharide**. **Figure 3-4** depicts the structures of cellulose, amylose, amylopectin, and glycogen.

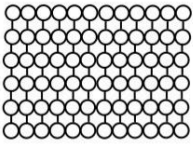
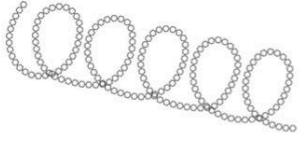
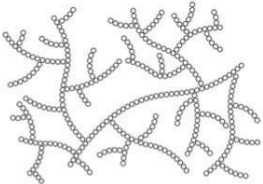
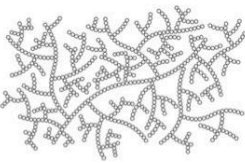
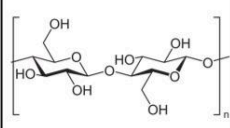
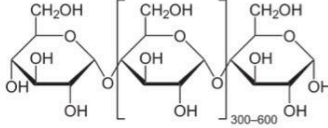
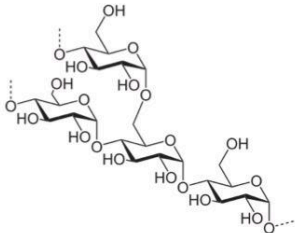
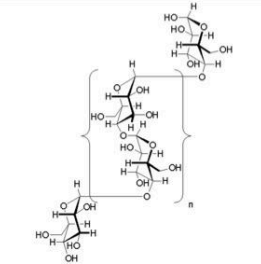
	Cellulose	Starch		Glycogen
		Amylose	Amylopectin	
Shape				
Structure				

Figure 3-4. Shape and structure of different types of polysaccharides.

Practice #3. Take a close examination at **Figure 3-4**. Which polysaccharide(s) would you categorize as linear? Which one(s) would you categorize as branched?

4. Types and Properties of Polysaccharides

In Section 3, we examined the carbohydrate taxonomy and dived deep into examples from each taxonomic group. We also learned that polysaccharides are an important source of energy and structure for animal and plant cells, and we looked at three main examples: cellulose, starch, and glycogen.

4.1. Types of polysaccharides

Each of the polysaccharides mentioned above are composed of glucose subunits, and can be referred to as **homopolysaccharides**. A homopolysaccharide is a polysaccharide composed of only one type of monosaccharide. A **heteropolysaccharide** on the other hand, is a polysaccharide composed of different types of monosaccharides. One example is **hyaluronic acid**, which is made up of the monosaccharides D-glucuronic acid and N-acetyl-glucosamine, and is a natural substance found in our connective tissues and skin. Hyaluronic acid is also a **glycosaminoglycan** (or GAG), a negatively charged polysaccharide that is made up of repeating disaccharide units. The structure of hyaluronic acid is displayed in **Figure 4-1**.

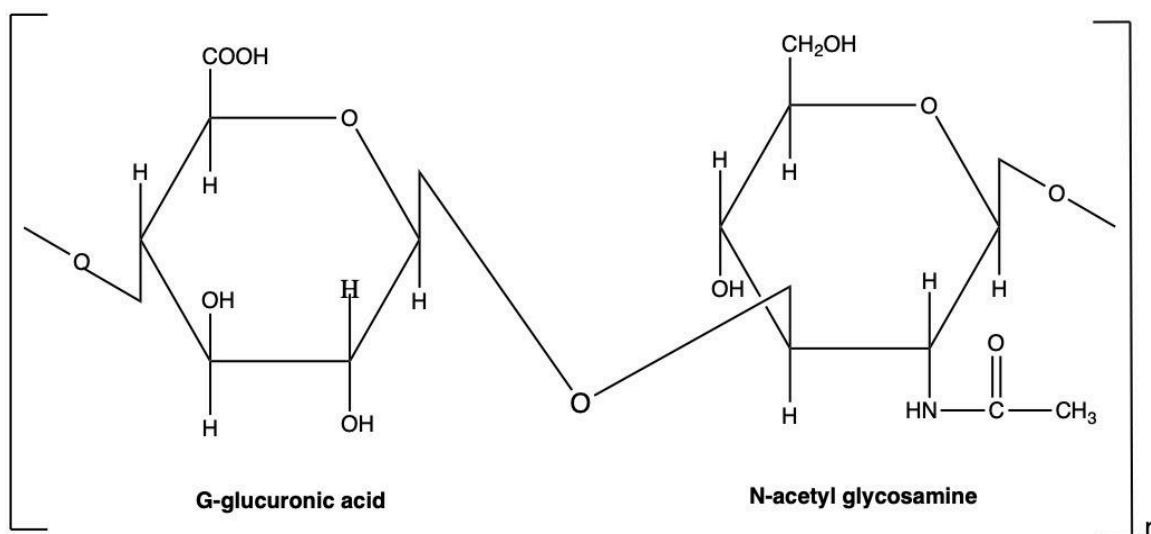


Figure 4-1. The repeating disaccharide unit of hyaluronic acid.



