Chapter 4

Carbon and the Molecular Diversity of Life

PowerPoint® Lecture Presentations for

Biology

Eighth Edition

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Overview: Carbon: The Backbone of Life

- Although cells are 70–95% water, the rest consists mostly of carbon-based compounds.
- Carbon is unparalleled in its ability to form large, complex, and diverse molecules because *each carbon atom makes 4 bonds.*
- Proteins, DNA, carbohydrates, and other molecules that distinguish living matter are all composed of carbon compounds.

- What properties of carbon underlie its role as the molecular basis of life?

Organic chemistry is the study of carbon compounds

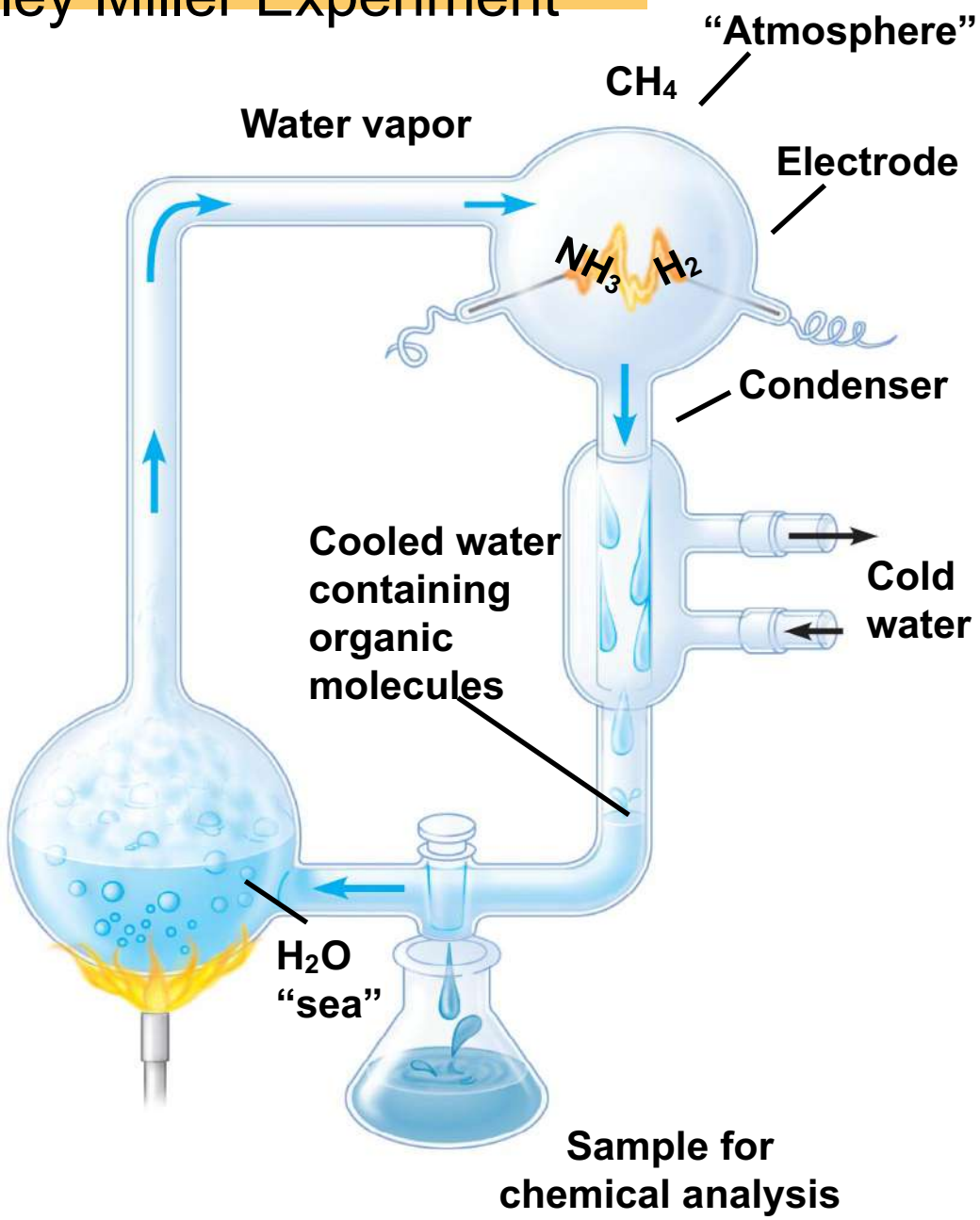
- ***Organic chemistry*** is the study of compounds that contain *carbon.*
- Organic compounds range from simple molecules to colossal ones.
- Most organic compounds contain hydrogen atoms in addition to carbon atoms.

Stanley Miller Experiment

Primative Earth Environment

Simple Organic Compounds

Synthesized



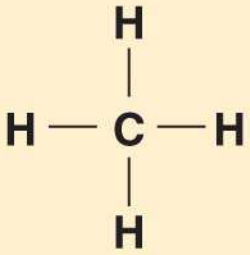
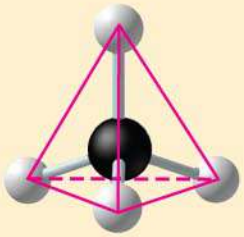
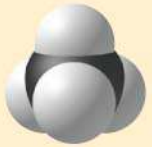
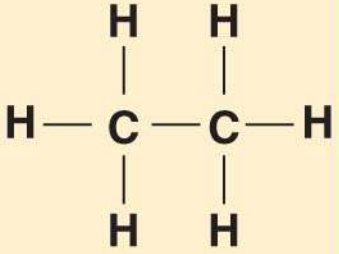
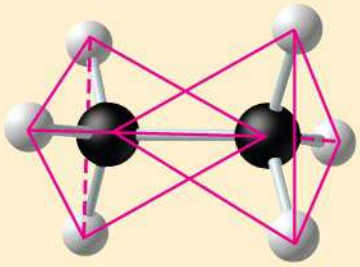
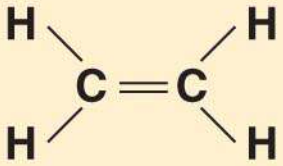
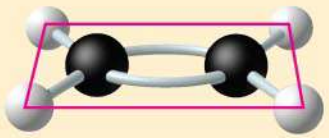
Carbon atoms can form diverse molecules by bonding to four other atoms

