Carbohydrates and Lipids

Although carbohydrates and lipids can be quite large, they are relatively simple biochemical molecules. They are composed mostly of carbon, hydrogen, and oxygen, arranged in a variety of configurations. Although simple in structure, however, they perform many complex functions in cells. Carbohydrates and lipids are best known for their role as energy sources in the body, yet they are much more than this (**Figure 1**). Carbohydrates play a role in structural support and cell-to-cell communication. They are the raw material that is used to build other important molecules, such as amino acids, lipids, and nucleic acids. Lipids also play an important structural role in cells—all biological membranes are composed of lipid molecules. As well, hormones, certain vitamins, and defence mechanisms are based on lipids. Lipids provide insulation for nerve cells and have waterproofing qualities. The functional groups on carbohydrates and lipids influence their properties and functions.

CAREER LINK

Figure 1 Bees produce honey, a carbohydrate, and store it in hives constructed from waxes, a type of lipid.

Carbohydrates

Carbohydrates, or simple and complex sugar molecules, are among the most common biological molecules on Earth. The term "carbohydrate" comes from the terms *carbo*, meaning carbon, and *hydrate*, meaning water. In photosynthesizing plants and other photosynthesizing organisms, carbon dioxide and water molecules are used as raw materials to build carbohydrates. Plants and algae produce millions of tonnes of carbohydrates each year. These and other organisms use carbohydrates as an energy source, as a building material, and for cell communication. Carbohydrates are in the foods you eat, including fruits, vegetables, and grains. Nutritionists study the composition of food and determine the amounts of carbohydrates that are present in the different foods we eat. CAREER LINK

carbohydrate a biomolecule that consists of carbon, oxygen, and hydrogen

Monosaccharides

The simplest type of carbohydrate is called a **monosaccharide**, because it contains a single sugar. Monosaccharides generally have a combination of carbon, hydrogen, and oxygen atoms in the ratio of 1 carbon : 2 hydrogen : 1 oxygen. This is represented by the chemical formula $(CH_2O)_n$, or its derivative $C_nH_{2n}O_n$, where n is the number of carbon atoms. Carbohydrates appear either as monosaccharides or as two or more monosaccharide units linked together. Glucose is perhaps the most widely used monosaccharide. Plants produce glucose during photosynthesis, and it provides energy for countless functions in both plants and animals.

monosaccharide the simplest form of carbohydrate, consisting of a single sugar unit; a building block for more complex carbohydrates

Monosaccharides that contain three carbons (triose), five carbons (pentose), and six carbons (hexose) are the most common in living organisms (**Figure 2(a)**, next page). Although all monosaccharides can occur in a linear form, when formed in water, monosaccharides with five or more carbon atoms fold back on themselves to form a ring. Folding into a ring occurs through a reaction between two functional groups in the same monosaccharide. This can be seen in the monosaccharide glucose, when the carbonyl group interacts with a hydroxyl group to form a ring (**Figure 2(b)**, next page). Carbon atoms in the glucose molecule have numbers assigned to them. Scientists use these numbers when discussing the structures of sugars.

When glucose forms a ring, there are two possible arrangements of the –OH group, which is bound to the carbon at position 1: α-glucose and β-glucose (**Figure 2(c)**, next page). These two different forms of glucose are isomers. An **isomer** is a molecule that has the same chemical formula as another, but a different arrangement of the atoms. The different arrangements of the –OH group on glucose can give chemicals different properties. For example, humans can easily digest starches composed of α-glucose. However, cellulose, assembled from β-glucose, is completely indigestible for humans. Glucose, fructose, and galactose are isomers of each other.

isomer a molecule that has the same composition as another, but a different arrangement of atoms