Practice #4. Recall from Section 2 that all carbohydrates are made up of carbon, hydrogen, and oxygen atoms. From **Figure 4-1**, what do you notice that is different about the structure of N-acetyl glucosamine? Elaborate below.

4.2. Properties of polysaccharides

Polysaccharides, as you already know, are macromolecules composed of a large number of monosaccharides. They thus have a **high molecular weight**. The molecular weight of polysaccharides can reach as high as 100,000 daltons or more if enough monosaccharides are joined together. This makes polysaccharides very large, complex molecules that are **hydrophobic** and unable to diffuse through cell membranes. They can pass through membranes only when broken down into their component monomers, i.e. simple sugars. Similarly, polysaccharides are also not sweet in taste. However, enzymes such as amylase can break down polysaccharides like amylose, into their glucose subunits, which do in fact taste sweet.

5. Molecular Visualization of Carbohydrates

In this activity, you will learn how to build simple monosaccharide units in Maestro, as well as compare the structures of two different polysaccharides using the graphical user interface.

Computational Exercise #1: Building carbohydrate biopolymers

This exercise involves three parts:

- 1) Build a D-glucose molecule using the 2D sketcher
- 2) Translate the 3D glucose structure to a 2D Fischer projection
- 3) Build and compare the structures of cellulose and amylose

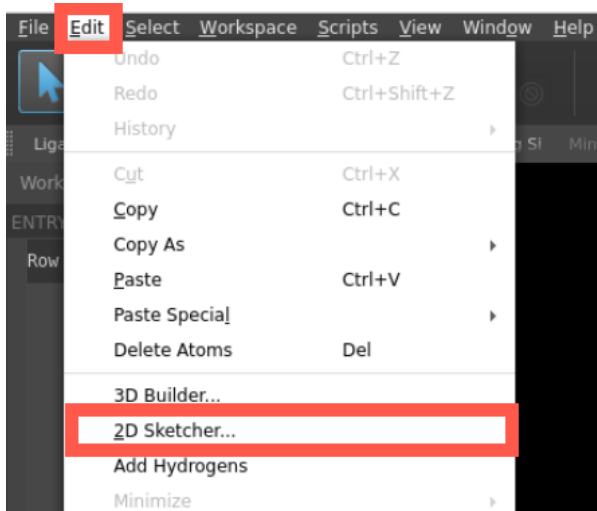


Figure 5-1. Open 2D Sketcher.

Part 1. Building D-glucose

In Part 1, you will learn how to draw a 'zigzag' structure of D-glucose using the 2D sketcher. A zigzag structure (or Natta projection) is a way of representing three-dimensional molecules in which the carbon skeleton is drawn in a continuous "w" shape (hence the name zigzag structure), and the stereochemistry at each carbon is denoted with wedges and dashes.

Learn More: Take a look at our lesson on [Stereoisomers](#) to learn more about the three-dimensional, spatial arrangement of atoms and molecules!

1. Go to Edit > 2D Sketcher. If any existing structures are still in the 2D Sketcher workspace, use the eraser to delete the structure.

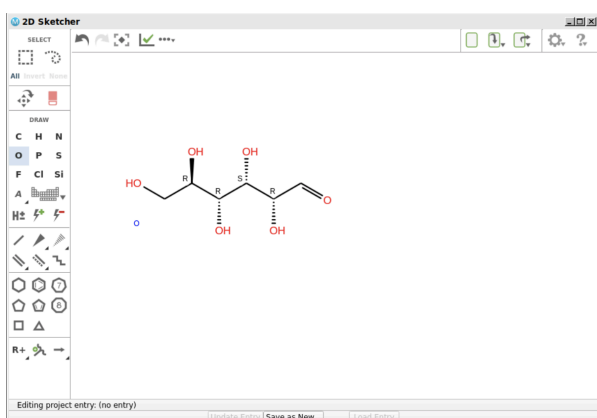


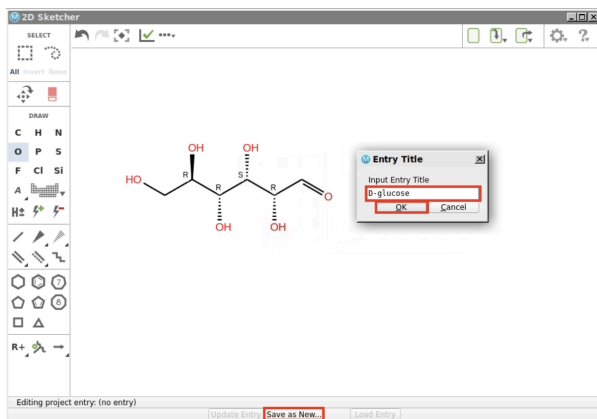
Figure 5-2. Drawing D-glucose.