- *Electron configuration* is the key to an atom's characteristics.
- *Electron configuration determines chemical bonding: the kinds and number of bonds an atom will form with other atoms*.

The Formation of Bonds with *Carbon*

- With *four valence electrons (outer shell)*, carbon can form four covalent bonds with a variety of atoms.
- This *tetravalence* makes large, complex molecules possible.
- In molecules with multiple carbons, each carbon bonded to four other atoms has a tetrahedral shape.
- However, when two carbon atoms are joined by a double bond, the molecule has a flat shape.

The Shapes of Tree Dimensional Organic Molecules

Name	Molecular Formula	Structural Formula	Ball-and-Stick Model	Space-Filling Model
(a) Methane	CH_4			
(b) Ethane	C_2H_6			
(c) Ethene (ethylene)	C_2H_4			

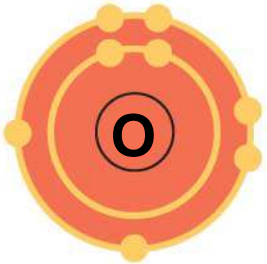
Valences of the major elements of organic molecules

Carbon is versatile and most frequently bonds with: H, O, N, and other C atoms.

Hydrogen (valence = 1)

H·

Oxygen (valence = 2)



·Ö:

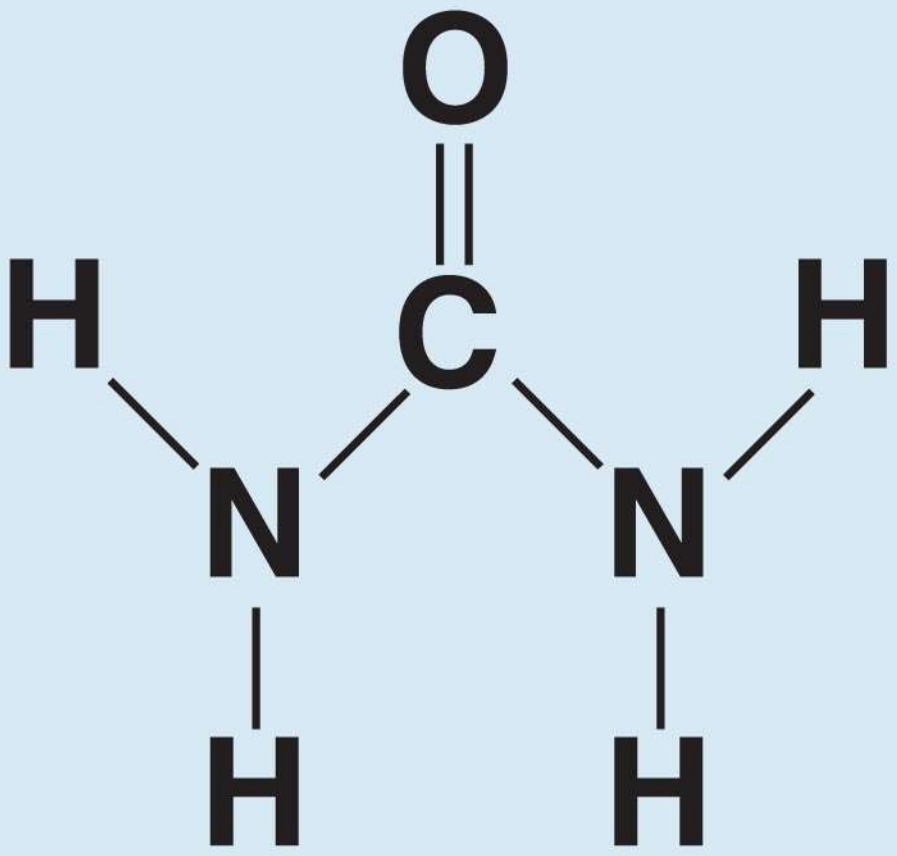
Nitrogen (valence = 3)

·N·

Carbon (valence = 4)

·C·

- Carbon atoms partner with other atoms to form compounds such as:
  - Carbon dioxide: CO_2 O = C = O
  - Urea: $CO(NH_2)_2$
  - Glucose: $C_6H_{12}O_6$

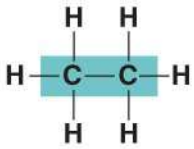


Urea

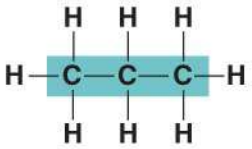
Molecular Diversity Arising from Carbon Skeleton Variation

- Carbon chains form the skeletons of most organic molecules.
- Carbon chains vary in length and shape.

