Chapter 4
Carbon and the Molecular Diversity of Life

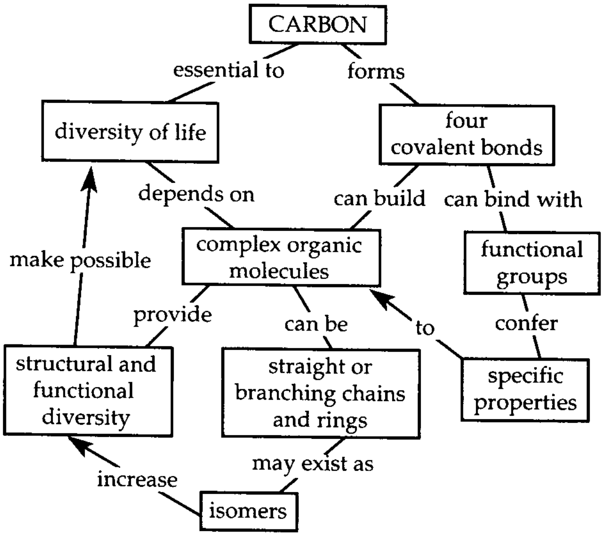
Key Concepts

4.1 **Organic chemistry is the study of carbon compounds**

4.2 **Carbon atoms can form diverse molecules by bonding to four other atoms**

4.3 **Functional groups are the parts of molecules involved in chemical reactions**

Framework



Chapter Review

4.1 Organic chemistry is the study of carbon compounds

Organic chemistry is the study of carbon-containing molecules. Early organic chemists could not synthesize the complex molecules found in living organisms and, therefore, attributed the existence of life and the formation of these molecules to a life force independent of physical and chemical laws, a belief known as vitalism. Mechanism, the philosophy underlying modern organic chemistry, holds that physical and chemical laws and explanations are sufficient to account for all natural phenomena, even the origin of life.

4.2 Carbon atoms can form diverse molecules by bonding to four other atoms

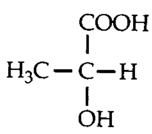
Formation of Bonds with Carbon Carbon has six electrons. To complete its valence shell, carbon forms four covalent bonds with other atoms. This *tetravalence* is at the center of carbon's ability to form large and complex molecules with characteristic three-dimensional shapes and properties. When carbon forms four single covalent bonds, its hybrid orbitals create a tetrahedral shape. When two carbons are joined by a double bond, the other carbon bonds are in the same plane, forming a flat molecule.

Molecular Diversity Arising from Carbon Skeleton Variation Carbon atoms readily bond with each other, producing chains or rings of carbon atoms. These molecular backbones can vary in length, branching, placement of double bonds, and location of atoms of other elements. The simplest organic molecules are **hydrocarbons,** consisting of only carbon and hydrogen. The nonpolar C—H bonds in hydrocarbon chains account for their hydrophobic properties.

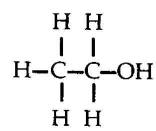
Isomers are compounds with the same molecular formula but different structural arrangements and, thus, different properties. **Structural isomers** differ in the covalent arrangement of atoms and often in the location of double bonds. **Geometric isomers** have the same sequence of covalently bonded atoms but differ in spatial arrangement due to the inflexibility of double bonds. A *cis* isomer has non-hydrogen atoms attached to double-bonded carbons on the same side of the double bond; a *trans* isomer has these atoms on opposite sides of the double bond. **Enantiomers** are left- and right-handed versions of each other and can differ greatly in their biological activity. An asymmetric carbon is one that is covalently bonded to four different kinds of atoms or groups of atoms. Due to the tetrahedral shape of the asymmetric carbon, the four groups can be attached in spatial arrangements that are not superimposable on each other.

■ INTERACTIVE QUESTION 4.1

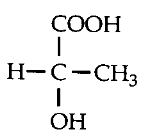
Identify the structural isomers, geometric isomers, and enantiomers from the following compounds. Which of the geometric isomers is the *cis* isomer?



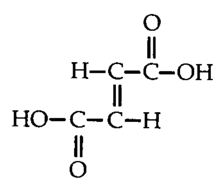
L-lactic acid



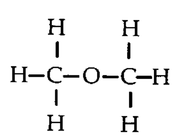
ethanol



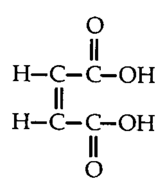
D-lactic acid



fumaric acid



dimethyl ether



maleic acid

4.3 Functional groups are the parts of molecules involved in chemical reactions

The Functional Groups Most Important in the Chemistry of Life The properties of organic molecules are largely determined by groups of atoms, known as **functional groups,** that bond to the carbon skeleton and behave consistently from one carbon-based molecule to another. Because the functional groups considered here are hydrophilic, they increase the solubility of organic compounds in water.