2. **Draw** the zigzag structure of D-glucose exactly how it is shown in Figure 5-2
 - o Go to the Draw Tools on the left
 - o Create the carbon skeleton by choosing the C atom and clicking in the 2D workspace.
 - o A methyl group appears

- Drag rightwards from the methyl group to draw a carbon skeleton consisting of seven bond lines
- Add an OH group to the leftmost tail end of the skeleton by selecting the O atom from Draw Tools and clicking on the end of the bond line
- Add an aldehyde group to the rightmost tail end of the skeleton by changing the last bond line to a double bond and adding an O atom to the end of the bond line
- Create a wedge bond on the second carbon from the left by choosing the wedge bond and dragging up from the carbon atom
- Add an OH group to the wedge by selecting the O atom from Draw Tools and clicking on the end of the wedge bond
- Create a dashed bond on the third carbon atom from the left by choosing the dashed bond and dragging down from the carbon atom
- Add an OH group to the dashed bond by selecting the

O atom from Draw Tools and clicking on the end of the dashed bond

- Repeat the steps for creating a dashed bond with an OH group for carbon atoms 4 and 5 as shown in Figure 5-2



3. Click on **Save as New** and for **Input Entry Title** write **D-glucose**.
4. Click **OK**.

Figure 5-3. Saving D-glucose.



Pause & Think #1: How many chiral carbons does a D-glucose molecule have? Identify the positions of each chiral carbon and list them below.



Pause & Think #2: Take a screenshot of your D-glucose structure in the 3D workspace and paste it below. What do you notice about the directions of each OH group?



Pause & Think #3: Based on your observation in Question 2, what conclusions can you draw about wedged and dashed bonds

Part 2. Translating a 3D structure to a 2D Fischer projection

Sugars can be drawn in the straight chain form as either Fischer projections or as zigzag formulas that organic chemists often prefer. When drawing Fischer projections, the aldehyde group is written at the top, and the H and OH groups that are attached to each chiral carbon are written to the right or left. The arrangement of the atoms distinguishes one stereoisomer from the other.



Pause & Think #4: Using the 3D structure of D-glucose you generated using the 2D sketcher and 3D workspace, sketch a Fischer projection of the same molecule in the space below.



Question #5: What is one advantage of Fischer projections over zigzag structures of organic molecules?

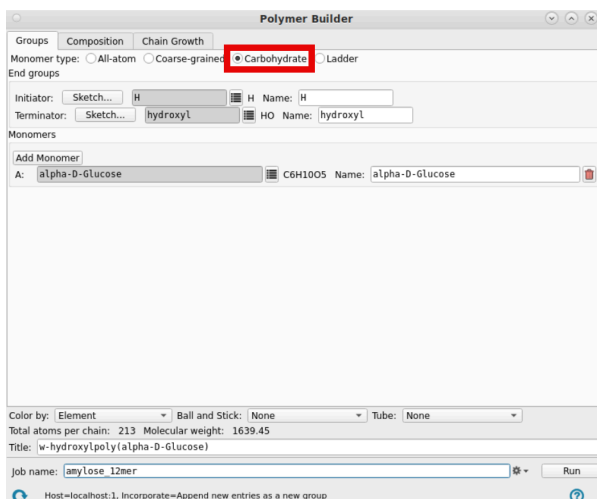


Figure 5-4. Polymer Builder panel with the Carbohydrate default parameters.

Part 3. Build and compare the structures of cellulose and amylose

5. Go to **Tasks > Structure Builders > Polymer**
6. For *Monomer type* select **Carbohydrate**
 - The panel updates to the specialized carbohydrate parameters
7. Leave *End Groups* as the default: H
8. For amylose, leave alpha-D-Glucose as monomer A, which again is the default.
9. Go to the **Composition** tab

Note: Hydroxyl is also available as an end group selection, if needed. To see which end of the monomer is the head versus the tail, hover over the molecular formula and the 2D Sketch will appear with R1 and R2 labeled for head and tail, respectively