Variation in carbon skeletons

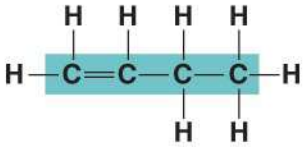


Ethane

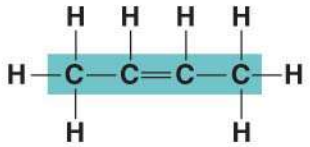


Propane

(a) **Length**

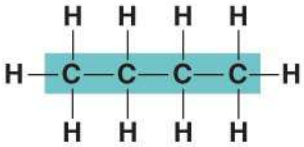


1-Butene

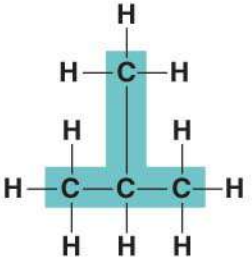


2-Butene

(c) **Double bonds**

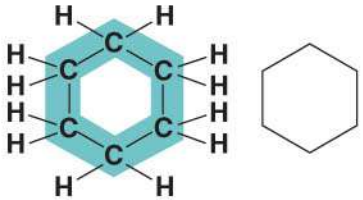


Butane

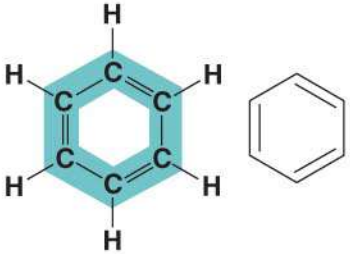


2-Methylpropane
(commonly called isobutane)

(b) **Branching**



Cyclohexane



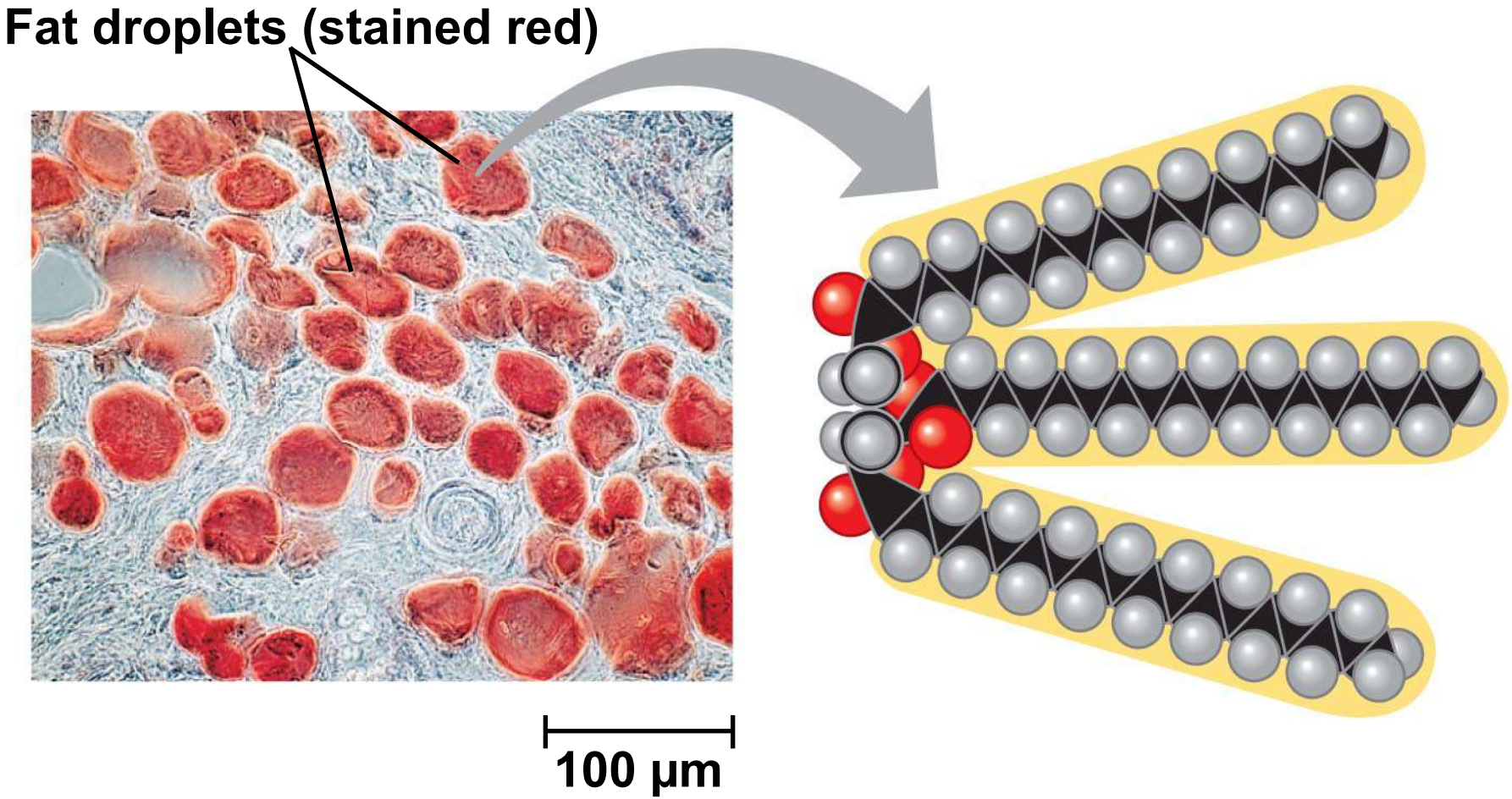
Benzene

(d) **Rings**

Hydrocarbons

- **Hydrocarbons** are organic molecules consisting of only carbon and hydrogen.
- Many organic molecules, such as fats, have hydrocarbon components in long hydrocarbon chains.
- Hydrocarbons can undergo reactions that release a large amount of energy.