The **hydroxyl group** consists of an oxygen and hydrogen (—OH) covalently bonded to the carbon skeleton. Organic molecules with hydroxyl groups are called **alcohols,** and their names often end in *-ol.*

Carbonyl groups consist of a carbon double-bonded to an oxygen (>CO). If the carbonyl group is at the end of the carbon skeleton, the compound is called an **aldehyde.** Otherwise, the compound is called a **ketone.**

A **carboxyl group** consists of a carbon double-bonded to an oxygen and also attached to a hydroxyl group (—COOH). Compounds with a carboxyl group are called **carboxylic acids** or organic acids because they tend to dissociate to release H^+, becoming —COO^-.

An **amino group** consists of a nitrogen atom bonded to two hydrogens (—NH_2) and to the carbon skeleton. Compounds with an amino group, called **amines,** can act as bases. The nitrogen, with its pair of unshared electrons, can attract a hydrogen ion, becoming —NH_3^+.

The **sulfhydryl group** consists of a sulfur atom bonded to a hydrogen (—SH). **Thiols** are compounds containing sulfhydryl groups.

A **phosphate group** is bonded to the carbon skeleton by an oxygen attached to PO_3^{2-}, a phosphorus atom that is bonded to three other oxygen atoms (—OPO_3^{2-}). It is an ionized form of a phosphoric acid group (—PO_3H_2). Compounds containing phosphate groups are called **organic phosphates.** The group is an anion due to the dissociation of hydrogen ions.

The chemical elements of life: a review

Carbon, oxygen, hydrogen, nitrogen, and smaller quantities of sulfur and phosphorus, all capable of forming strong covalent bonds, are combined into the complex organic molecules of living matter. The versatility of carbon in forming four covalent bonds, linking readily with itself to produce chains and rings, and binding with other elements and functional groups makes possible the incredible diversity of organic molecules.

Word Roots

hydro- = water (*hydrocarbon:* an organic molecule consisting only of carbon and hydrogen)

iso- = equal (*isomer:* one of several organic compounds with the same molecular formula but different structures and, therefore, different properties)

enanti- = opposite (*enantiomer:* molecules that are mirror images of each other)

carb- = coal (*carboxyl group:* a functional group present in organic acids, consisting of a carbon atom double-bonded to an oxygen atom and a hydroxyl group)

sulf- = sulfur (*sulfhydryl group:* a functional group that consists of a sulfur atom bonded to an atom of hydrogen)

thio- = sulfur (*thiol:* organic compounds containing sulfhydryl groups)

Structure Your Knowledge

1. Construct a concept map that illustrates your understanding of the characteristics and significance of the three types of isomers. *A suggested map is in the answer section. Comparing and discussing your map with that of a study partner would be most helpful.*
2. Fill in the following table on the functional groups.

Functional Group	Molecular Formula	Names and Characteristics of Organic Compounds Containing Functional Group
	—OH	
		Aldehyde or ketone; polar group
Carboxyl		
	$—NH_2$	
		Thiols; cross-links stabilize protein structure
Phosphate		

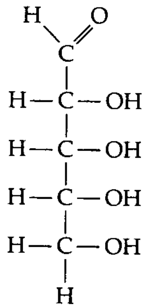
Test Your Knowledge

MULTIPLE CHOICE: *Choose the one best answer.*

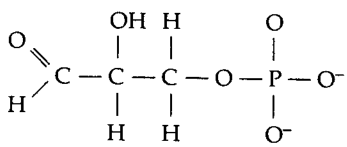
1. The tetravalence of carbon most directly results from
   a. its tetrahedral shape.
   b. its very slight electronegativity.
   c. its four electrons in the valence shell that can form four covalent bonds.
   d. its ability to form single, double, and triple bonds.
   e. its ability to form chains and rings of carbon atoms.
2. Hydrocarbons are not soluble in water because
   a. they are hydrophilic.
   b. the C—H bond is nonpolar.
   c. they do not ionize.
   d. they store energy in the many C—H bonds along the carbon backbone.
   e. they are lighter than water.
3. Which of the following is *not* true of an asymmetric carbon atom?
   a. It is attached to four different atoms or groups.
   b. It results in right- and left-handed versions of a molecule.
   c. It can be a part of enantiomers.
   d. Its configuration is in the shape of a tetrahedron.
   e. It can be a part of geometric isomers.
4. A reductionist approach to considering the structure and function of organic molecules would be based on
   a. mechanism.
   b. holism.
   c. determinism.
   d. vitalism.
   e. evolution.
5. The functional group that can cause an organic molecule to act as a base is
   a. —COOH.
   b. —OH.
   c. —SH.
   d. $—NH_2$.
   e. $—OPO_3^{2-}$.
6. The functional group that confers acidic properties to organic molecules is
   a. —COOH.
   b. —OH.
   c. —SH.
   d. $—NH_2$.
   e. $>C=O$.
7. Which is *not* true about structural isomers?
   a. They have different chemical properties.
   b. They have the same molecular formula.
   c. Their atoms and bonds are arranged in different sequences.
   d. They are a result of restricted movement around a carbon double bond.
   e. Their possible numbers increase as carbon skeletons increase in size.
8. The fats stored in your body consist mostly of
   a. amino acids.
   b. alcohols.
   c. carboxylic acids.
   d. hydrocarbons.
   e. organic phosphates.