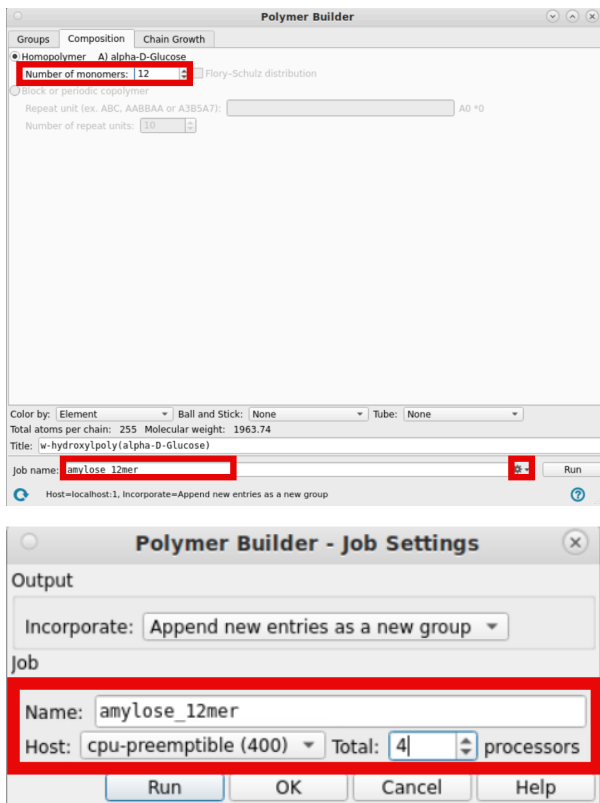



Figure 5-5. Composition tab and running the job.

10. In the *Composition* tab, set the number of monomers to **12**
 - We will construct a 12mer
 - The *Total atoms per chain:* and *Molecular weight:* update accordingly

We do not need to change anything in the Chain Growth tab.

11. Change the *Job name:* to **amylose_12mer**
12. Adjust the job settings ()
 - Host: **cpu-preemptible (400)**
 - Total: **4 processors**
13. Click **Run**
 - The job should be completed within a few minutes.

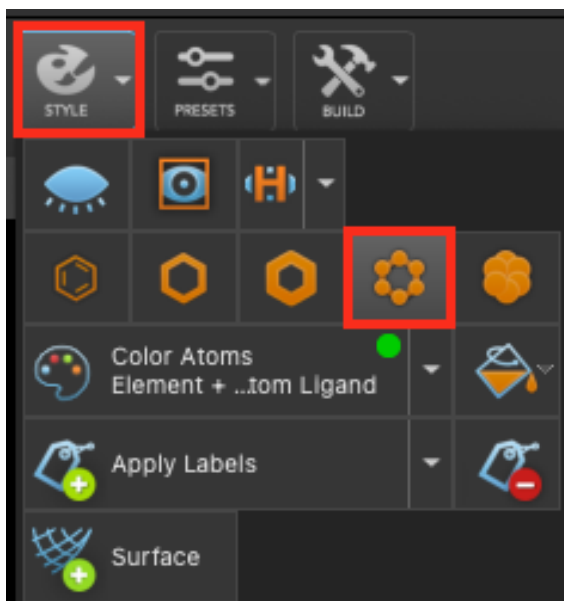


Figure 5-6. Updating the style to ball-and-stick.

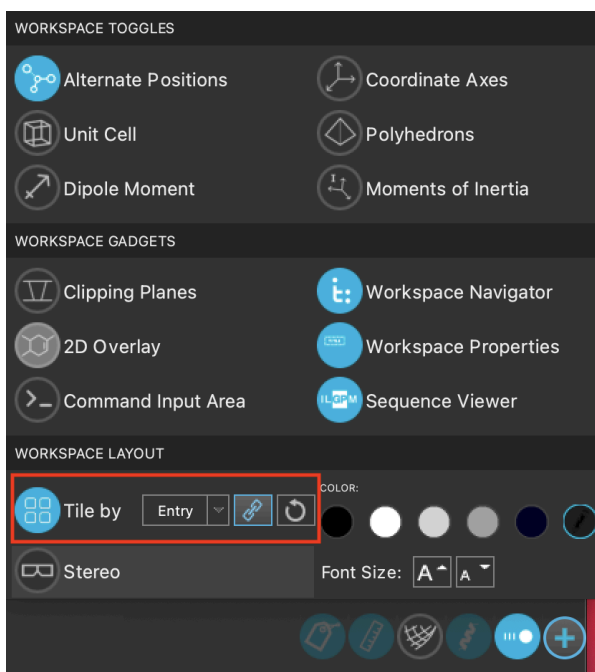


Figure 5-7. Selecting Tile view.