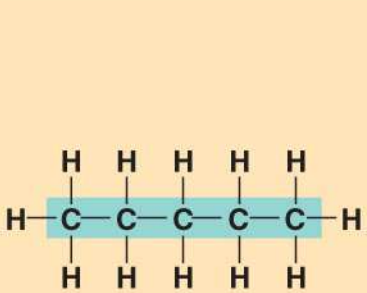
The role of hydrocarbons in fats - fatty acids (H-C chains)



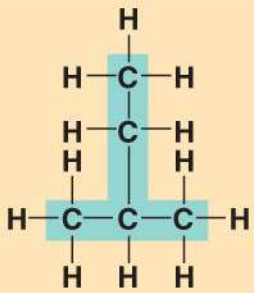
Isomers

- ***Isomers*** are compounds with the *same molecular formula* but *different structures* and *properties:*
  - **Structural isomers** have different covalent arrangements of their atoms.
  - **Geometric isomers** have the same covalent arrangements but differ in spatial arrangements.
  - **Enantiomers** are isomers that are *mirror images* of each other.

Three types of Isomers

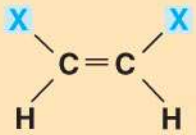


Pentane

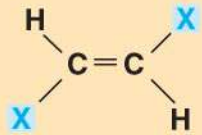


2-methyl butane

(a) **Structural** isomers

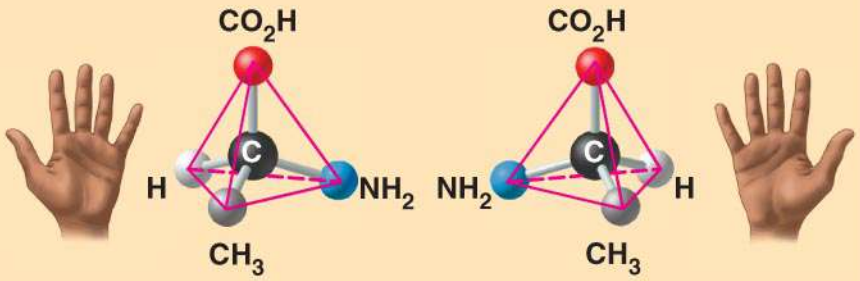


cis isomer: The two Xs are on the same side.



trans isomer: The two Xs are on opposite sides.

(b) **Geometric** isomers



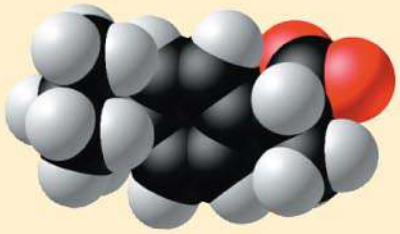
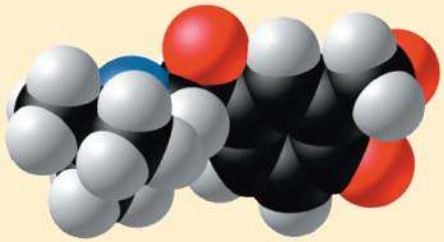
L isomer

D isomer

(c) **Enantiomers**

- *Enantiomers, mirror image isomers,* are important in the *pharmaceutical industry*.
- Two enantiomers of a *drug* may have different *effects.*
- Differing effects of enantiomers demonstrate that organisms are sensitive to even subtle variations in molecules.

The pharmacological importance of enantiomers

Drug	Condition	Effective Enantiomer	Ineffective Enantiomer
Ibuprofen	Pain; inflammation	 ***S*-Ibuprofen**	 ***R*-Ibuprofen**
Albuterol	Asthma	 ***R*-Albuterol**	 ***S*-Albuterol**

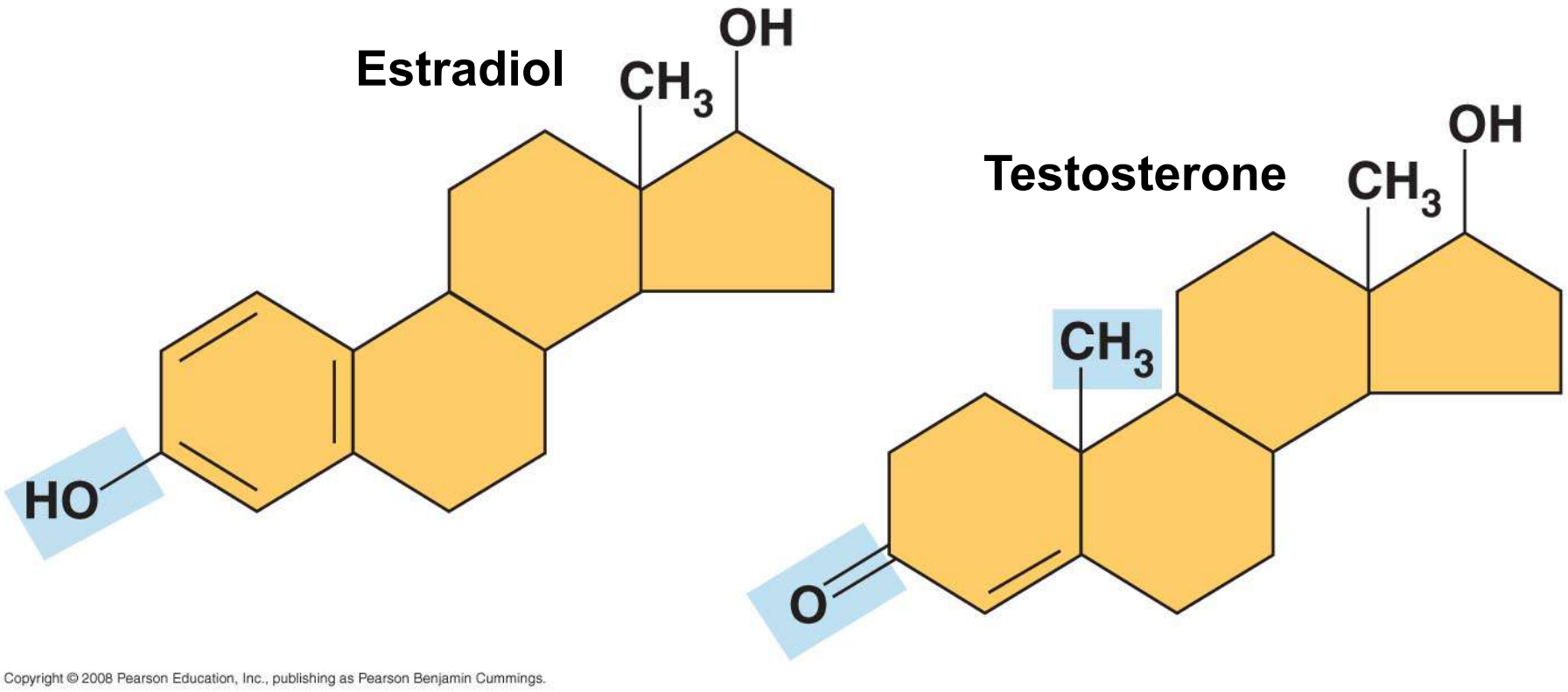
A small number of chemical groups are key to the functioning of biological molecules

