The Carbon Chemistry of Life

1.3

Carbon atoms make up the base of every organic molecule, including the molecules within cells. Carbon is unparalleled in the biological world in its ability to form the backbone of large diverse molecules. This unique role arises from carbon's bonding properties—carbon can assemble into an astounding variety of chain and ring structures. Carbon has four electrons in its valence shell, and therefore each carbon atom is capable of forming four covalent bonds with other atoms. As a result, carbon is able to form such substances as multi-ringed molecules, diamonds, and nanotubes. Each carbon atom is a connecting point from which a molecule can branch out, in up to four directions. With combinations of single, double, and triple bonds, an almost limitless array of molecules is possible.

Carbon Chains: The Backbone of Biochemistry

As well as forming bonds with other atoms (chiefly hydrogen, nitrogen, oxygen, and sulfur), carbon atoms bind to each other to form long chains, rings, or branched structures. Molecules consisting only of carbon atoms bonded to hydrogen atoms are called hydrocarbons. The smallest hydrocarbon is methane. Methane is a single carbon atom bound to four hydrogen atoms (**Figure 1(a)**). Since carbon always has four bonds, if a carbon atom is bound to two other carbon atoms, the remaining bonds are available to bond to hydrogen, an additional carbon, or other elements (**Figure 1(b)**).

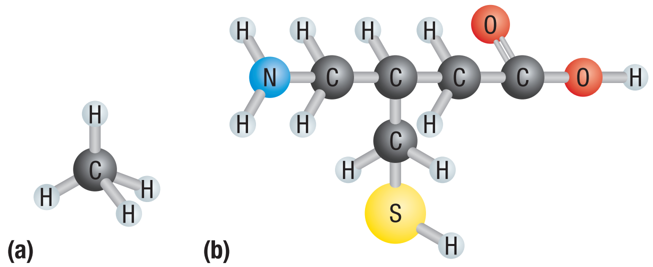


Figure 1 (a) Methane is the simplest hydrocarbon. It consists of 1 carbon atom bound to 4 hydrogen atoms. (b) Carbon atoms can form chains that branch.

The chain of carbon atoms in a biochemical molecule is the carbon skeleton of the molecule. Carbon skeletons can be linear or branched or form a closed ring shape, as in cyclohexane, C_6H_{12} (**Figure 2**). Many carbon-containing rings can join to produce polymers, such as the string of sugar molecules that make up a complex sugar chain.

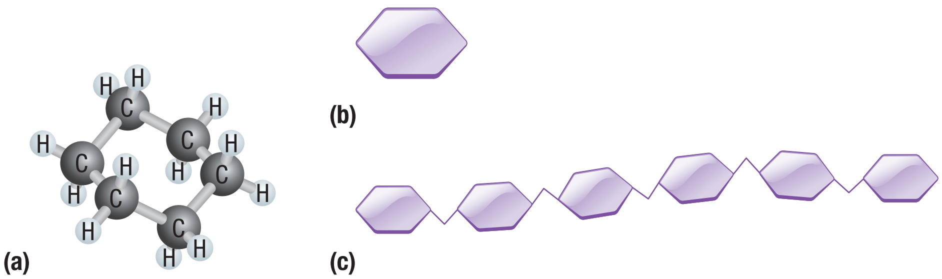


Figure 2 (a) The ring structure of cyclohexane is formed by 6 carbon atoms and 12 hydrogen atoms. (b) The hexagon symbol is frequently used for a carbon ring. (c) Carbon rings may contain an oxygen atom at one corner and can be joined into a chain.

Double or triple bonds can form between two carbon atoms, decreasing the number of remaining bonding sites by one or two, respectively (**Figure 3**). There is almost no limit to the number of different hydrocarbon structures that are possible, but they are rarely used by living organisms. Instead, the molecules of living organisms almost invariably contain other elements in addition to C and H. These other elements give the biological molecules different functional properties. These molecules fall into four major groups, based on their function: carbohydrates, lipids (fats), proteins, and nucleic acids.

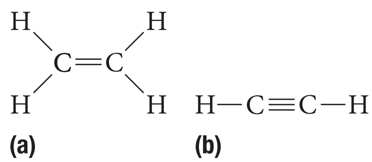


Figure 3 (a) A double bond forms between two carbons, decreasing the number of bonds that can form with other atoms by one. (b) A triple bond can form between two carbon atoms, decreasing the available binding sites by two for each carbon.

Functional Groups

functional group a group of atoms that affects the function of a molecule by participating in chemical reactions

Carbohydrates, lipids, proteins, and nucleic acids undergo synthesis and degradation in living organisms through interactions between small reactive groups of atoms that are, themselves, part of these large biochemical molecules. These small reactive groups are called **functional groups** (**Figure 4**). Unlike non-polar hydrocarbon chains, functional groups are usually ionic or strongly polar. Functional groups on large molecules interact with other molecules and introduce different types of bonding.

