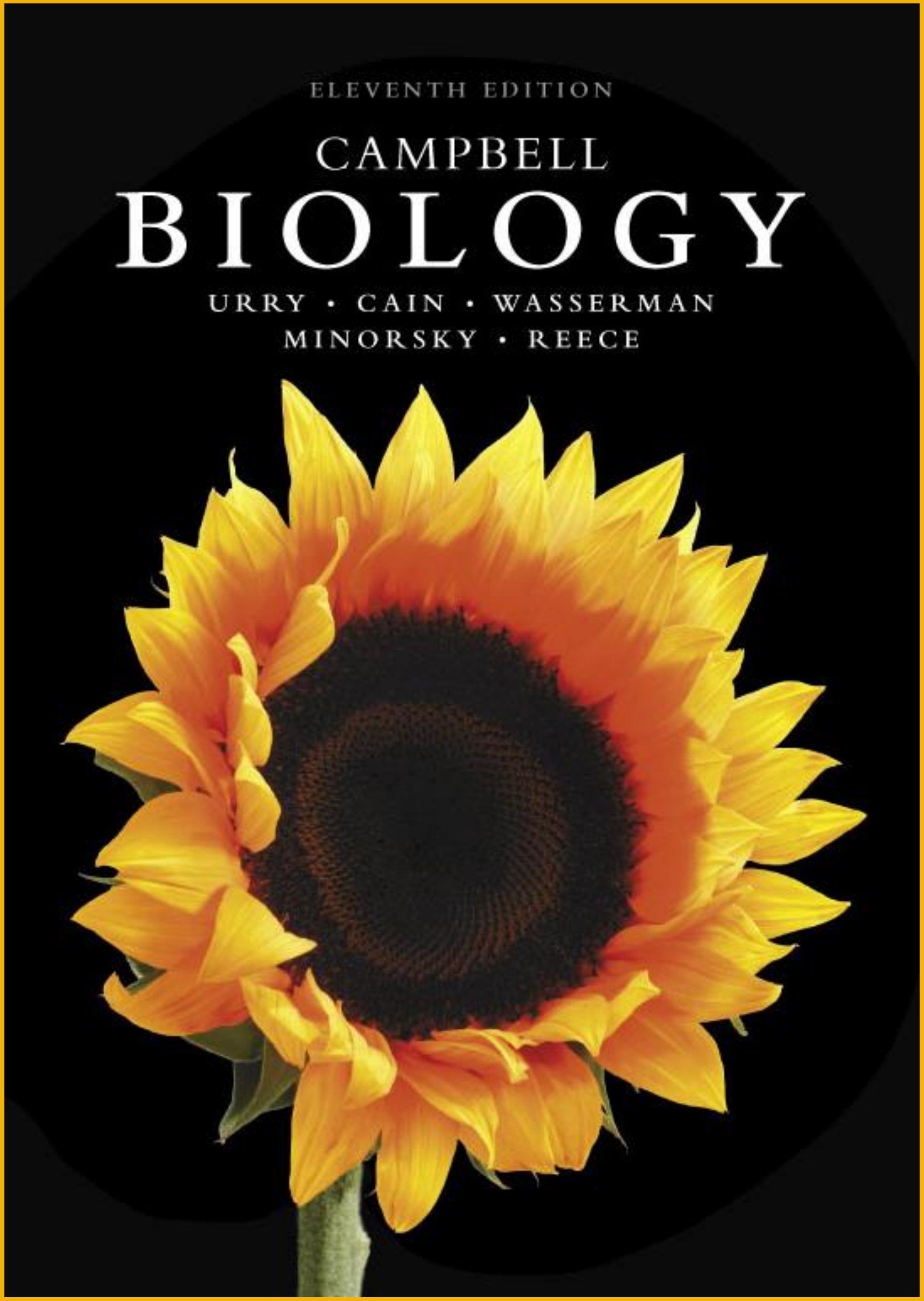


Chapter 4

Carbon and the Molecular Diversity of Life

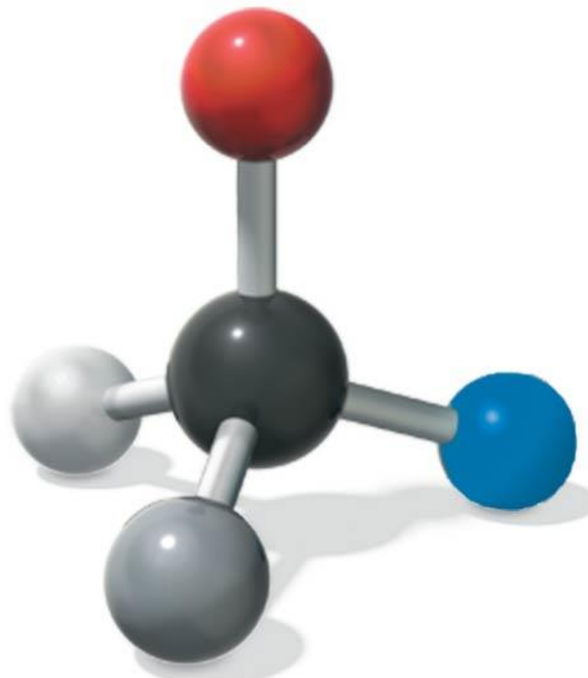
Lecture Presentations by
Nicole Tunbridge and
Kathleen Fitzpatrick

Carbon: The Backbone of Life

- Living organisms consist mostly of carbon-based compounds
- Carbon is unparalleled in its ability to form large, complex, and varied molecules
- Proteins, DNA, carbohydrates, and other molecules that distinguish living matter are all composed of carbon compounds

Figure 4.1 What Properties Make Carbon the Basis of All Life?