- *Distinctive properties* of organic molecules depend not only on the *carbon skeleton* but also on the *molecular components attached* to it.
- A number of *characteristic groups* are often attached to skeletons of organic molecules. *These are called functional groups.*

The Chemical Groups Most Important in the Processes of Life

- ***Functional groups*** are the components of organic molecules that are *most commonly involved in chemical reactions.*
- The number and arrangement of functional groups give each molecule its unique properties.

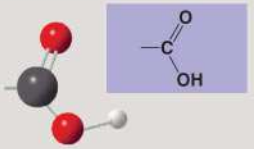
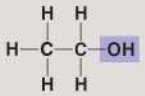
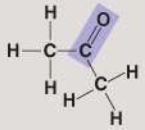
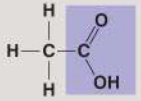
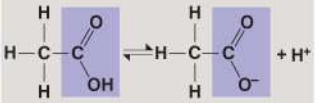
A comparison of chemical groups of female (estradiol) and male (testosterone) sex hormones



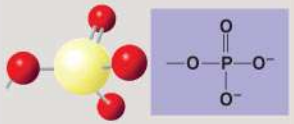
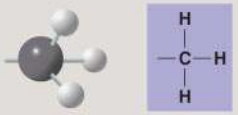
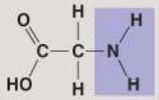
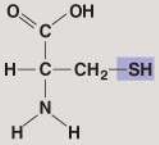
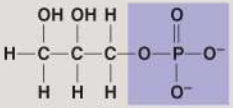
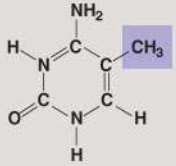
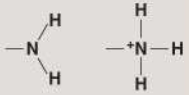
KEY Functional Groups

- The seven *functional groups* that are most important in the chemistry of life:
  - *Hydroxyl* group *-OH*
  - Carbonyl group -C=O
  - *Carboxyl* group *-COOH*
  - *Amino* group *-NH_2*
  - Sulfhydryl group -SH
  - *Phosphate* group *-OPO_3^{2-}*
  - Methyl group -CH_3

Important Chemical Groups

CHEMICAL GROUP	Hydroxyl	Carbonyl	Carboxyl
STRUCTURE	 (may be written HO—)		
	In a hydroxyl group (—OH), a hydrogen atom is bonded to an oxygen atom, which in turn is bonded to the carbon skeleton of the organic molecule. (Do not confuse this functional group with the hydroxide ion, OH^-.)	The carbonyl group ($>$CO) consists of a carbon atom joined to an oxygen atom by a double bond.	When an oxygen atom is double-bonded to a carbon atom that is also bonded to an —OH group, the entire assembly of atoms is called a carboxyl group (—COOH).
NAME OF COMPOUND	Alcohols (their specific names usually end in *-ol*)	Ketones if the carbonyl group is within a carbon skeleton Aldehydes if the carbonyl group is at the end of the carbon skeleton	Carboxylic acids, or organic acids
EXAMPLE	 Ethanol, the alcohol present in alcoholic beverages	 Acetone, the simplest ketone  Propanal, an aldehyde	 Acetic acid, which gives vinegar its sour taste
FUNCTIONAL PROPERTIES	• Is polar as a result of the electrons spending more time near the electronegative oxygen atom. • Can form hydrogen bonds with water molecules, helping dissolve organic compounds such as sugars.	• A ketone and an aldehyde may be structural isomers with different properties, as is the case for acetone and propanal. • These two groups are also found in sugars, giving rise to two major groups of sugars: aldoses (containing an aldehyde) and ketoses (containing a ketone).	• Has acidic properties because the covalent bond between oxygen and hydrogen is so polar; for example,  Acetic acid Acetate ion • Found in cells in the ionized form with a charge of 1– and called a carboxylate ion (here, specifically, the acetate ion).