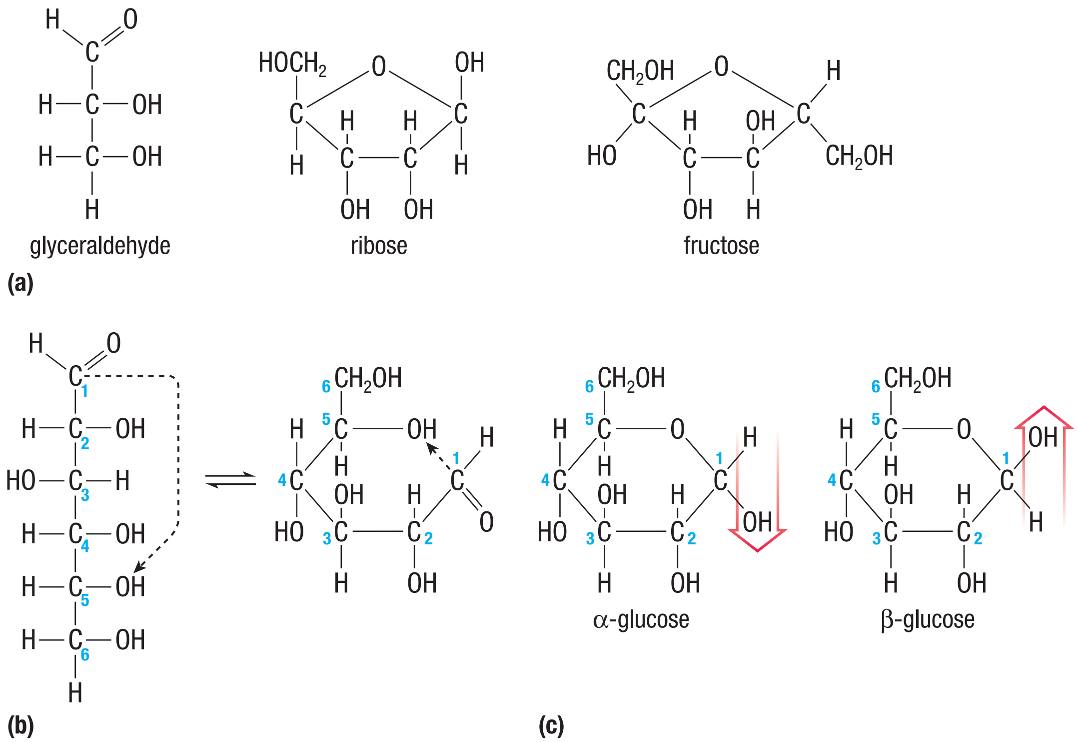

Figure 2 Common monosaccharides are (a) glyceraldehyde, ribose sugar, and fructose sugar. (b) Glucose forms a ring structure due to the interaction of two of its functional groups. (c) There are two possible arrangements of the —OH group on carbon 1 in glucose: α-glucose and β-glucose.

Sugars typically have many polar functional groups attached to them. This makes them very hydrophilic and means that small sugars are highly soluble in water. The sweet taste that is associated with carbohydrates requires them to be dissolved in water. Monosaccharides are the sweetest. As the number of monosaccharide units that are linked together increases, the sweetness decreases.

Disaccharides

disaccharide a carbohydrate molecule that is made from two monosaccharide units

glycosidic bond a bond between two monosaccharides

Disaccharides consist of two monosaccharides that are joined together by a dehydration synthesis reaction (Section 1.3). For example, the disaccharide maltose forms through the linkage of two α-glucose molecules, with oxygen as a bridge between the 1-carbon of one glucose unit and the 4-carbon of the second glucose unit (**Figure 3(a)**, next page). Bonds of this type, which link monosaccharides into larger carbohydrates, are called **glycosidic bonds.** A glycosidic bond forms between α-glucose and fructose monosaccharide, resulting in the disaccharide sucrose (**Figure 3(b)**, next page). Lactose, the disaccharide milk sugar, forms when galactose and β-glucose bond together (**Figure 3(c)**, next page). The chemical shorthand for representing a glycosidic bond between a 1-carbon and a 4-carbon is 1→ 4. Other linkages, such as 1→ 2, 1→ 3, and 1→ 6, are also common in carbohydrate chains. Linkages are designated as α or β, depending on the orientation of the —OH group bonded to the 1-carbon. The linkage in maltose and sucrose is an α-linkage, but the linkage in lactose is a β-linkage.

Disaccharide carbohydrate molecules contain the same functional groups that make monosaccharides hydrophilic. Therefore, they are easily dissolved in water. Maple syrup, produced from the sap of maple trees, consists mostly of sucrose molecules dissolved in water (**Figure 4**). Maple syrup is a sugar source that was first used by Aboriginal people. In the spring, they collected maple sap and boiled it into syrup. Using the knowledge obtained from the Aboriginal people, European settlers learned to use maple syrup as a sweetener. Québec is now the world's largest producer of maple syrup. Other major sources of sucrose (table sugar) are sugar cane and sugar beets.

Figure 4 Sap from a sugar maple tree consists of sucrose molecules dissolved in water.

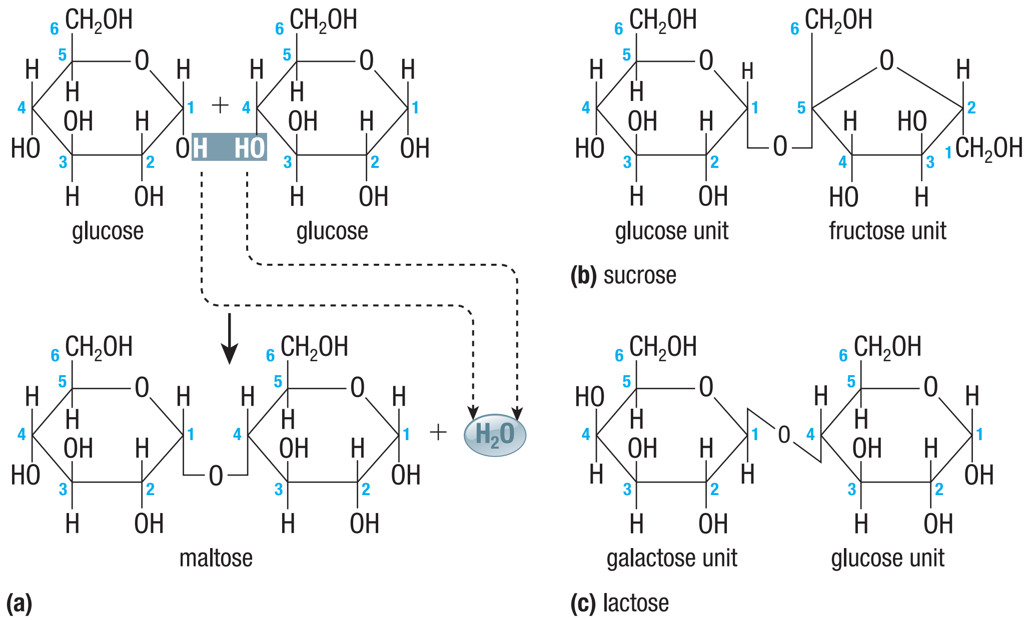

Figure 3 (a) A glycosidic bond between the 1-carbon and 4-carbon atoms of two glucose molecules creates maltose. (b) Sucrose has an α-linkage. (c) Lactose has a β-linkage.

