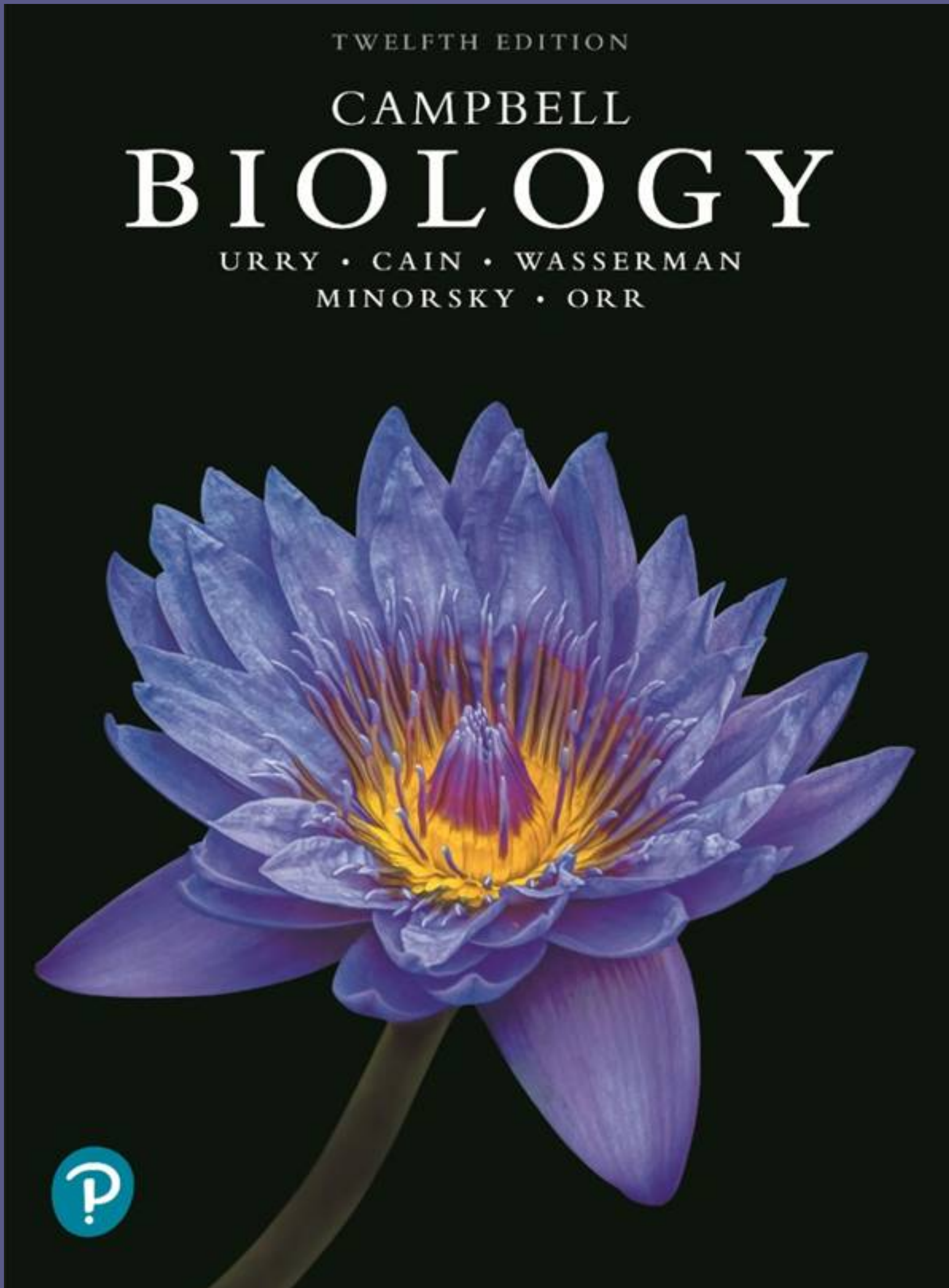


Chapter 4

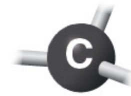
Carbon and the Molecular Diversity of Life

Lecture Presentations by
Nicole Tunbridge and
Kathleen Fitzpatrick

Figure 4.1

What makes carbon the basis for all biological molecules?

Carbon can form four bonds.



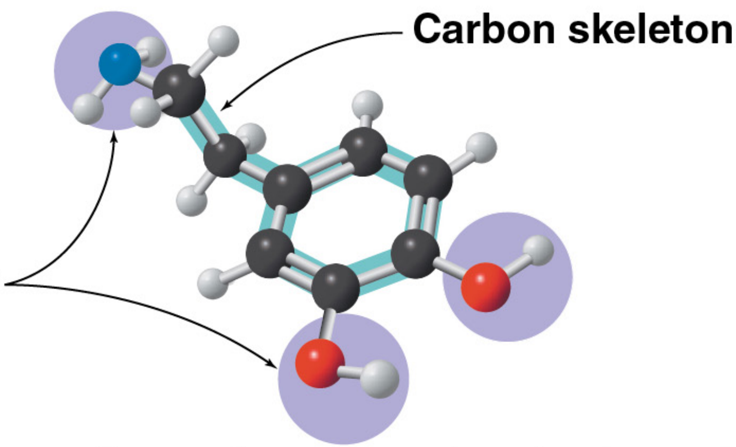
Carbon can bond to other carbons, resulting in carbon skeletons. Carbon also commonly bonds to

H hydrogen,

O oxygen, and

N nitrogen.

Properties of a carbon-containing molecule depend on its carbon skeleton and chemical groups.



Dopamine, the molecule shown here, promotes mother-infant bonding.