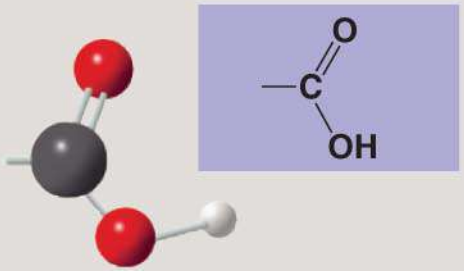
Important Chemical Groups

CHEMICAL GROUP	Amino	Sulfhydryl	Phosphate	Methyl
STRUCTURE		 (may be written HS—)		
	The amino group ($—NH_2$) consists of a nitrogen atom bonded to two hydrogen atoms and to the carbon skeleton.	The sulfhydryl group consists of a sulfur atom bonded to an atom of hydrogen; resembles a hydroxyl group in shape.	In a phosphate group, a phosphorus atom is bonded to four oxygen atoms; one oxygen is bonded to the carbon skeleton; two oxygens carry negative charges. The phosphate group ($—OPO_3^{2-}$, abbreviated Ⓟ) is an ionized form of a phosphoric acid group ($—OPO_3H^2$; note the two hydrogens).	A methyl group consists of a carbon bonded to three hydrogen atoms. The methyl group may be attached to a carbon or to a different atom.
NAME OF COMPOUND	Amines	Thiols	Organic phosphates	Methylated compounds
EXAMPLE	 Glycine	 Cysteine	 Glycerol phosphate	 5-Methyl cytidine
	Because it also has a carboxyl group, glycine is both an amine and a carboxylic acid; compounds with both groups are called amino acids.	Cysteine is an important sulfur-containing amino acid.	In addition to taking part in many important chemical reactions in cells, glycerol phosphate provides the backbone for phospholipids, the most prevalent molecules in cell membranes.	5-Methyl cytidine is a component of DNA that has been modified by addition of the methyl group.
FUNCTIONAL PROPERTIES	• Acts as a base; can pick up an H^+ from the surrounding solution (water, in living organisms).  (nonionized) (ionized) • Ionized, with a charge of 1+, under cellular conditions.	• Two sulfhydryl groups can react, forming a covalent bond. This "cross-linking" helps stabilize protein structure. • Cross-linking of cysteines in hair proteins maintains the curliness or straightness of hair. Straight hair can be "permanently" curled by shaping it around curlers, then breaking and re-forming the cross-linking bonds.	• Contributes negative charge to the molecule of which it is a part (2– when at the end of a molecule; 1– when located internally in a chain of phosphates). • Has the potential to react with water, releasing energy.	• Addition of a methyl group to DNA, or to molecules bound to DNA, affects expression of genes. • Arrangement of methyl groups in male and female sex hormones affects their shape and function.

Some biologically important chemical groups—carboxyl group

Carboxyl

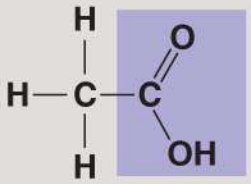
STRUCTURE



NAME OF COMPOUND

Carboxylic acids, or **organic acids**

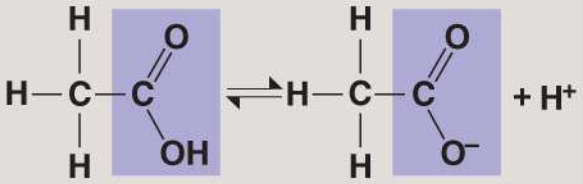
EXAMPLE



Acetic acid, which gives vinegar its sour taste

FUNCTIONAL PROPERTIES

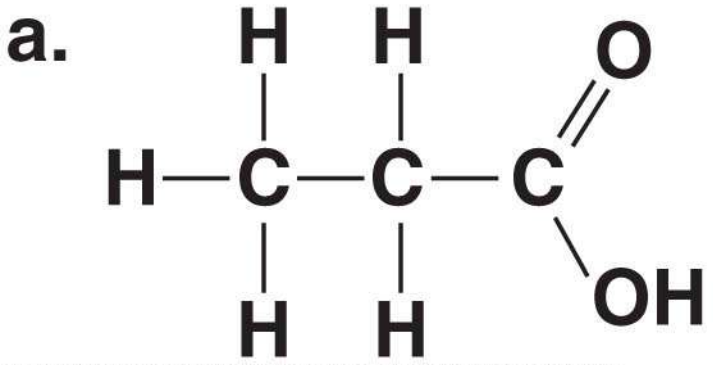
- Has **acidic** properties because the covalent bond between oxygen and hydrogen is so polar; for example,

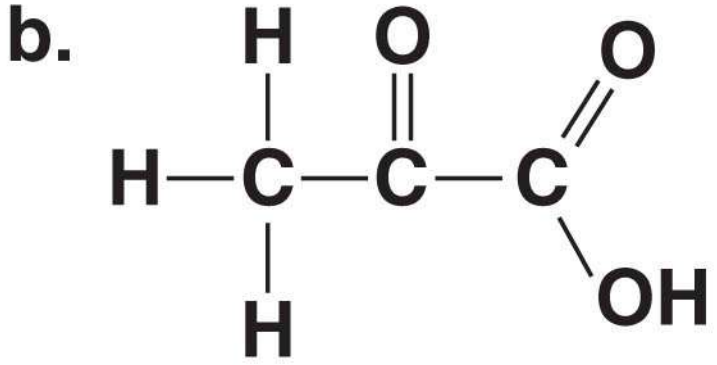


Acetic acid Acetate ion

- Found in cells in the ionized form with a charge of 1– and called a carboxylate ion (here, specifically, the acetate ion).