Complex Carbohydrates: Polysaccharides

Hundreds to thousands of monosaccharides can link together to form a **complex carbohydrate**. Some complex carbohydrates are important for energy storage in cells, while others are essential for structural support. Starch and glycogen are examples of storage carbohydrates, and cellulose and chitin are examples of structural complex carbohydrates.

complex carbohydrate a molecule that is composed of hundreds to thousands of monosaccharides linked together; an essential part of nutrition and a valuable energy source

POLYSACCHARIDES

A **polysaccharide molecule** is a chain of monosaccharides with many subunits joined by glycosidic linkages (**Figure 5**, next page). A polysaccharide is a macromolecule, which is a very large molecule assembled by the covalent linkage of smaller subunit molecules. The dehydration synthesis reactions that assemble polysaccharides are examples of polymerization. **Polymerization** is the process in which identical or variable subunits, called **monomers**, link together in a long chain to form a larger molecule. This molecule is called a **polymer**, hence the term "polymerization." The linkage of non-identical subunits creates highly diverse and varied biological molecules. Many kinds of polymers are found in cells, not just polysaccharides. For example, DNA is another type of polymer.

polysaccharide molecule a molecule that contains many linked monosaccharides

polymerization a process in which small subunits are linked to form a large molecule

monomer a small molecule that can bind chemically to other molecules

polymer a large molecule that is formed when monomers link together chemically in a chain

The most common polysaccharides are plant starches, glycogen, and cellulose. They assemble from hundreds or thousands of glucose units. Cellulose is the main component of plant cell walls and the most abundant organic molecule on Earth. Cellulose molecules are long and straight and have very large numbers of polar OH groups. These two features enable many cellulose molecules to assemble side by side and form hundreds or thousands of hydrogen bonds. These numerous hydrogen bonds are what give cellulose fibres their great strength. Other polysaccharides form from a variety of different sugar monomers. Polysaccharides may be linear unbranched molecules, or they may contain branches in which side chains of sugar units attach to a main chain.

Polysaccharides are very polar and therefore very hydrophilic. However, since polysaccharides are such huge molecules, they attract water but cannot dissolve. This is the principle behind absorbent paper towels. Paper towels are made of cellulose, a long fibrous polysaccharide. Paper towels attract water, but they do not dissolve in the water. If they did, they would not be useful for cleaning up spills. **Table 1** (page 33) is a summary of the different types of carbohydrate molecules.