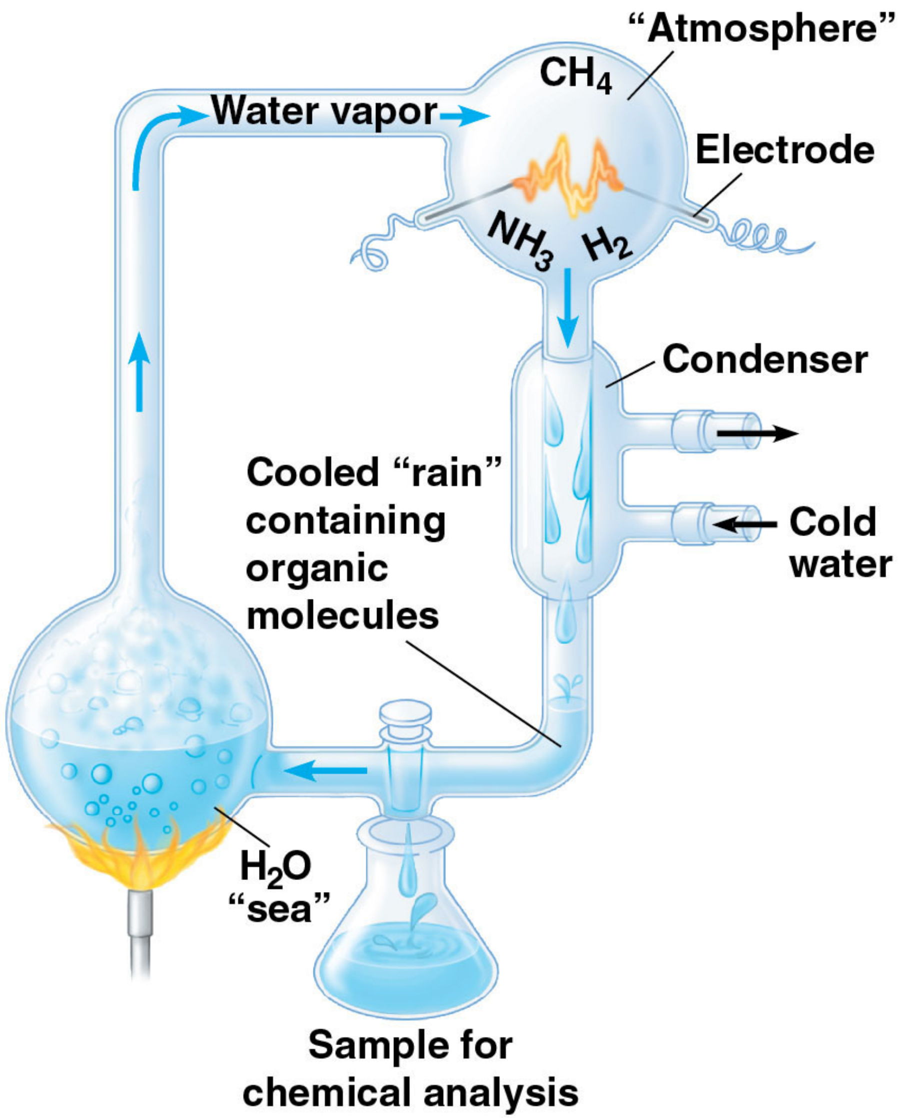
CONCEPT 4.1: Organic chemistry is key to the origin of life

- **Organic chemistry** is the study of compounds that contain carbon, regardless of origin
- Organic compounds range from simple molecules to colossal ones

Organic Molecules and the Origin of Life on Earth

- Stanley Miller's classic experiment demonstrated the abiotic synthesis of organic compounds
- Experiments support the idea that abiotic synthesis of organic compounds, perhaps near volcanoes, could have been a stage in the origin of life

Figure 4.2



"Atmosphere"
CH_4
Water vapor
Electrode
NH_3
H_2
Condenser
Cold water
Cooled "rain" containing organic molecules
H_2O "sea"
Sample for chemical analysis

- The overall percentages of the major elements of life—C, H, O, N, S, and P—are quite uniform from one organism to another
- Because carbon can form four bonds, these building blocks can be used to make an inexhaustible variety of organic molecules
- The great diversity of organisms on the planet is due to the versatility of carbon

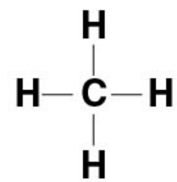
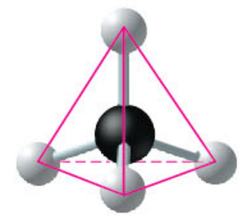
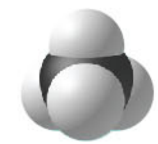
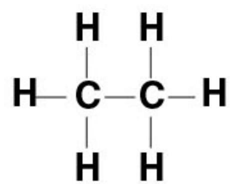
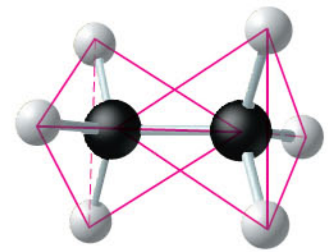
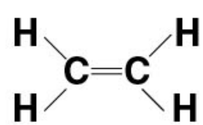
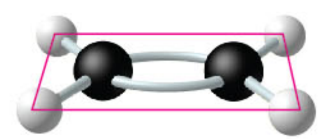
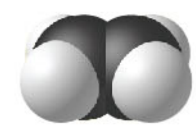
CONCEPT 4.2: Carbon atoms can form diverse molecules by bonding to four other atoms

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

The Formation of Bonds with Carbon

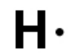
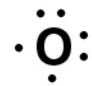
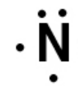
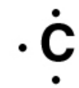
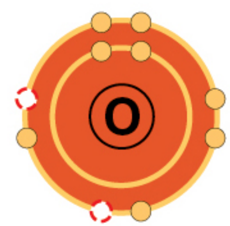
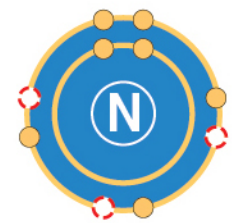
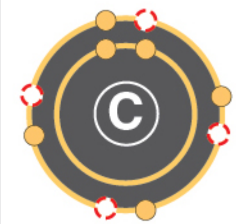
- With four valence electrons, carbon can form four covalent bonds with a variety of atoms
- This enables carbon to form large, complex molecules
- In molecules with multiple carbons, each carbon bonded to four other atoms has a tetrahedral shape
- However, when two carbon atoms are joined by a double bond, the atoms joined to the carbons are in the same plane as the carbons

Figure 4.3

Molecule and Molecular Shape	Molecular Formula	Structural Formula	Ball-and-Stick Model (molecular shape in pink)	Space-Filling Model
(a) Methane	CH_4			
(b) Ethane	C_2H_6			
(c) Ethene (ethylene)	C_2H_4			

- The number of unpaired electrons in the valence shell of an atom is generally equal to its **valence**, the number of covalent bonds it can form

Figure 4.4

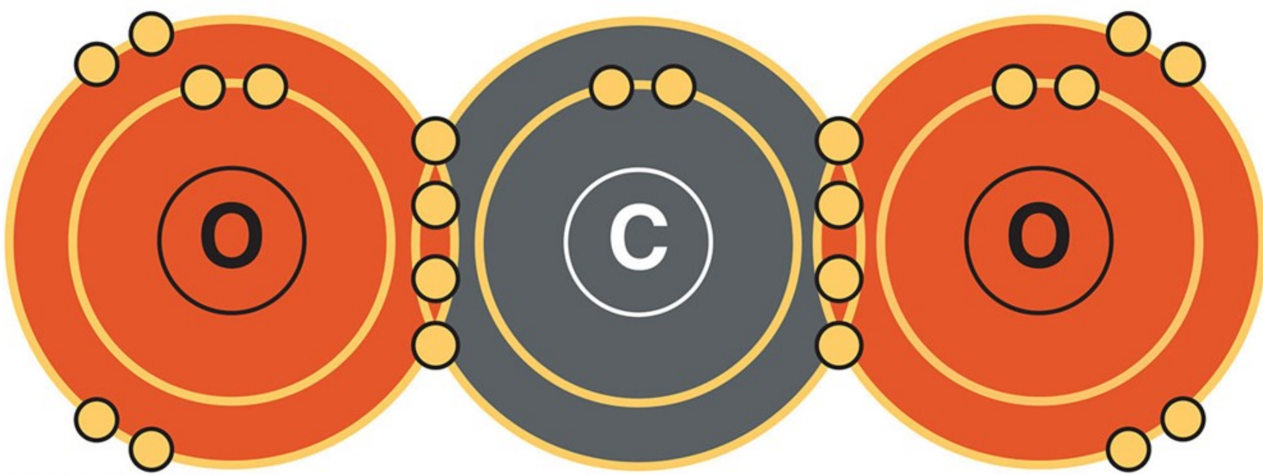
	Hydrogen	Oxygen	Nitrogen	Carbon
Lewis dot structure showing existing valence electrons				
Electron distribution diagram with red circles showing electrons needed to fill the valence shell				
Number of electrons needed to fill the valence shell	1	2	3	4
Valence: Number of bonds the element can form	1	2	3	4