- *Carboxyl group at the end of each molecule*

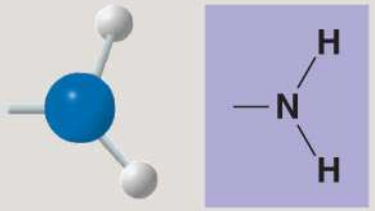




Some biologically important chemical groups—amino group

Amino

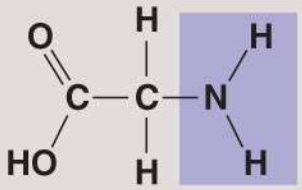
STRUCTURE



Amines

NAME OF COMPOUND

EXAMPLE

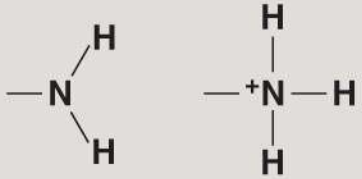


Glycine

Because it also has a carboxyl group, glycine is both an amine and a carboxylic acid; compounds with both groups are called amino acids.

FUNCTIONAL PROPERTIES

- **Acts as a base; can pick up an H^+ from the surrounding solution (water, in living organisms).**



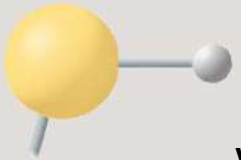
(nonionized) (ionized)

- **Ionized, with a charge of 1+, under cellular conditions.**

Some biologically important chemical groups—sulfhydryl group

Sulfhydryl

STRUCTURE



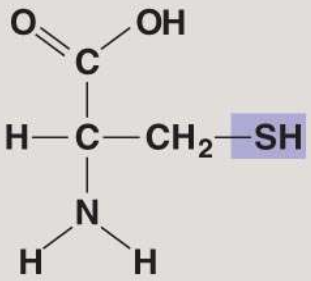
—SH

(may be written HS—)

NAME OF COMPOUND

Thiols

EXAMPLE



Cysteine

Cysteine is an important sulfur-containing amino acid.

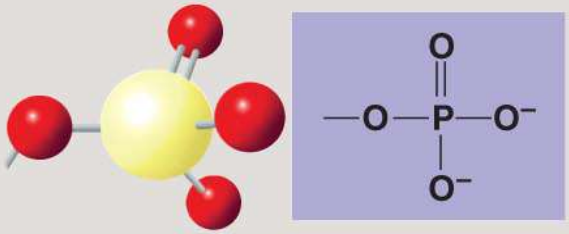
FUNCTIONAL PROPERTIES

- Two sulfhydryl groups can react, forming a covalent bond. This **"cross-linking"** helps **stabilize protein structure.**
- Cross-linking of cysteines in hair proteins maintains the curliness or straightness of hair. Straight hair can be "permanently" curled by shaping it around curlers, then breaking and re-forming the cross-linking bonds.

Some biologically important chemical groups—phosphate group

Phosphate

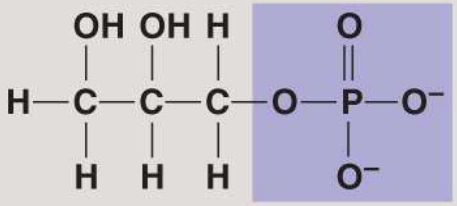
STRUCTURE



NAME OF COMPOUND

Organic phosphates

EXAMPLE



Glycerol phosphate

In addition to taking part in many important chemical reactions in cells, glycerol phosphate provides the backbone for phospholipids, the most prevalent molecules in cell membranes.

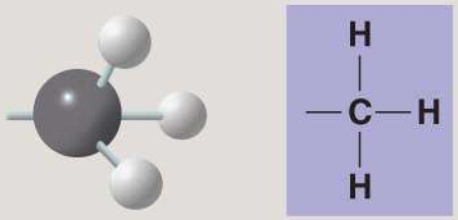
FUNCTIONAL PROPERTIES

- **Contributes negative charge to the molecule of which it is a part (2– when at the end of a molecule; 1– when located internally in a chain of phosphates).**
- **Has the potential to react with water, releasing energy.**

Some biologically important chemical groups—methyl group

Methyl

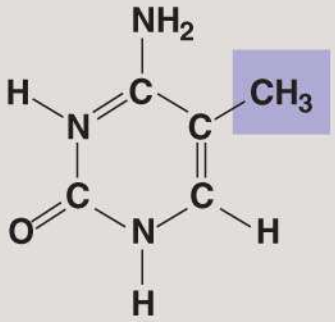
STRUCTURE



NAME OF COMPOUND

Methylated compounds

EXAMPLE



5-Methyl cytidine

5-Methyl cytidine is a component of DNA that has been modified by addition of the methyl group.