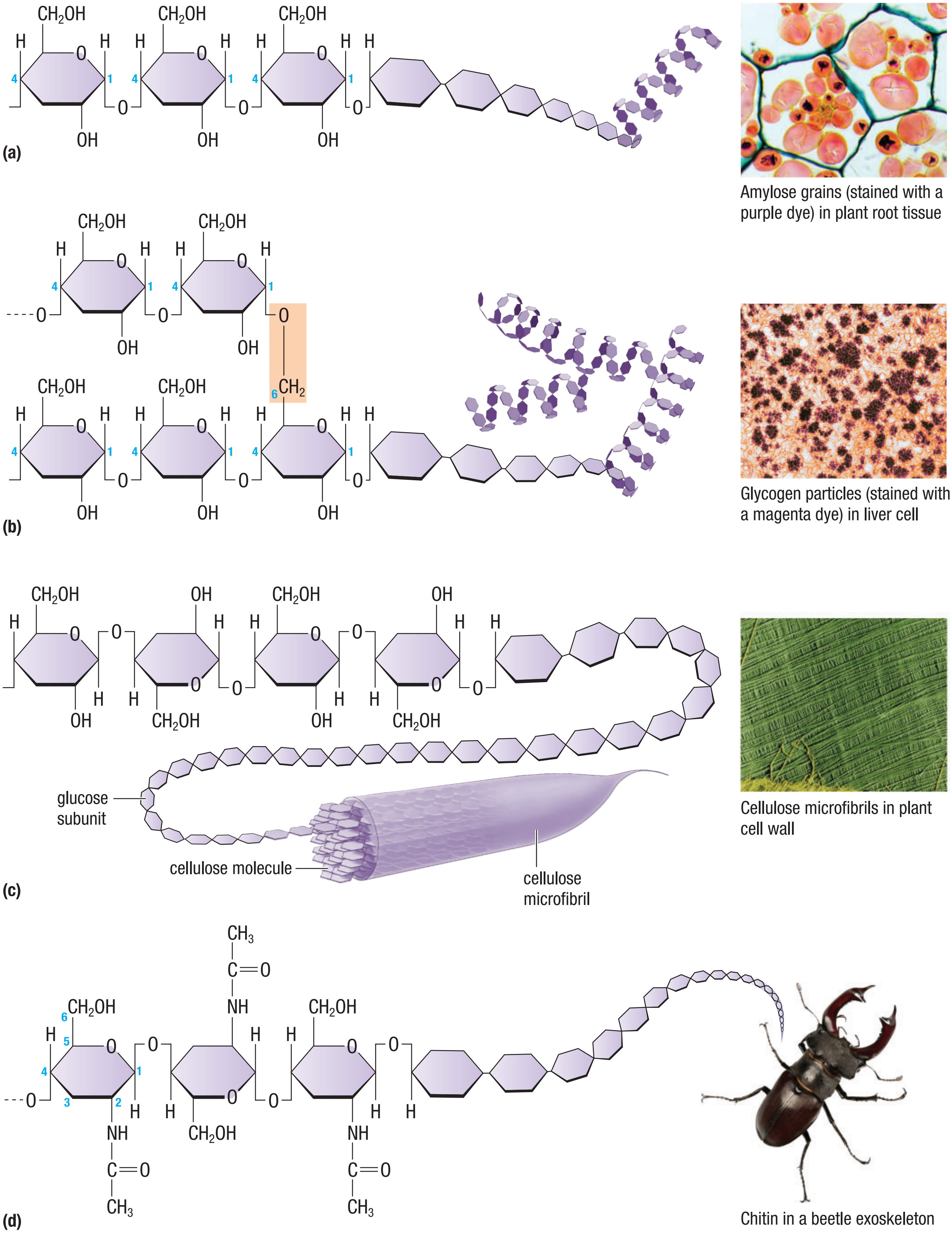

Figure 5 Examples of polysaccharides and their structure. (a) Amylose is the soluble component of starch. (b) Glycogen is used for energy storage in animals. (c) Cellulose is the main component of plant cell walls. It is the most abundant organic molecule on Earth. (d) Chitin is used by insects and crustaceans to produce hard exoskeleton. It is also a component of fungal cell walls. Chitin is one of the few carbohydrates that contain functional groups with nitrogen atoms.

Table 1 Structures and Functions of Carbohydrates

Type	Structure	Function	Example
monosaccharide	chain, α-ring, or β-ring	energy source, building blocks	glucose, ribose, and deoxyribose
disaccharide	two monomer subunits, with α or β linkage	energy source	sucrose, maltose, and lactose
polysaccharide	very long chain or branching chain with α or β linkages	energy storage, structural support, and cell-to-cell communication	starch and cellulose

Mini **Investigation**

Modelling Carbohydrates

Skills: Performing, Observing, Analyzing, Evaluating

SKILLS HANDBOOK A2.1

In this investigation, you will build and observe three-dimensional models of simple carbohydrates to understand how they are assembled into larger units.

Equipment and Materials: chemical modelling kit

1. With a partner, use the chemical modelling kit to construct a model of α-glucose and a model of fructose.
2. Perform a dehydration synthesis reaction to form a sucrose disaccharide.
3. Perform a hydrolysis reaction to re-form the two monosaccharides.
4. Rearrange the atoms in fructose to change it into glucose.
5. Convert both glucose molecules to their β forms. Link them using a dehydration reaction.
6. Link your two β-glucose disaccharides with another group's β-glucose disaccharides.

A. What is the waste product of the dehydration synthesis reaction? T/I

B. What is the overall chemical formula of each of the three molecules you created? Determine the C:H:O ratio for the monosaccharides. T/I

C. How are fructose and glucose similar? How do they differ? Are they isomers? T/I

D. What large polysaccharide is similar to the glucose chain you created? What other polysaccharide could you have formed if the glucose molecules had been in their α form? T/I

E. Observe the number of OH groups on these molecules. What can the number of —OH bonds tell you about the molecule and its relationship with water? How does the —OH group influence solubility? T/I

Lipids

The term **lipid** is a general term for a variety of non-polar biological molecules. Lipids are composed mostly of hydrogen, carbon, and lesser amounts of oxygen. They are smaller than complex carbohydrates, so they are not considered to be macromolecules, and they are not polymers of defined monomeric subunits. Since lipids are generally non-polar, they do not dissolve in water. Their insolubility in water contributes to their ability to form cell membranes. Lipids have other functions as well. Some lipids are stored by cells, to be used as an energy source (**Figure 6**). Other lipids serve as hormones that regulate cellular activities and as vitamins. Lipids in living organisms fall into five main categories: fatty acids, fats, phospholipids, steroids, and waxes.

lipid a non-polar compound that is made mostly of carbon and hydrogen

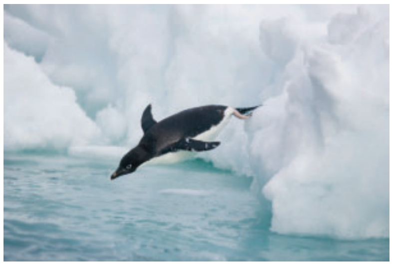

Figure 6 As penguins dive into extremely cold water, a layer of fat under their skin acts as thermal insulation.

Fatty Acids

The structural backbone of most lipids is derived from fatty acids. A **fatty acid** consists of a single hydrocarbon chain with a carboxyl functional group (—COOH) at one end (**Figure 7(a)**, next page). The carboxyl group gives the fatty acid its acidic properties. Fatty acids in living organisms contain four or more carbons in their hydrocarbon chain. The most common forms of fatty acids have even-numbered chains of 14 to 22 carbons. As their chain length increases, fatty acids become progressively less water soluble.

fatty acid a molecule that consists of a carboxyl group and a hydrocarbon chain

If the hydrocarbon chain of a fatty acid binds the maximum possible number of hydrogen atoms, and if all the carbons are linked to each other with single bonds, the fatty acid is said to be saturated (**Figure 7(b)**). If there are double bonds in the fatty acid chain, then it is said to be unsaturated. This means that the carbon chain has the potential to form more bonds with hydrogen (**Figure 7(c)**). Fatty acids with one double bond are monounsaturated, and those with more than one double bond are polyunsaturated. The presence of a double bond in an unsaturated fatty acid creates a kink in the molecule, which causes it to bend.