- The electron configuration of carbon gives it covalent compatibility with many different elements
- The most frequent bonding partners of carbon are hydrogen, oxygen, and nitrogen

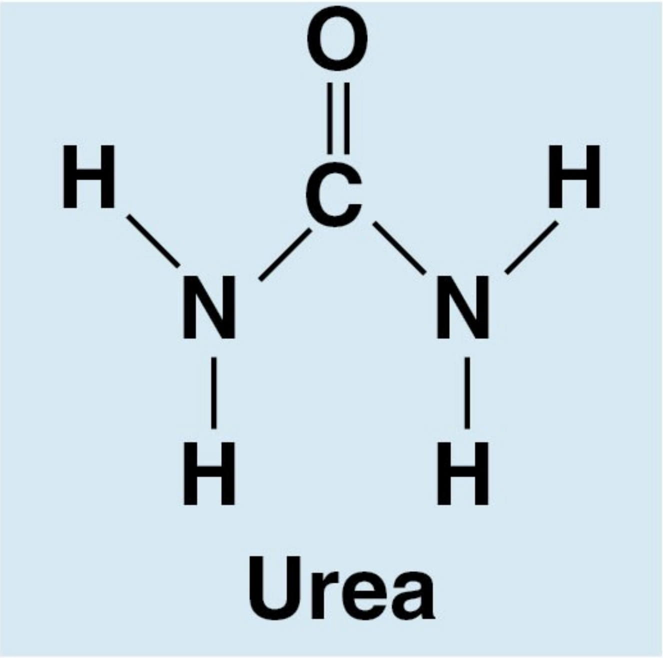
Molecular Diversity Arising from Variation in Carbon Skeletons

- Carbon atoms can partner with atoms other than hydrogen, such as the following:
  - Carbon dioxide: CO_2