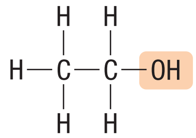
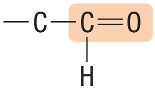
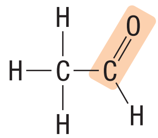
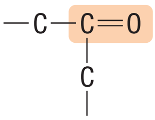
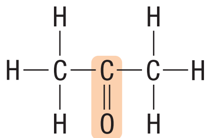
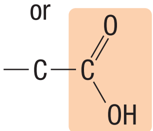
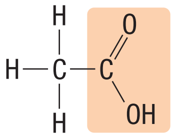
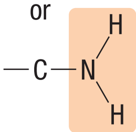
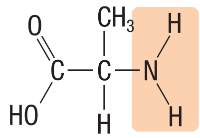
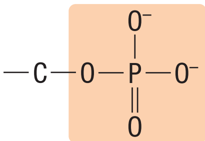
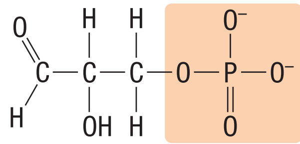
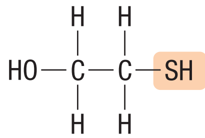
Functional group	Major classes of molecule	Example
hydroxyl —C—OH	alcohols	 ethyl alcohol (in alcoholic beverages)
carbonyl 	aldehydes	 acetaldehyde
	ketones	 acetone (a solvent)
carboxyl —C—COOH or 	organic acids	 acetic acid (in vinegar)
amino $—C—NH_2$ or 	amino acids	 alanine (an amino acid)
phosphate 	nucleotides, nucleic acids, many other cellular molecules	 glyceraldehyde-3-phosphate (product of photosynthesis)
sulfhydryl —C—SH	many cellular molecules	 mercaptoethanol

Figure 4 Common functional groups in biological molecules

Characteristics of Functional Groups

Most functional groups are either ionic or strongly polar. This makes them very attracted to other ionic or polar molecules, including water molecules. Therefore, the chemical or physical properties of a large biological molecule are influenced by the polar and ionic characteristics of its functional groups. The forces of attraction that are created by ionic and polar groups are necessary in a chemical reaction in order to form new bonds. The non-polar portions of a large biological molecule do not attract other molecules. Therefore, they do not help to initiate chemical reactions.

Polar groups often act as "handles" on a large molecule. For example, some polar functional groups are strongly attracted to water and therefore can often be dissolved in the cytosol of the cell. The comparison of ethane, CH_3CH_3, and ethanol, CH_3CH_2OH, gives an example of how polar functional groups can influence the physical and chemical properties of a molecule. Ethane, a hydrocarbon, has no functional group and is non-polar. Although it has a lot of potential energy and could make a great fuel, ethane is a gas at room temperature and is not soluble in water. In comparison, ethanol has an alcohol functional group (—OH), which gives it polar characteristics. It is a liquid at room temperature and highly soluble in water. Ethanol's high solubility

UNIT TASK **BOOKMARK**

Consider what you are learning about the structure and function of functional groups as you work on your Unit Task (p. 108). How can this information help you understand your molecule?

means that it can be dissolved in the cell cytosol, where it can be used as a fuel, providing energy for the cell. Ethane has slightly higher energy content than ethanol, but it has no value as a fuel for most living organisms since it is lacking a polar group that would make it soluble in their cytosol.

The carboxyl, amino, and phosphate groups are ionic functional groups (**Figure 5**). The carboxyl group, COOH, can release a proton to become COO^-. The release of H^+ in water makes the carboxyl group an acid. The amino group, NH_2, can attract and bond to an H^+ proton to become an NH_3^+ group. This characteristic makes the amino group a weak base. When you study proteins, you will learn that they are made of amino acids. As the name implies, an amino acid has both an acid (carboxyl) and a base (amino) as functional groups. Phosphate functional groups are also acidic. These groups lose their H^+ ions and become negatively charged. DNA, or deoxyribonucleic acid, is an acid because it contains a huge number of these phosphate groups along the backbone of its structure. For this reason, the overall charge of DNA is negative.

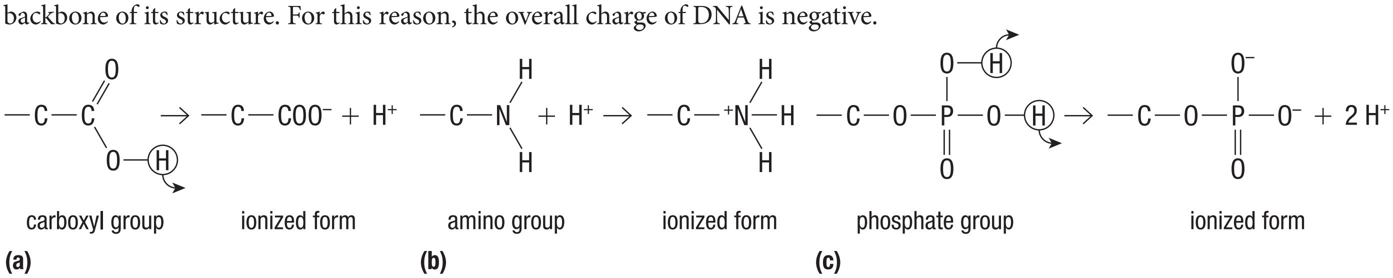


Figure 5 Ionic functional groups: (a) The carboxyl group acts like an acid, releasing H^+ ions to become negatively charged. (b) The amino group acts like a base, accepting H^+ ions to become positively charged. (c) The phosphate group acts like an acid, releasing H^+ ions to become negatively charged.