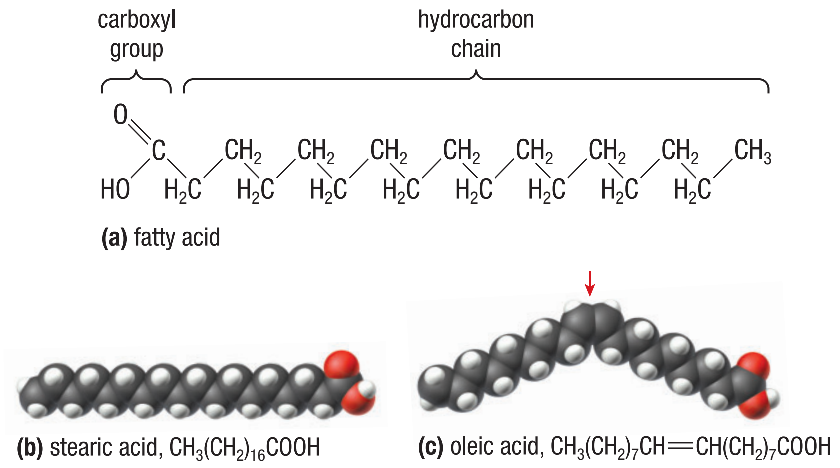

Figure 7 (a) A fatty acid consists of a carboxyl group attached to a long hydrocarbon chain. (b) Stearic acid is a saturated fatty acid. (c) Oleic acid is an unsaturated fatty acid.

Fats

triglyceride a fat; three fatty acid chains linked to a glycerol molecule

A fat is a lipid that is made from two types of molecules: fatty acid and a glycerol molecule. In a fat molecule, one to three fatty acid chains are joined to a single glycerol molecule through dehydration synthesis between –OH functional groups on the glycerol and carboxyl functional groups on the fatty acids. **Triglycerides** are the most well-known fats. They contain three fatty acid chains (**Figure 8**). A fat molecule can have identical fatty acid chains, or different fatty acid chains, linked to glycerol.

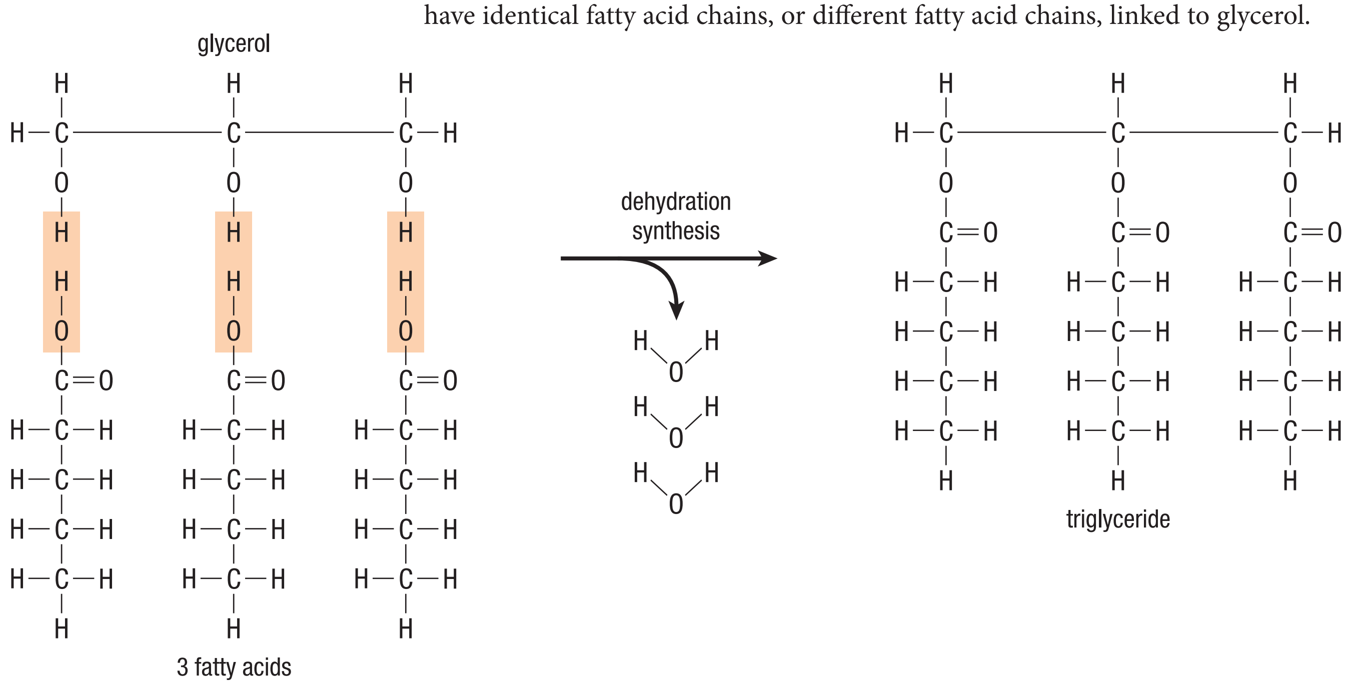

Figure 8 A triglyceride forming from one glycerol and three fatty acid molecules in a dehydration synthesis reaction