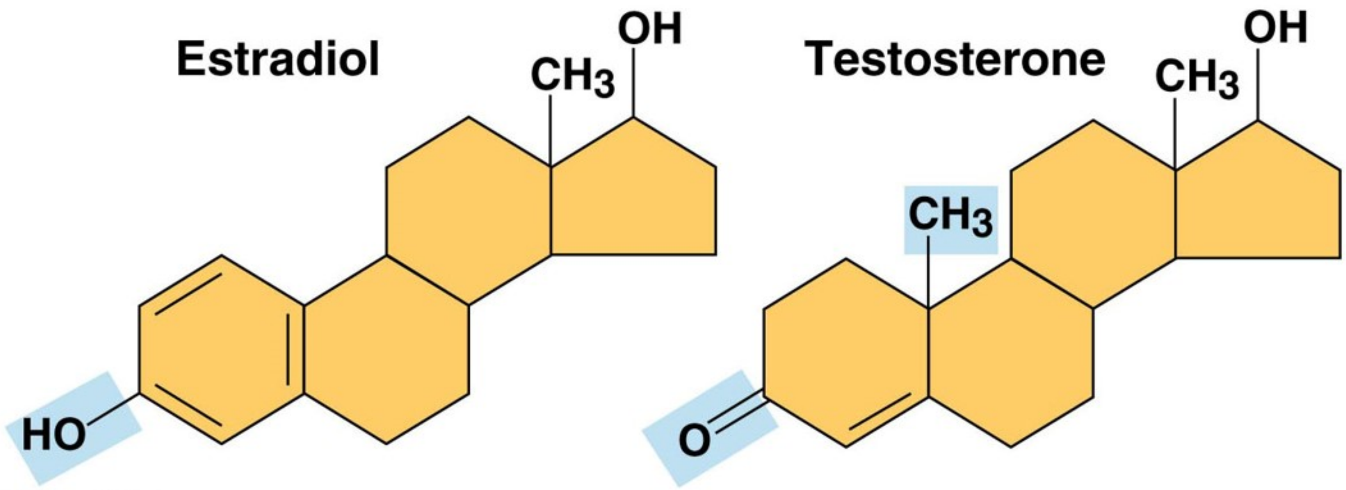
$$O = C = O$$



– Urea: $CO(NH_2)_2$

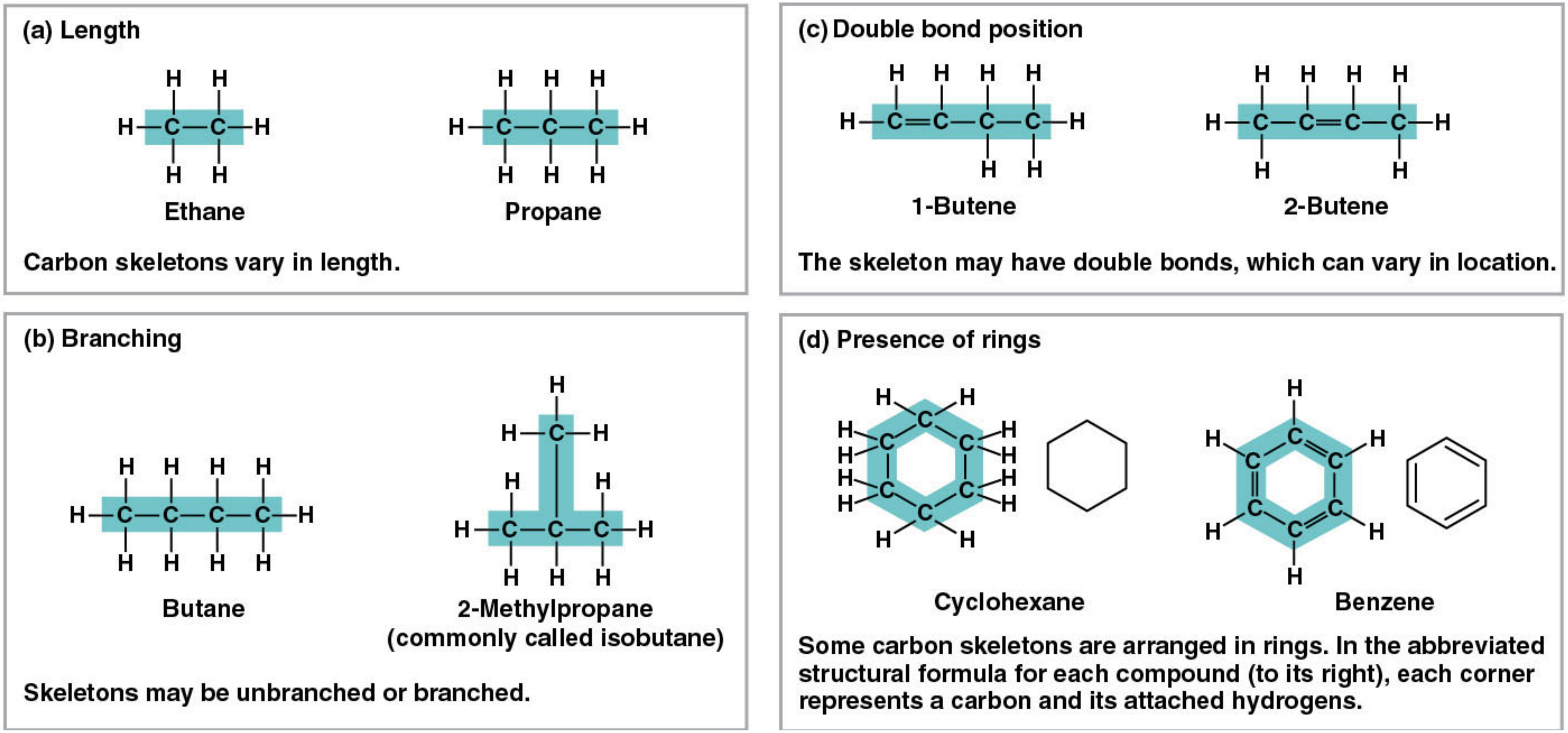


– Carbon atoms can also be linked into chains as shown for C_3H_8



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

Figure 4.5


(a) Length
Ethane
Propane
Carbon skeletons vary in length.
(b) Branching
Butane
2-Methylpropane
(commonly called isobutane)
Skeletons may be unbranched or branched.
(c) Double bond position
1-Butene
2-Butene
The skeleton may have double bonds, which can vary in location.
(d) Presence of rings
Cyclohexane
Benzene
Some carbon skeletons are arranged in rings. In the abbreviated structural formula for each compound (to its right), each corner represents a carbon and its attached hydrogens.

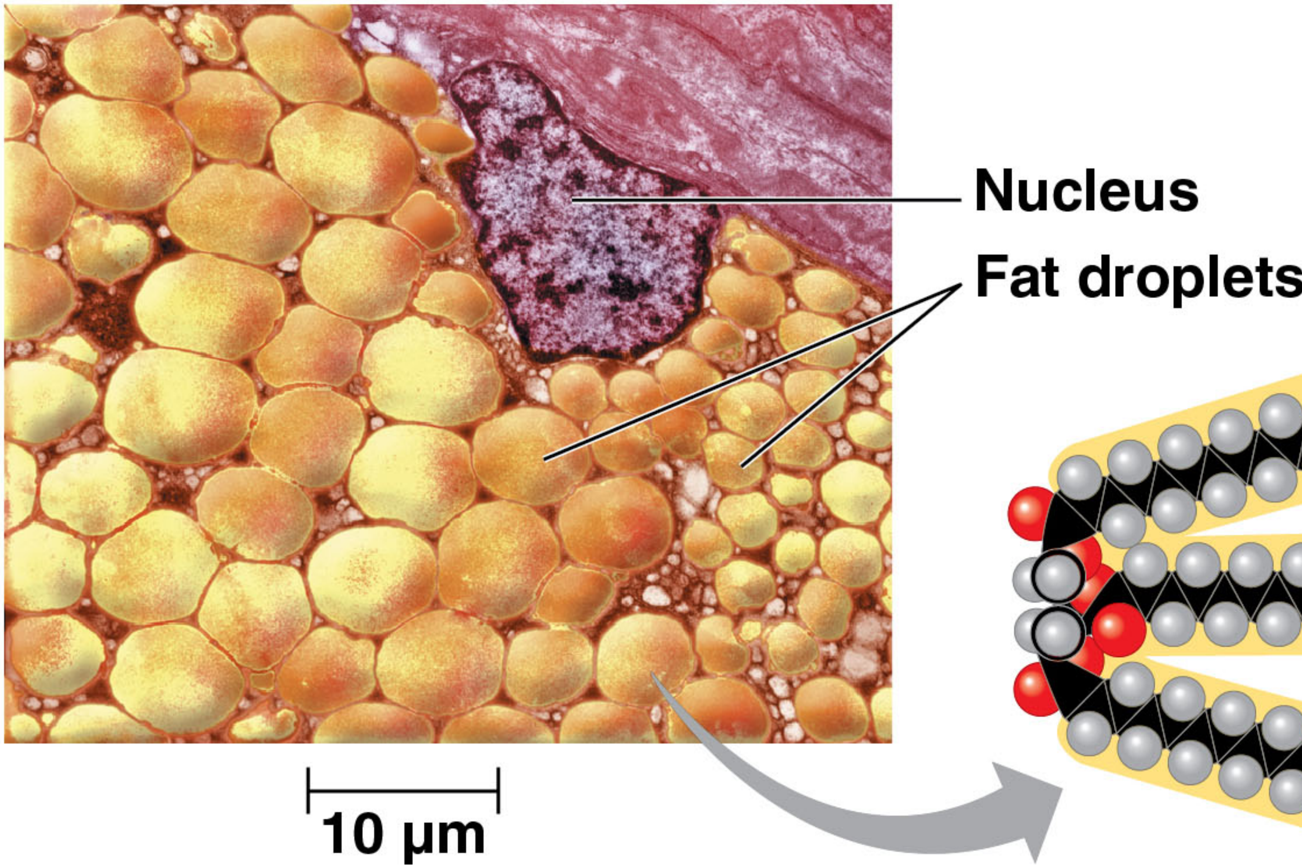
Animation: Diversity of Carbon-Based Molecules

[redacted]