9. How many asymmetric carbons are there in the sugar ribose?

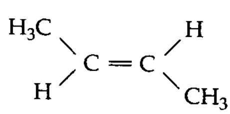
a. 1
b. 2
c. 3
d. 4
e. 5



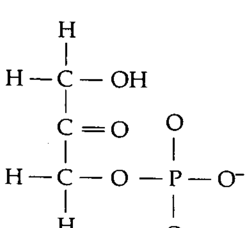
MATCHING: *Match the formulas (a–f) to the terms at the right. Choices may be used more than once; more than one right choice may be available.*



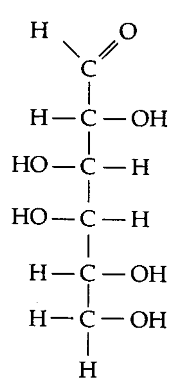
a.



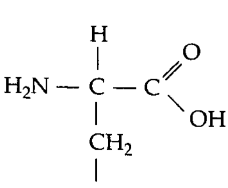
b.



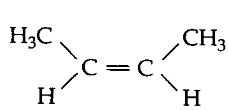
c.



d.



e.



f.

_______ 1. structural isomers
_______ 2. geometric isomers
_______ 3. can have enantiomers
_______ 4. carboxylic acid
_______ 5. can make cross-link in protein
_______ 6. hydrophilic
_______ 7. hydrocarbon
_______ 8. amino acid
_______ 9. organic phosphate
_______ 10. aldehyde
_______ 11. amine
_______ 12. ketone

CARBON—THE BACKBONE OF BIOLOGICAL MOLECULES

1. Although cells are 70-95% water, the rest consists mostly of _____________compounds.
2. Carbon is unparalleled in its ability to form large, _____________, and diverse molecules.
3. Carbon accounts for the diversity of _______________molecules and has made possible the great diversity of living things.
4. Proteins, DNA, carbohydrates, and other molecules that distinguish living matter from _______________ material are all composed of carbon atoms bonded to each other and to atoms of other elements.
5. These other elements commonly include hydrogen (H), oxygen (O), nitrogen (N), ___________, and phosphorus (P).
6. The study of carbon compounds, ______________________, deals with any compound with carbon (organic compounds).
7. Organic compounds can range form simple molecules, such as CO2 or CH4, to complex molecules such as_____________, which may weigh more than 100,000 daltons.
8. The overall ________________of the major elements of life (C, H, O, N, S, and P) are quite uniform from one organism to another.
9. However, because of carbon's ________________, these few elements can be combined to build and inexhaustible variety of organic molecules.
10. Variations in organic molecules can distinguish between individuals of a ____________ species.
11. The science of organic chemistry began in attempts to ____________and improve the yield of products obtained from other organisms.
12. Initially, chemists learned to ______________simple compounds in the laboratory, but had no success with more complex compounds.
13. The Swedish chemist Jons Jacob Berzelius was the first to make a distinction between organic compounds that seemed to arise only in living organisms and inorganic compounds that were found in the _______________world.
14. This led early organic chemists to propose_______________, the belief that physical and chemical laws did not apply to living things.
15. Support for vitalism began to wane as organic chemists learned to synthesize complex organic compounds in the_______________.
16. In the early 1800s, the German chemist Fredrich Wohler and his students were able to synthesize ____________from totally inorganic materials.
17. In 1953, Stanley Miller at the University of Chicago set up a laboratory ______________of chemical conditions on the primitive Earth and demonstrated the spontaneous synthesis of organic compounds.
18. Such _______________synthesis of organic compounds may have been an early stage in the origin of life.
19. Organic chemists finally rejected vitalism and embraced______________, accepting that the same physical and chemical laws govern all natural phenomena including the processes of life.
20. Organic chemistry was redefined as the study of carbon compounds ______________of their origin.
21. Organisms do produce the _____________ of organic compounds.
22. The laws of _______________apply to inorganic and organic compounds alike.

t	v	r	s	t	u	x	z	a	a	c	c	v	u	d	c	c	b	a	d	e	v
a	c	b	y	r	e	g	a	r	d	l	e	s	s	c	z	s	a	d	b	m	c
d	a	o	x	e	f	i	w	g	y	h	j	l	k	n	n	i	o	r	t	a	e
f	r	u	m	v	g	y	x	h	y	q	s	i	p	i	j	n	m	k	u	j	l
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