Different organisms usually have distinctive combinations of fatty acids in their triglycerides. For example, fats obtained from animals, such as butter and lard, usually contain only saturated fatty acids, so they are called **saturated fats**. Fats derived from plants, such as olive oil, usually contain more unsaturated and polyunsaturated fatty acids, so they are called **unsaturated fats**. Unsaturated fats are generally referred to as oils. Like individual fatty acids, triglycerides generally become less fluid as the length of their fatty acid chain increases. Those with shorter chains remain liquid, as oils, at room temperature. The more saturated fats, such as butter, are solids because their chains are long and straight and can be packed closely together to form a solid structure at room temperature. Fatty acid chains that have kinks are bent and cannot be packed as tightly as saturated fats, Therefore, these molecules stay more fluid and are liquid at room temperature.

Living organisms need flexible cells so they can move around easily. If large amounts of fat in animals were solid, it would be difficult for animals to move about. Warm-blooded mammals and birds are the exception in having mostly saturated fats, but these fats are liquids because of relatively high body temperature. Many plant seeds contain mostly unsaturated fats, which are liquids even at lower temperatures. Cold-water fish need their bodies to stay flexible at lower temperatures, so the fats in their bodies are mostly unsaturated fish "oils." This is one of the benefits of eating fish.

Triglycerides function widely as stored energy. Gram for gram, they yield more than twice as much energy as carbohydrates. Therefore, fats are an excellent source of energy in a diet. Storing the equivalent amount of energy as carbohydrates rather than fats would add more than 45 kg to the average person. A layer of fatty tissue just under the skin serves as insulation in mammals and birds.

Most plant fats are unsaturated fats, which are generally considered healthier than saturated animal fats for the human diet. Diets rich in saturated fats can lead to heart disease, whereas diets rich in unsaturated fats can improve your health. The Inuit, who live in the Arctic, depend on a diet that is very high in animal proteins from fish, seal, whales, caribou, and waterfowl. Their diet is high in both fat and protein, but very low in carbohydrates. The high fat (high energy) content is beneficial for living in such a cold climate. Most of the fats in their diet are made of monounsaturated and omega-3 fatty acids. Therefore, the fat they eat is healthier fat than the saturated animal fats in a typical North American diet.

Phospholipids

Cells could not exist without the phosphate-containing lipids called **phospholipids**. Phospholipids are the primary lipids of cell membranes. In the most common phospholipids, as in triglycerides, glycerol forms the backbone of the molecules. Only two of its binding sites, however, link to fatty acids. The third site links to a charged phosphate group, which often binds to another polar or charged unit (**Figure 9**). Thus, a phospholipid contains two hydrophobic fatty acids at one end, attached to a hydrophilic polar group, often called the head group (**Figure 10(a)** and **(b)**, next page). Molecules that contain both hydrophobic and hydrophilic regions are called amphipathic molecules. The head of an amphipathic molecule is the polar and hydrophilic region. The tail is the hydrophobic lipid, which is composed of a carbon chain.

Phospholipids make up the lipid bilayer of cell membranes, an important structural feature of cells. The hydrophilic end of a phospholipid faces outward toward water, and the hydrophobic fatty acid tails face inward toward each other (**Figure 10(c)**, next page).

saturated fat a lipid that is composed of saturated fatty acids with single bonds in their hydrocarbon chain

unsaturated fat a lipid that is composed of unsaturated fatty acids with double bonds in their hydrocarbon chain

phospholipid a lipid that consists of two fatty acids and a phosphate group bound to glycerol

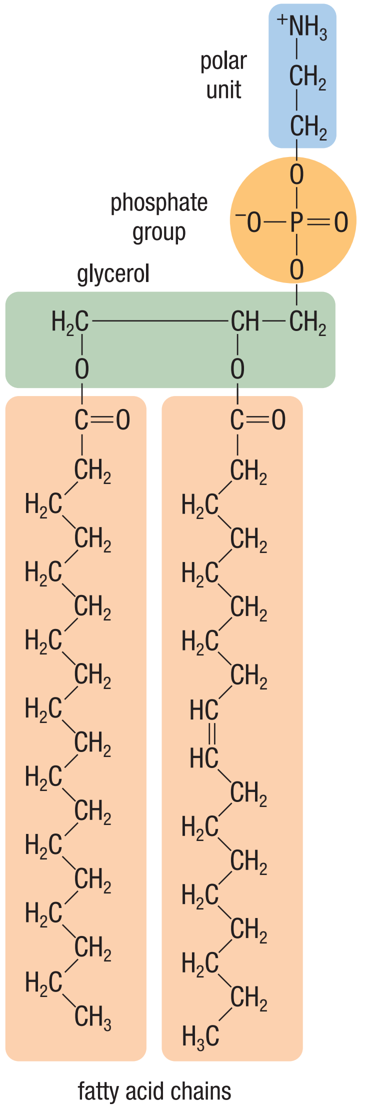

Figure 9 A phospholipid has a polar end and a non-polar end. The non-polar end consists of glycerol bonded to two fatty acids. Phosphattidyl ethanolamine is an example of a phospholipid.