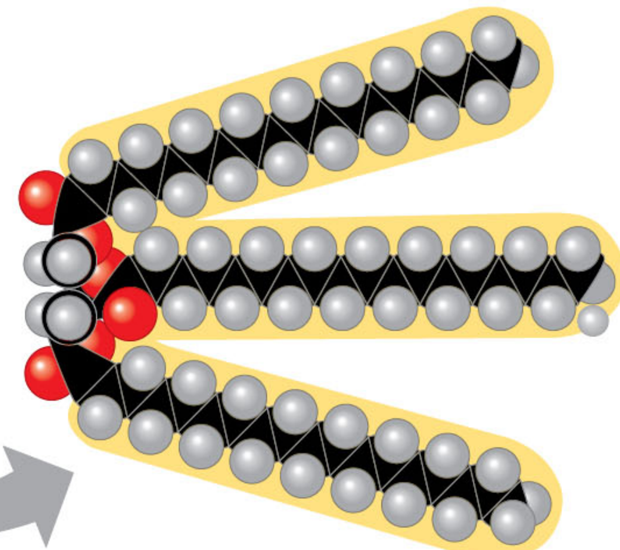
Hydrocarbons

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

Figure 4.6



(a) Part of a human adipose cell

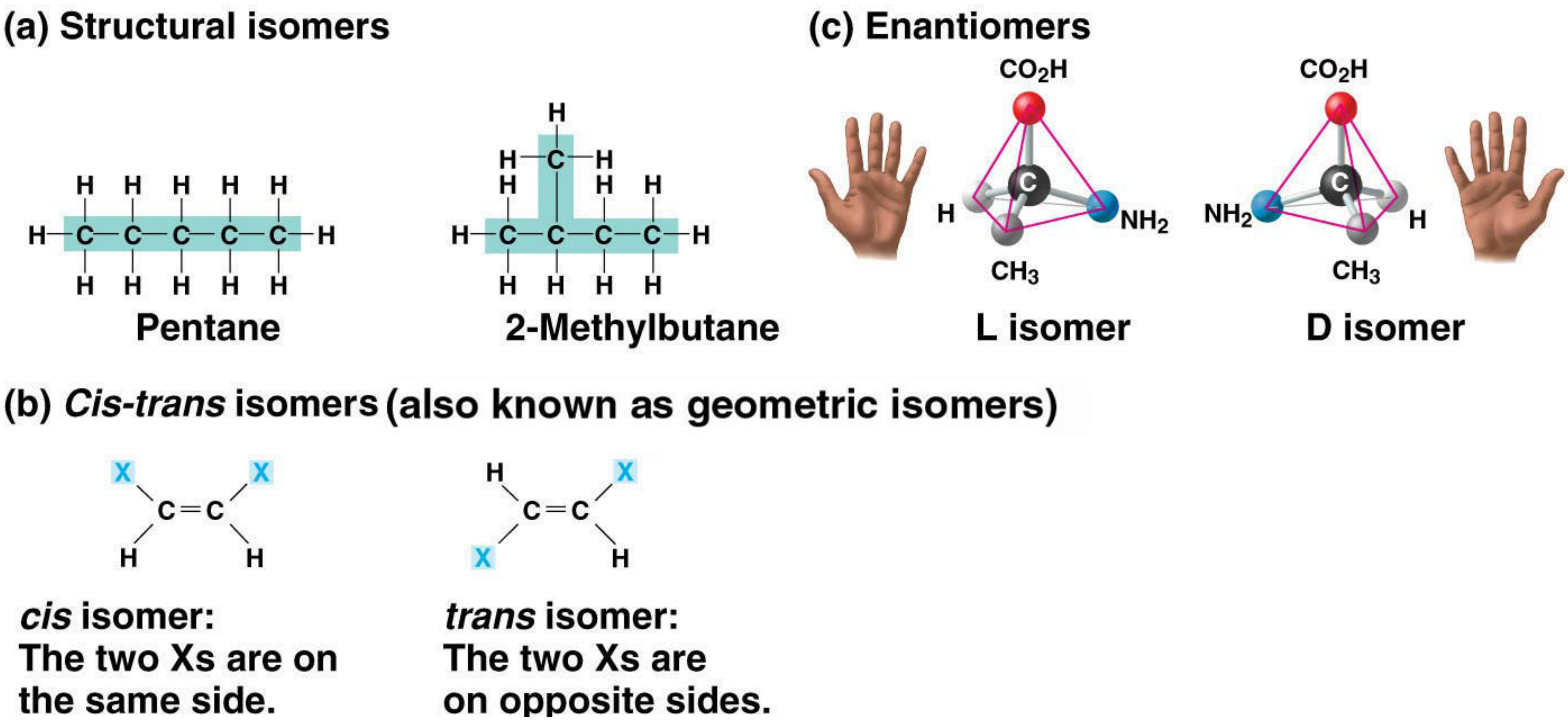


(b) A fat molecule

Isomers

- **Isomers** are compounds with the same molecular formula but different structures and properties
  - **Structural isomers** have different covalent arrangements of their atoms
  - ***Cis-trans* isomers** (also called geometric isomers) have the same covalent bonds but differ in their spatial arrangements
  - **Enantiomers** are isomers that are mirror images of each other

Figure 4.7

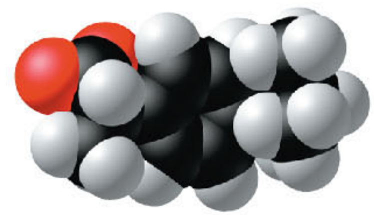
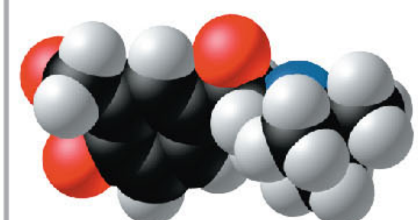
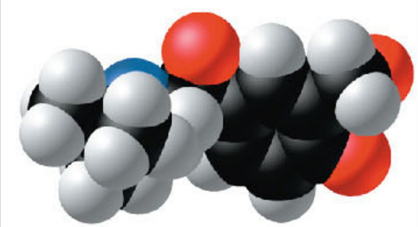

(a) Structural isomers
Pentane
2-Methylbutane
(c) Enantiomers
CO_2H
NH_2
CH_3
L isomer
D isomer
(b) *Cis-trans* isomers (also known as geometric isomers)
cis isomer:
The two Xs are on the same side.
trans isomer:
The two Xs are on opposite sides.

Animation: Isomers

[redacted]

- Enantiomers are important in the pharmaceutical industry
- Two enantiomers of a drug may have different effects
- Often only one enantiomer is biologically active
- Differing effects of enantiomers demonstrate that organisms are sensitive to even subtle variations in molecules

Figure 4.8

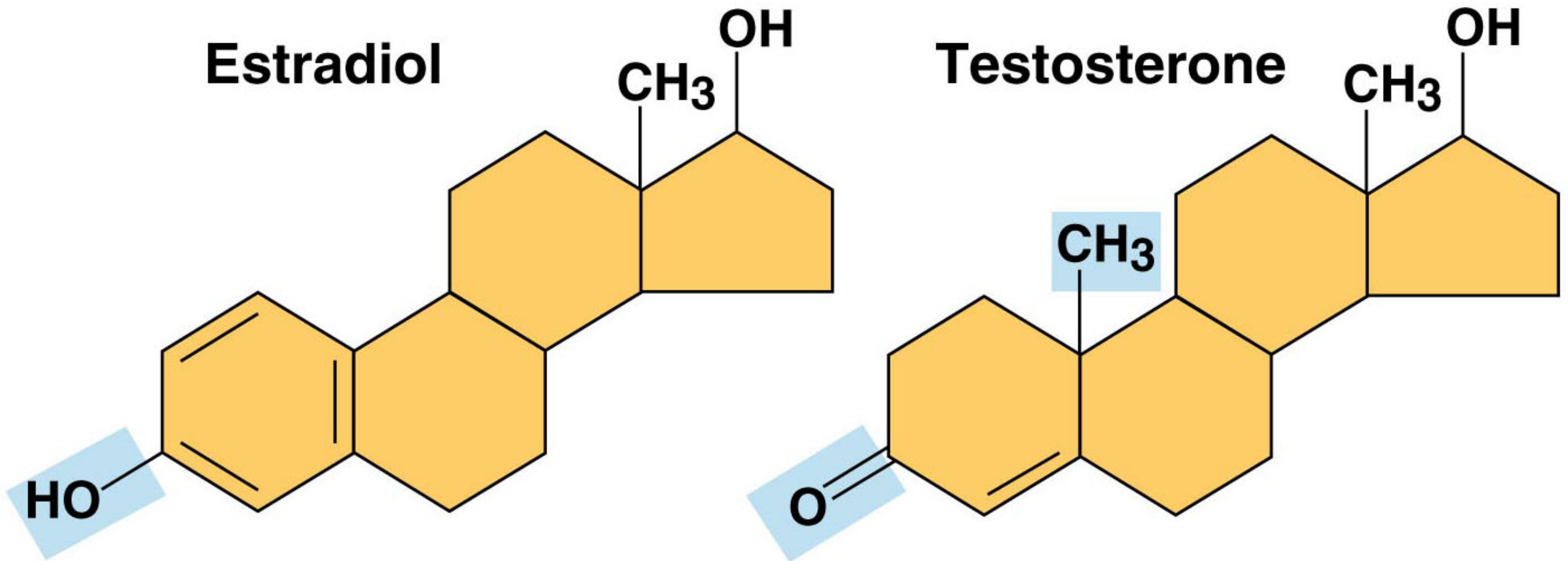
Drug	Effects	Effective Enantiomer	Ineffective Enantiomer
Ibuprofen	Reduces inflammation and pain	 *S*-Ibuprofen	 *R*-Ibuprofen
Albuterol	Relaxes bronchial (airway) muscles, improving airflow in asthma patients	 *R*-Albuterol	 *S*-Albuterol