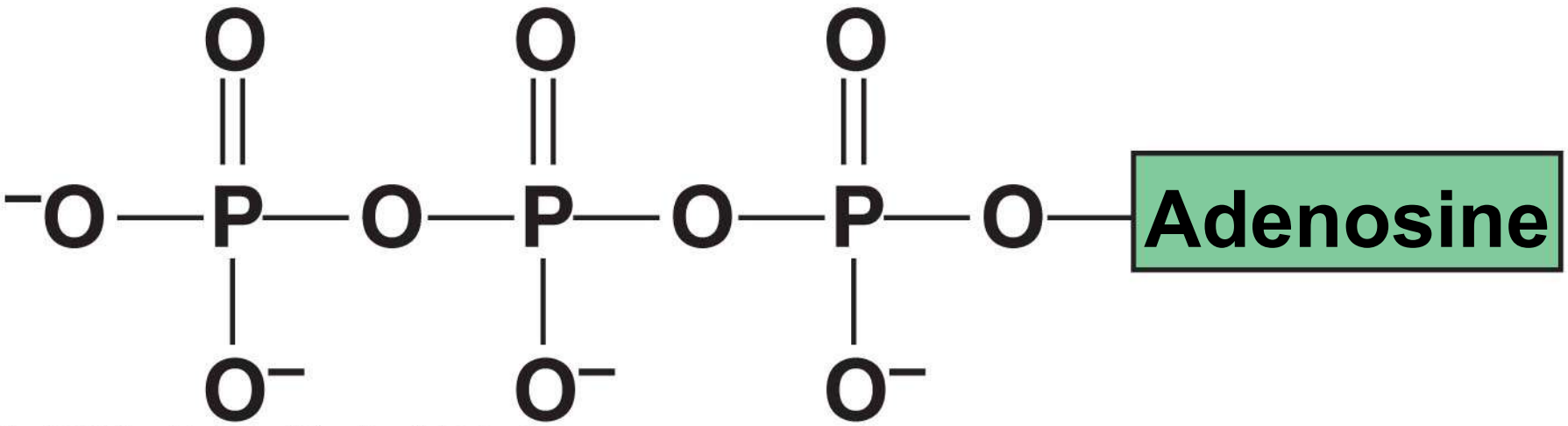
FUNCTIONAL PROPERTIES

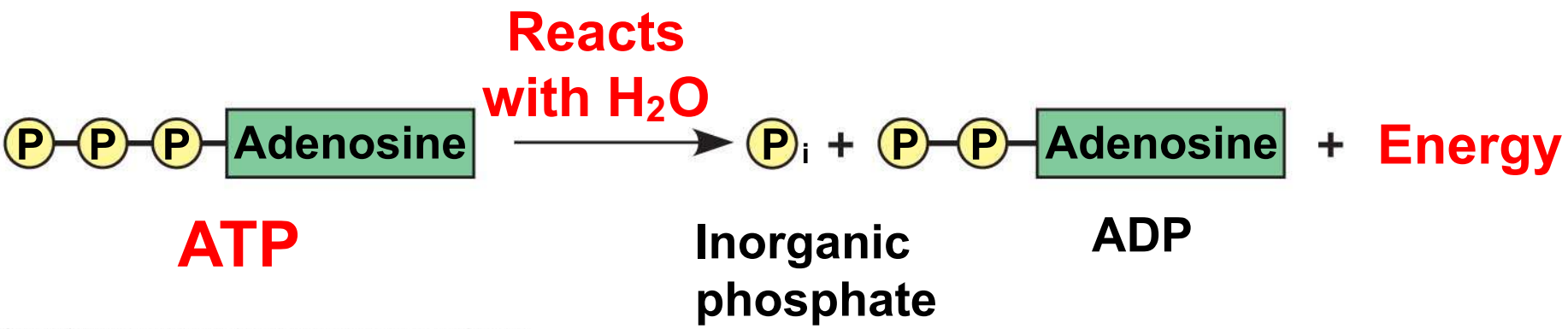
- **Addition of a methyl group to DNA, or to molecules bound to DNA, affects expression of genes.**
- **Arrangement of methyl groups in male and female sex hormones affects their shape and function.**

ATP: An Important Source of Energy for Cellular Processes

- One phosphate molecule, **adenosine triphosphate** (***ATP***), is the primary energy-transferring molecule in the cell.
- ATP consists of an organic molecule called adenosine attached to a string of three phosphate groups.

ATP

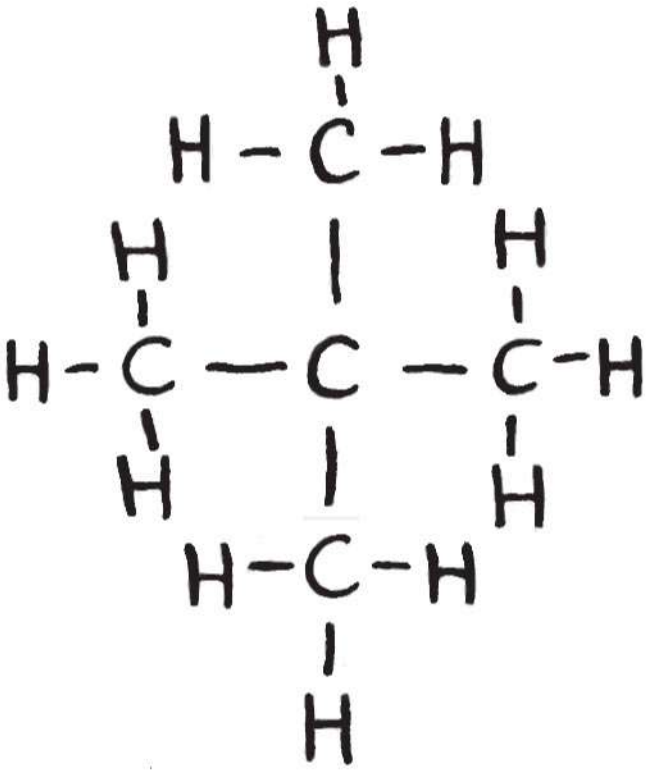




The Chemical Elements of Life: *A Review*

- The versatility of carbon makes possible the great diversity of organic molecules.
- Variation at the molecular level lies at the foundation of all biological diversity.

What is the molecular formula for this organic compound? Can you build it with a model?



You should now be able to:

1. Explain how *carbon's* electron configuration explains its *ability to form large, complex, diverse organic molecules.*
2. Describe how *carbon skeletons* may vary and explain how this variation contributes to the diversity and complexity of organic molecules.
3. Distinguish among the three types of *isomers*: structural, geometric, and enantiomer.

4. Name the major *functional groups* found in organic molecules; describe the basic structure of each functional group and outline the chemical properties of the organic molecules in which they occur.
5. Explain how *ATP* functions as the primary energy transfer molecule in living cells.