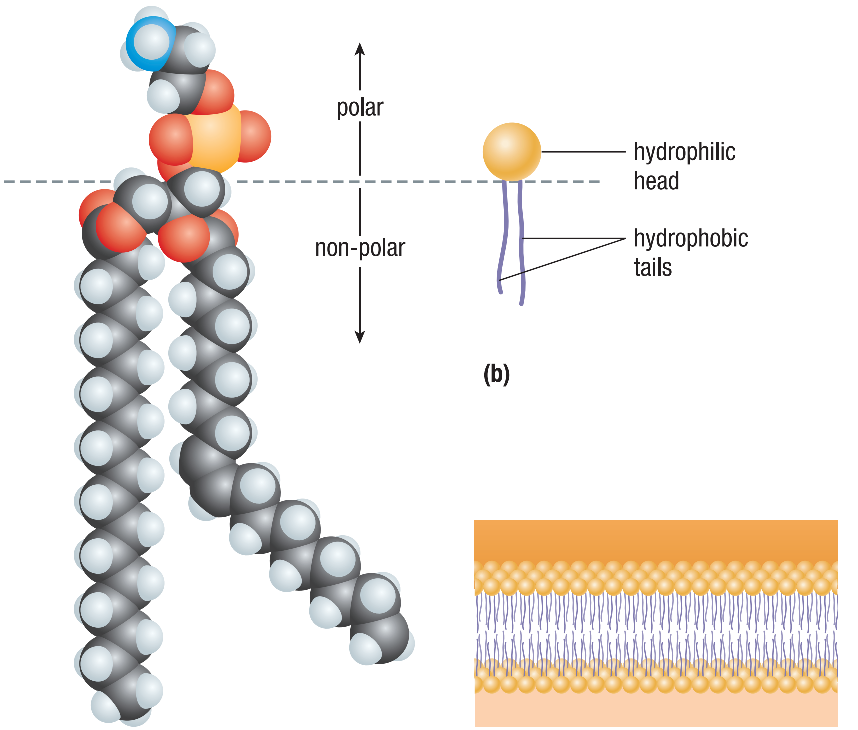

Figure 10 (a) This structural model of a phospholipid shows the polar and non-polar ends. (b) A phospholipid has a hydrophilic head and two hydrophobic tails. (c) A phospholipid bilayer forms the basic structure of a cell membrane.

Steroids

steroid a lipid that is composed of four carbon rings

Steroids are a group of lipids with structures that are based on a framework of four fused carbon rings. Small differences in the side groups that are attached to the rings distinguish one steroid from another. The most abundant steroids, the sterols, have a single polar –OH group at one end of the ring framework and a complex, non-polar hydrocarbon chain at the other end. Although sterols are almost completely hydrophobic, the single hydroxyl group gives one end a slightly polar, hydrophilic character. As a result, sterols also have dual solubility properties and, like phospholipids, tend to assume positions in cells that satisfy these properties. Cholesterol, a steroid, is an important component of the plasma membrane that surrounds animal cells. Similar sterols, called phytosterols, occur in plant cell membranes.

Cholesterol is a steroid that is essential for animal cell membranes and converts into a number of compounds, such as vitamin D. Too much dietary cholesterol, however, can be harmful to your body. A high concentration of cholesterol in the bloodstream and a diet rich in saturated fats have been linked to the development of atherosclerosis, a condition in which fat deposits, or plaques, form on the inner lining of blood vessels. This blocks the flow of blood to tissues, which often leads to a heart attack.

Sex hormones, such as testosterone, estrogens, and progesterone, are also steroids (**Figure 11**). They control the development of sexual traits and sex cells that are specific to males and females. Anabolic steroids, which are used by some athletes to build muscle mass, mimic the male sex hormone testosterone. The use of anabolic steroids is banned by all major sporting bodies, yet some athletes still use them to gain an advantage over their competitors. Anabolic steroids have many harmful effects on the body, including high blood pressure, depression, suicidal tendencies, changes in the levels of the sex hormones, and, in young people, reduced growth.

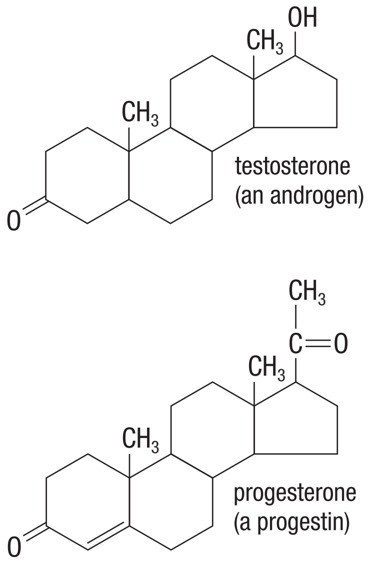

Figure 11 The sex hormones testosterone and progesterone belong to the sterol family of lipids. Notice their similar four-carbon ring structure.

Waxes

Waxes are large lipid molecules that are made of long fatty acid chains linked to alcohols or carbon rings. Waxes are hydrophobic, extremely non-polar, and soft solids over a wide range of temperatures. These characteristics are what make them ideal for flexible waterproof coatings on various plant and animal parts. One type of wax, cutin, is produced by certain plant cells to form a water-resistant coating on the surfaces of stems, leaves, and fruit (**Figure 12**). Cutin enables plants to conserve water, and it acts as a barrier to infections and diseases. Such functions are vital for life. Without this waxy coating, plants could not survive on land. Birds secrete a waxy material that helps to keep their feathers dry. Bees produce beeswax to make their honeycombs. **Table 2** is a summary of the different types of lipid molecules.

wax a lipid that is formed when long fatty acid chains are joined to alcohols or carbon rings

Figure 12 Cutin, a wax, is produced by the fruits, leaves, and stems of plants to create a waterproof barrier.