CONCEPT 4.3: A few chemical groups are key to molecular function

- Distinctive properties of organic molecules depend on the carbon skeleton and the chemical groups attached to it
- These groups help give each molecule its unique properties

The Chemical Groups Most Important in the Processes of Life

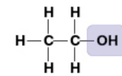
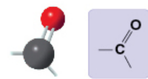
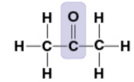
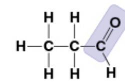
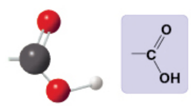
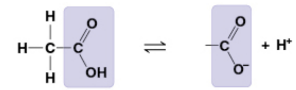
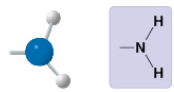
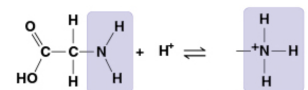
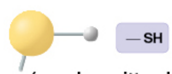
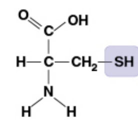
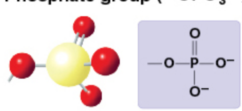
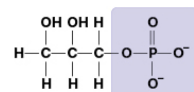
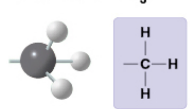
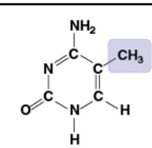
- Estradiol and testosterone are both steroids with a common carbon skeleton, in the form of four fused rings
- These sex hormones differ only in the chemical groups attached to the rings of the carbon skeleton


Estradiol
OH
CH3
HO
Testosterone
OH
CH3
CH3
O

- **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

- The seven functional groups that are most important in the chemistry of life are the following:
  - Hydroxyl group
  - Carbonyl group
  - Carboxyl group
  - Amino group
  - Sulfhydryl group
  - Phosphate group
  - Methyl group

Figure 4.9

Chemical Group	Compound Name	Examples
Hydroxyl group (—OH)  (may be written HO—)	Alcohol	 Ethanol
Carbonyl group (>C═O) 	Ketone Aldehyde	 Acetone  Propanal
Carboxyl group (—COOH) 	Carboxylic acid, or organic acid	 Acetic acid Ionized form of —COOH
Amino group (—NH_2) 	Amine	 Glycine Ionized form of —NH_2
Sulfhydryl group (—SH)  (may be written HS—)	Thiol	 Cysteine
Phosphate group (—OPO_3^{2-}) 	Organic phosphate	 Glycerol phosphate
Methyl group (—CH_3) 	Methylated compound	 5-Methylcytosine

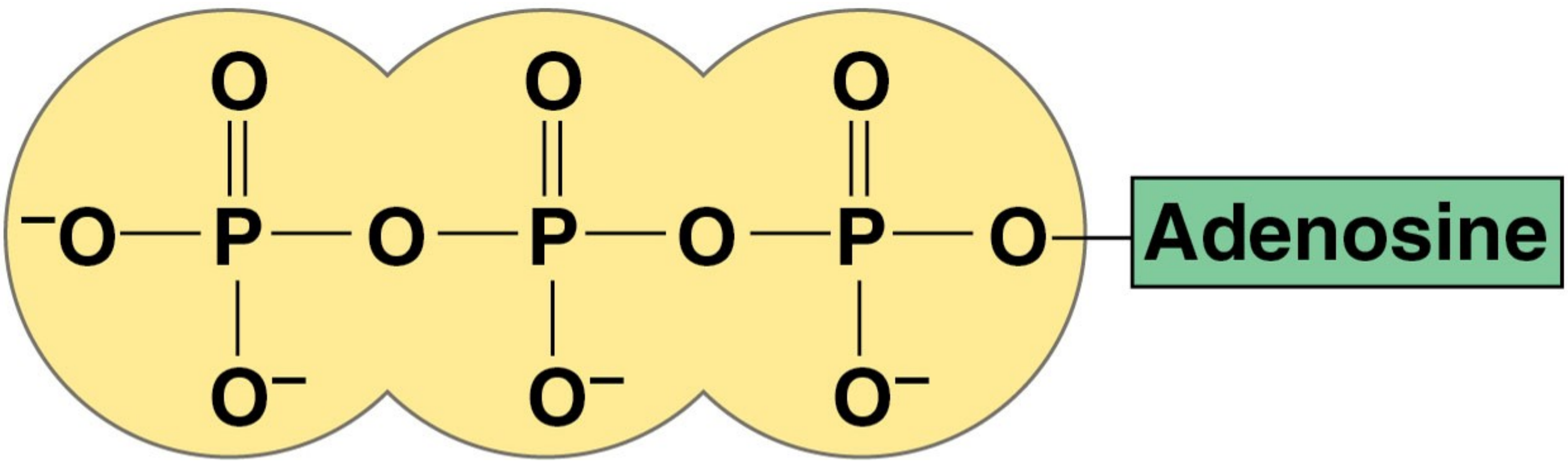
Animation: Functional Groups

[redacted]

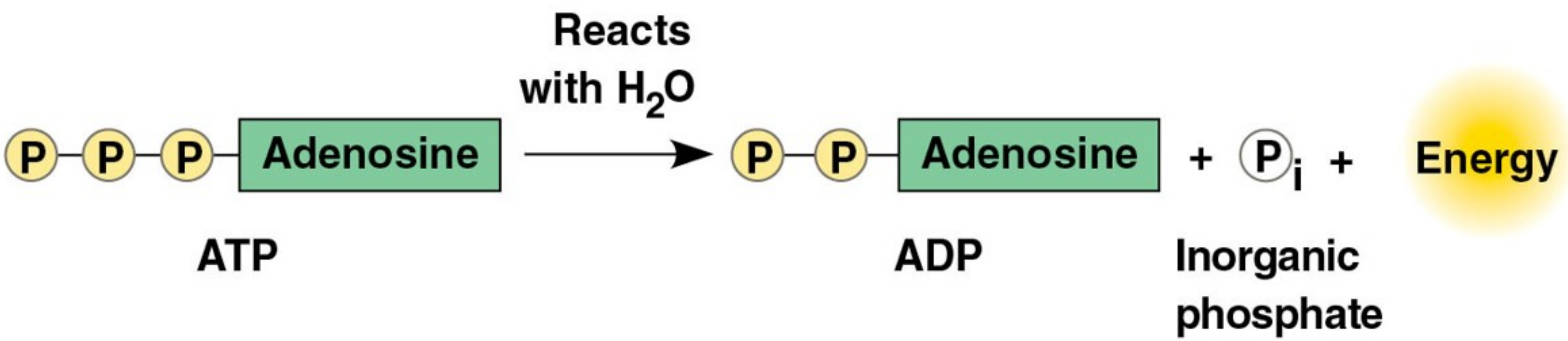
ATP: An Important Source of Energy for Cellular Processes