14. Once the job is incorporated, include poly(alpha-D-Glucose) in the workspace
15. Go to the **Style** dropdown and select **Apply ball-and-stick representation**
16. For cellulose, repeat steps 1 to 10 using the monomer beta-D-Glucose instead
17. Change the *Job name*: to **cellulose_12mer**
 - o The job should be completed within a few minutes.
18. **Close** the Polymer Builder panel
19. Once both jobs are incorporated, include poly(alpha-D-Glucose) and poly(beta-D-glucose) in the workspace
20. Go to the plus icon in the bottom right corner of the Maestro interface and select Tile view
21. Play around with your mouse and scroll wheel to zoom in/out into the structures.



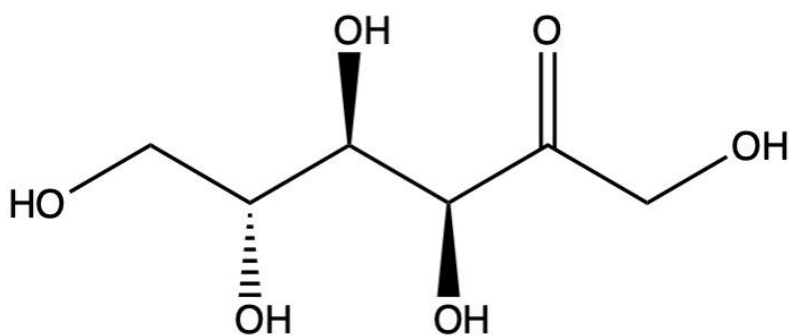
Pause & Think #6: Take a screenshot of your poly(alpha-D-Glucose) and poly(beta-D-Glucose) structures side-by-side in the tile view. Paste your screenshot in the table below. What similarities and differences do you observe between the two polymers? Note them down in the table below.

Amylose and cellulose side-by-side screenshot:	
Similarities	Differences

6. Individual Exercise

Recall from Section 3.1 of this lesson that apart from glucose, **fructose** is also another well-known monosaccharide and is the natural sugar found in fruits. Fructose has the same chemical formula as glucose, but the way the atoms are arranged in each carbohydrate molecule differ.

- 1) Repeat **steps 1- 4** of Part 1 of the computational exercise for a **D-fructose** molecule instead. The zigzag structure of D-fructose is given below.



- 2) Take a screenshot of your D-fructose molecule in the 3D workspace and paste it below.

- 3) Take a screenshot of your D-fructose and D-glucose structures side-by-side in the tile view. Paste your screenshot in the table below. What similarities and differences do you observe between the two monomers?

D-fructose and D-glucose side-by-side screenshot:	
Similarities	Differences

- 1) Draw a Fischer projection of a D-fructose molecule.

7. Summary, Additional Resources, and References

In this lesson, students learned how to use the 2D Sketcher and Polymer Builder to construct simple and complex carbohydrates, as well as translate the 3D structures to 2D representations. Using Maestro, students were able to interact with the carbohydrate polymers using the graphical user interface to zoom in/out, as well as compare and contrast each structure using Tile view.

For further learning:

- [Introduction to Computational Chemistry, 3rd Edition](#)
- [Essentials of Computational Chemistry: Theories and Models, 2nd Edition](#)
- See the Build Biopolymer help [documentation](#)

8. Glossary of Terms

Entry List - a simplified view of the Project Table that allows you to perform basic operations such as selection and inclusion

Included - the entry is represented in the Workspace, the circle in the In column is blue

Project Table - displays the contents of a project and is also an interface for performing operations on selected entries, viewing properties, and organizing structures and data

Recent actions - This is a list of your recent actions, which you can use to reopen a panel, displayed below the Browse row. (Right-click to delete.)

Scratch Project - a temporary project in which work is not saved. Closing a scratch project removes all current work and begins a new scratch project

Selected - (1) the atoms are chosen in the Workspace. These atoms are referred to as "the selection" or "the atom selection". Workspace operations are performed on the selected atoms. (2) The entry is chosen in the Entry List (and Project Table) and the row for the entry is highlighted. Project operations are performed on all selected entries

Working Directory - the location that files are saved

Workspace - the 3D display area in the center of the main window, where molecular structures are displayed

Biological macromolecule - a large, organic molecule such as carbohydrates, lipids, proteins, and nucleic acids

Monosaccharide - a carbohydrate composed of one type of sugar

Disaccharide - a carbohydrate formed when two monosaccharides are joined together via a condensation reaction

Polysaccharide - a carbohydrate composed of a large number of monosaccharides

Glycosidic linkage - a type of covalent bond that joins a carbohydrate molecule to another group, which may or may not be another carbohydrate