Table 2 Structure and Function of Lipids

Type	Structure	Function	Example
fatty acid	carboxyl group linked to a hydrocarbon chain	cellular functions and energy storage	stearic acid
fat	three fatty acid chains linked to glycerol	energy storage and insulation	butter and olive oil
phospholipid	two fatty acid chains and one phosphate group linked to glycerol	cell membrane	lipid bilayer
steroid	four carbon rings	hormonal signalling, cell response to the environment, and growth	testosterone and cholesterol
wax	long fatty acid chains linked to alcohol or carbon rings	water resistance and protection	wax coating on fruits, leaves, and stems

Mini **Investigation**

Modelling Lipids

Skills: Performing, Observing, Analyzing, Evaluating

SKILLS HANDBOOK A2.1

In this investigation, you will build and observe three-dimensional models of simple lipids.

Equipment and Materials: chemical modelling kit

1. In pairs, use the chemical modelling kit to construct a model of glycerol and three short fatty acids: a four-carbon saturated fatty acid, a four-carbon unsaturated fatty acid, and a five-carbon saturated fatty acid.
2. Perform three dehydration synthesis reactions to produce a triglyceride.
3. Perform hydrolysis reactions to re-form the individual components.
4. Research the structure of one steroid of your choosing, and build the steroid.

A. Which functional groups are involved in the dehydration synthesis reactions in Step 2? What are the waste products in this reaction? T/I

B. What is the overall chemical formula of the triglyceride? T/I

C. What is the C:H:O ratio in the triglyceride you synthesized? T/I

D. How does the C:H:O ratio in triglycerides compare with the overall C:H:O ratio in carbohydrates? T/I

E. Which element is less abundant in fats? T/I

F. Compare the polarity of the molecules before and after the formation of the triglyceride. T/I

G. Compare the overall acidity of the molecules before and after the formation of the triglyceride. T/I

H. Compare the steroid that your group built with the steroids that other groups built. Can you identify the steroids that the other groups built? How are the steroids similar? How are they different? T/I C

WEB LINK

1.4 Review

Summary

- Carbohydrates are simple and complex sugar molecules. They are the most abundant macromolecules found in living things on Earth.
- Monosaccharides are single sugar molecules that have a 1:2:1 ratio of C:H:O. Disaccharides consist of two single sugar subunits that are linked through a dehydration synthesis reaction. Polysaccharides are long chains of sugar monomers.
- Carbohydrates are polar molecules. They are soluble in water, unless they are very large.
- Lipids are generally non-polar molecules that do not readily dissolve in water.
- Fatty acids and triglycerides are primarily energy-storage molecules. Triglycerides consist of three fatty acid chains linked to glycerol.
- Phospholipids are the main component of all plasma membranes. They are formed from a glycerol molecule, two fatty acids, and an ionic phosphate-containing group.
- Steroids are small lipids with a four-carbon ring structure.
- Waxes are long fatty acid chains linked to alcohol or ring structures. They function primarily as waterproofing compounds.

Questions

1. (a) Define the term "isomer."
   (b) Which of the molecules in **Figure 13** are isomers? Explain your reasoning. K/U T/I

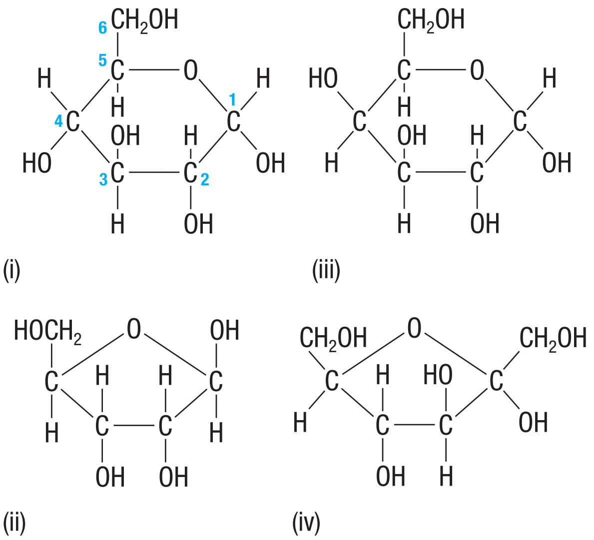

Figure 13

2. Relate the chemical structure of carbohydrates to their physical properties and uses. K/U
3. Humans use carbohydrates in many ways. Research how humans use monosaccharides, disaccharides, and polysaccharides. T/I
4. Compare the polarity of carbohydrates and lipids. How does their polarity relate to their physical properties? K/U
5. Why are most polysaccharides insoluble in water? K/U
6. (a) Distinguish between a fatty acid and a fat.
   (b) What happens to the acidic properties of a fatty acid when a fat is formed? K/U
7. Why are steroids important, even though they tend to have a bad reputation? T/I
8. Investigate the use of one performance-enhancing drug in the steroid group. What are the medical consequences of its use? How do sports federations check for the presence of steroids? T/I

WEB LINK