- An important organic phosphate is **adenosine triphosphate** (**ATP**)
- ATP consists of an organic molecule called adenosine attached to a string of three phosphate groups
- ATP stores the potential to react with water
- This reaction releases energy that can be used by the cell

UNF04-07



UNF04-08



Reacts with H_2O
P
P
P
Adenosine
ATP
P
P
Adenosine
ADP
+
P_i
+
Energy
Inorganic phosphate

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 on our planet

Figure 4.UN01a

Product Compound	Molecular Formula	Molar Ratio (Relative to Glycine)
Glycine	$C_2H_5NO_2$	1.0
Serine	$C_3H_7NO_3$	3.0×10^{-2}
Methionine	$C_5H_{11}NO_2S$	1.8×10^{-3}
Alanine	$C_3H_7NO_2$	1.1

Data from E. T. Parker et al., Primordial synthesis of amines and amino acids in a 1958 Miller H_2S-rich spark discharge experiment, *Proceedings of the National Academy of Sciences USA* 108:5526-5531 (2011). www.pnas.org/cgi/doi/10.1073/pnas.1019191108.

Figure 4.UN01b

114

March 24, 1958 Run #22

CH_4	25.8
CO_2	8.7
H_2S	10.0
NH_3	25. (3.5 ml Con NH_3)

300 ml H_2O

Started spark at 5:30 P.M. Monday March 24, 1958

After a few minutes there was yellowing of the soln but no green.

Figure 4.UN08

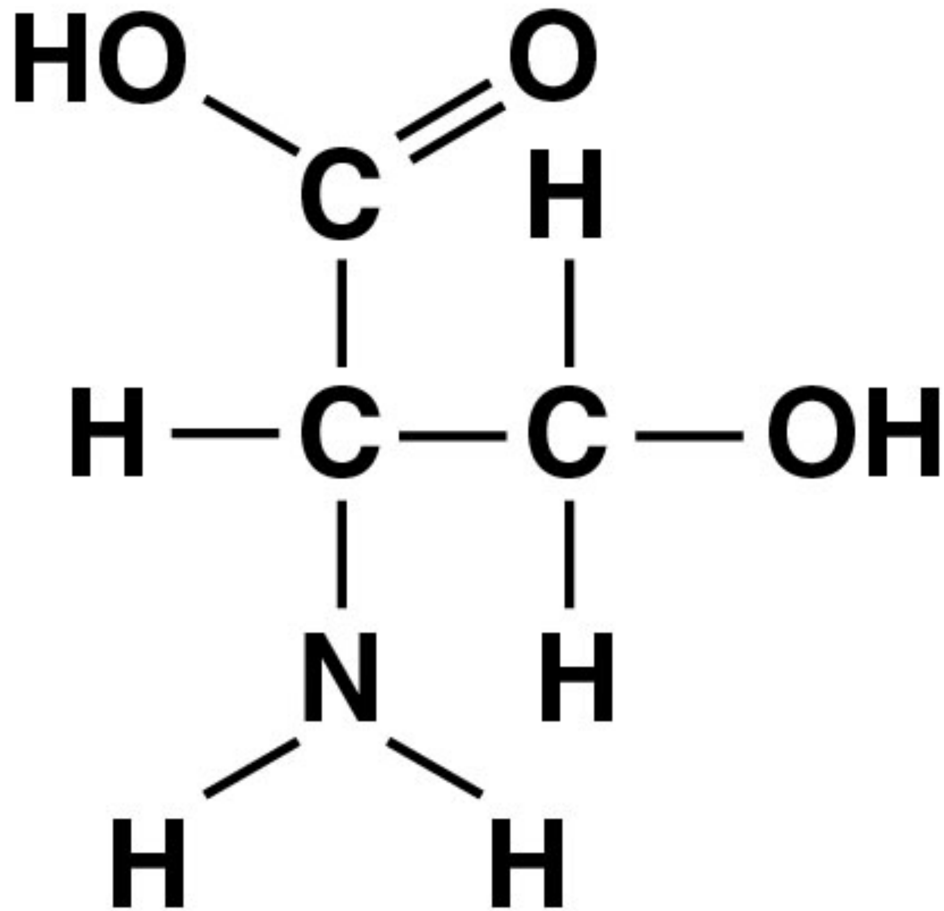
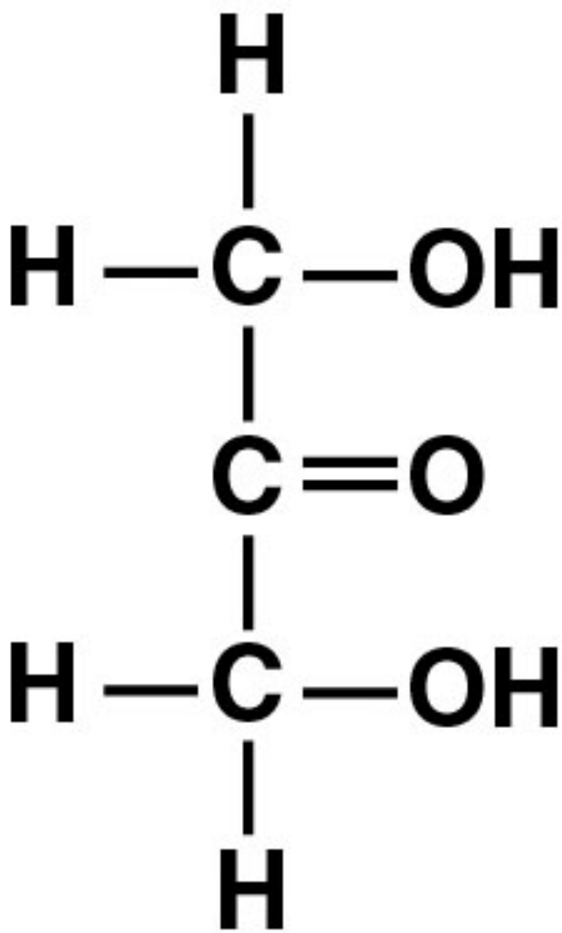