Dehydration and Hydrolysis Reactions

In many reactions, functional groups lose or gain an H^+ or OH^-, the components of water, as they interact with other molecules. As you learned in Section 1.1, dehydration removes components of a water molecule, usually during the assembly of a larger molecule from smaller subunits. An example of a dehydration reaction occurs when individual sugar molecules combine to form a starch molecule, which is a larger macromolecule (**Figure 6(a)**). Two −OH groups interact with each other during dehydration, with the oxygen atom in one group attracted to the hydrogen atom in the other group. Water forms during this reaction. The remaining oxygen atom forms a bridge as it bonds the two subunits together to form a larger molecular compound.

The reverse process of dehydration is hydrolysis. In this process, the components of a water molecule, H^+ and OH^-, are added to functional groups as the molecules break into smaller subunits. For example, the breakdown of starch into individual sugars occurs by hydrolysis (**Figure 6(b)**). Note that two hydroxyl groups are formed when water is added to the oxygen bridge in this hydrolysis reaction, and these hydroxyl groups can interact with each other. Hydrolysis and dehydration reactions are among the most important reactions in cells. Both the assembly and breakdown of large biological molecules depend on these reactions.

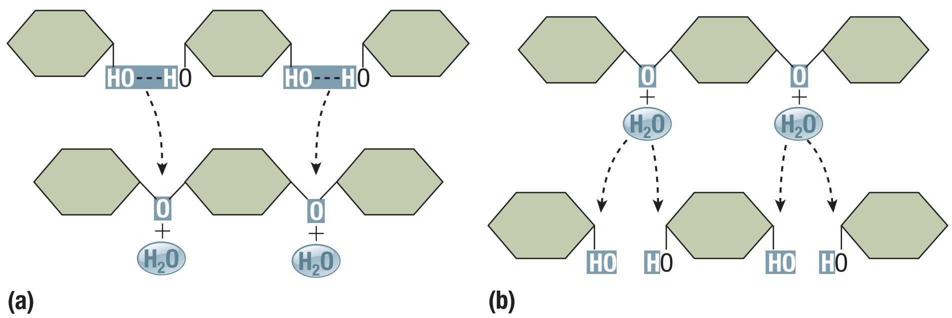


Figure 6 (a) During dehydration, water is produced as subunits join to form larger molecules. (b) During hydrolysis, water is used as a reactant to split larger molecules into smaller subunits.

1.3 Review

Summary

- Carbon atoms form the backbone of biological molecules. They can link together to form chains, branched structures, and rings.
- Functional groups have polar or ionic qualities that influence how they interact with water and other molecules.
- During a dehydration reaction, water is removed from subunits as they combine to form a larger molecule.
- During a hydrolysis reaction, larger molecules react with water and break down into smaller subunits.

Questions

1. Explain how the electron arrangement in carbon atoms enables them to form straight and branching chains and ring structures. K/U T/I
2. What is the primary purpose of the functional groups that are found in organic molecules? K/U
3. Considering the functional groups you have studied, why do you think that compounds with similar structures often have similar uses? K/U A
4. Explain how functional groups influence solubility and the forces of attraction between molecules. K/U
5. What role does oxygen play in most functional groups? T/I
6. Using a balanced chemical equation, show how each of the following functional groups changes in an aqueous solution. K/U T/I
   (a) carboxyl group
   (b) amino group
   (c) phosphate group
7. Draw an example of a dehydration reaction and a hydrolysis reaction. Explain your examples to a classmate. K/U C
8. Compare and contrast dehydration synthesis and hydrolysis. K/U
9. Is the following reaction an example of dehydration synthesis or hydrolysis? Explain your answer. K/U

$$C_{12}H_{22}O_{11} + H_2O \rightarrow C_6H_{12}O_6 + C_6H_{12}O_6$$

10. When would a cell use the dehydration and hydrolysis reactions of polysaccharides? K/U T/I
11. Investigate some of the properties and uses of one of the major classes of functional groups shown in Figure 4 (page 26). Write a paragraph describing them. T/I
12. Examine each of the following molecules. T/I C
    (a) Identify the functional group on the molecule (**Figures 7** and **8**).

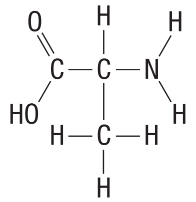


Figure 7

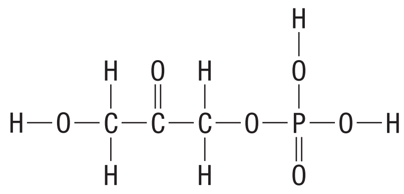


Figure 8

    (b) How will each functional group influence the solubility and/or acidity of the molecule?
    (c) Research these molecules. Write a paragraph to describe how they are used by living cells.

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