Figure 4.UN09



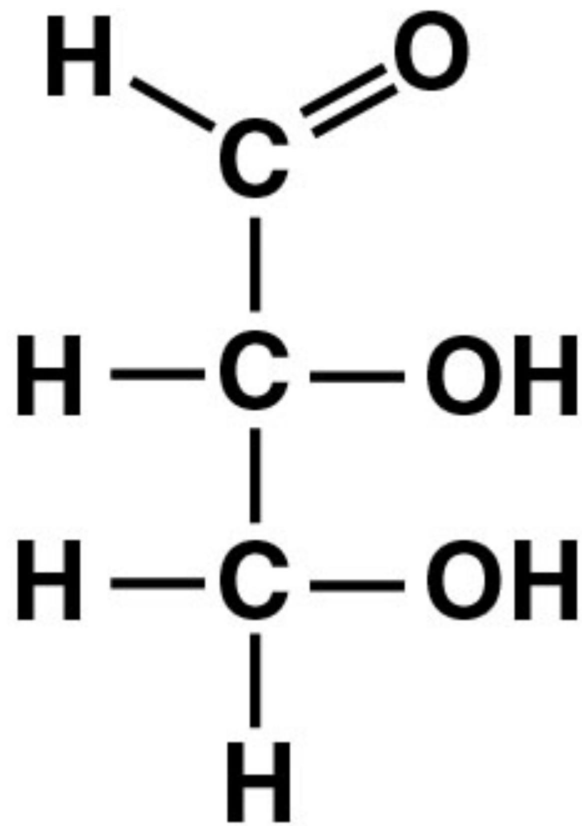


Figure 4.UN10

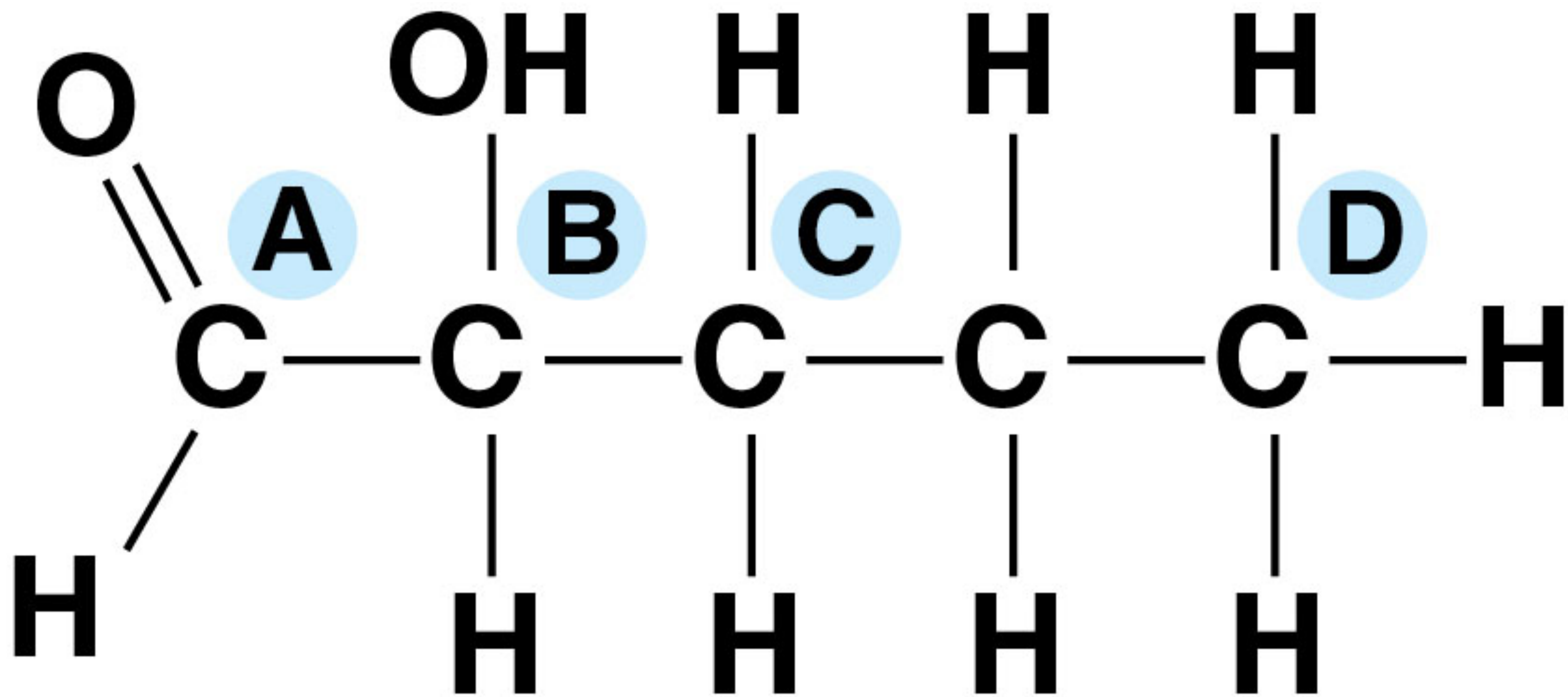
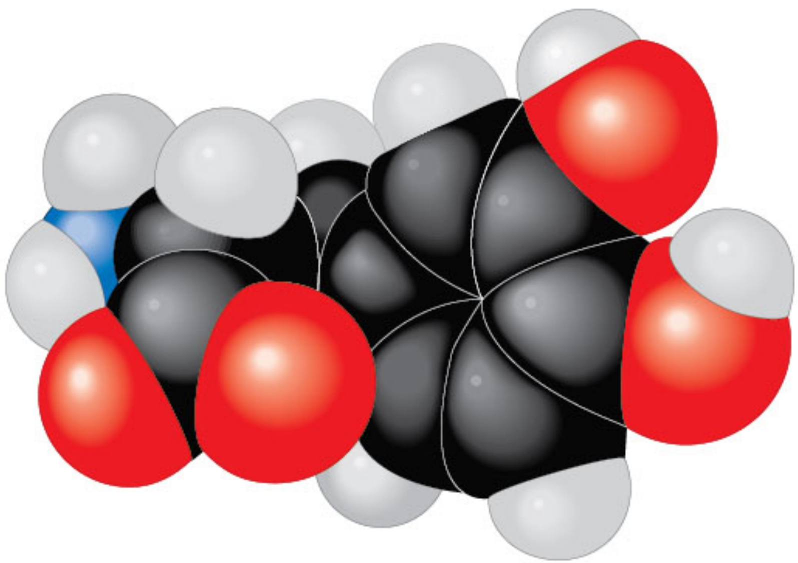
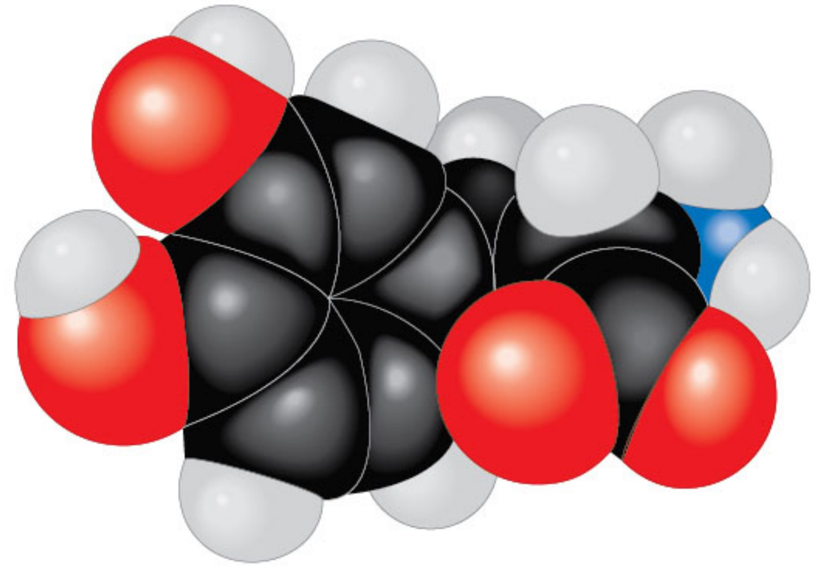


Figure 4.UN11



L-dopa



D-dopa

Figure 4.UN12