Figure 4.1a What Properties Make Carbon the Basis of All Life? (Part 1: Carbon Atom)



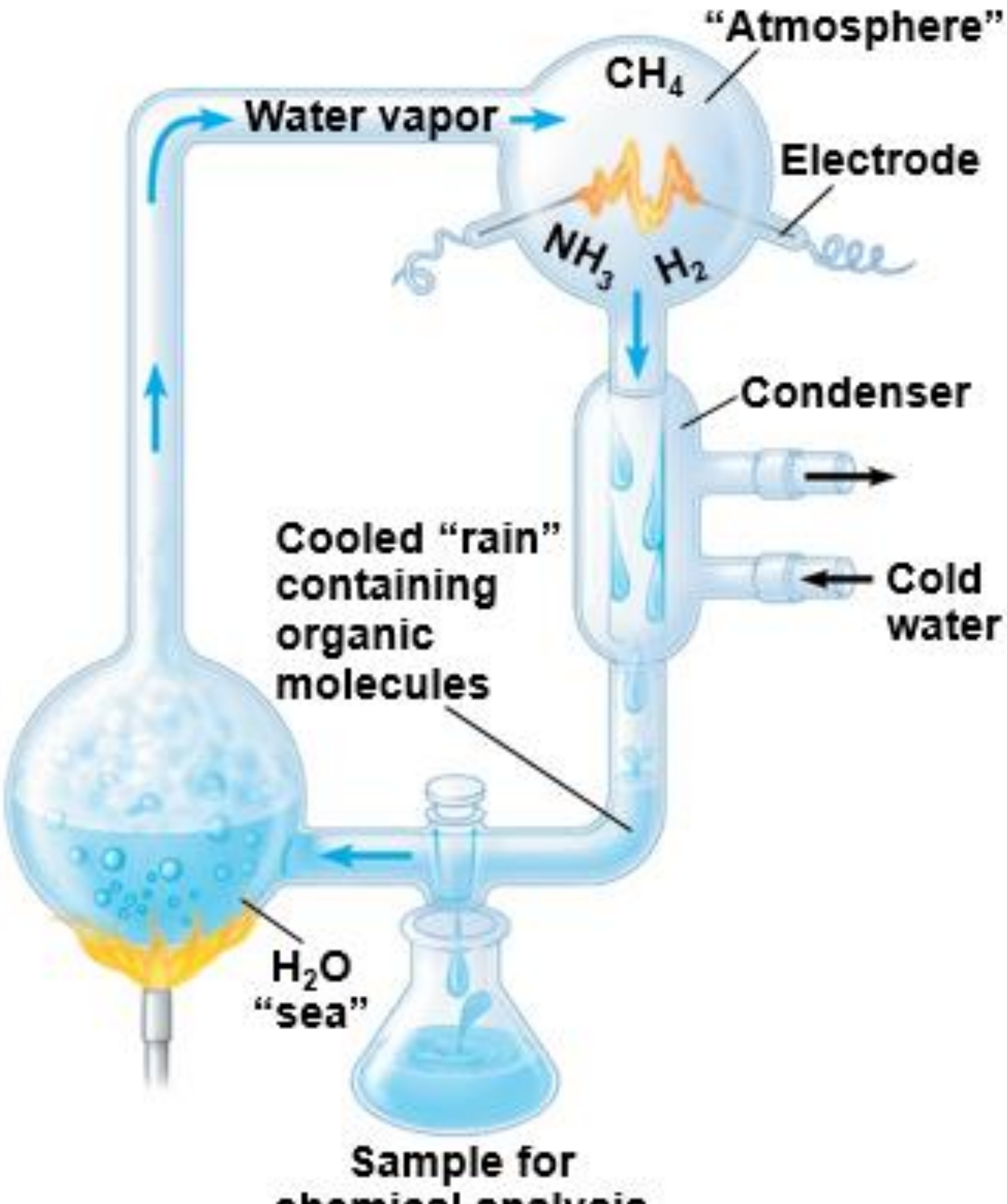
Concept 4.1: Organic chemistry is the study of carbon compounds

- **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 Inquiry: Can Organic Molecules form Under Conditions Estimated to Simulate those on the Early Earth?



Organic Molecules and the Origin of Life on Earth, Continued

- 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 of carbon's ability to 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

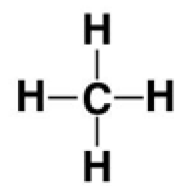
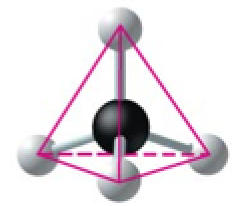
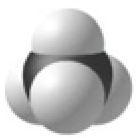
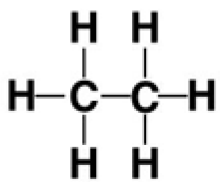
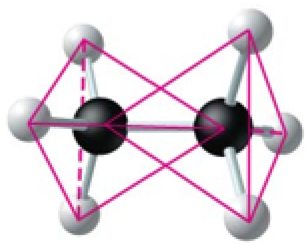
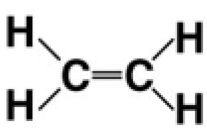
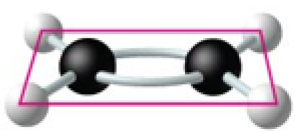
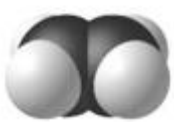
Concept 4.2: Carbon atoms can form diverse molecules by bonding to four other atoms

- Electron configuration is the key to an atom's 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 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 atoms joined to the carbons are in the same plane as the carbons

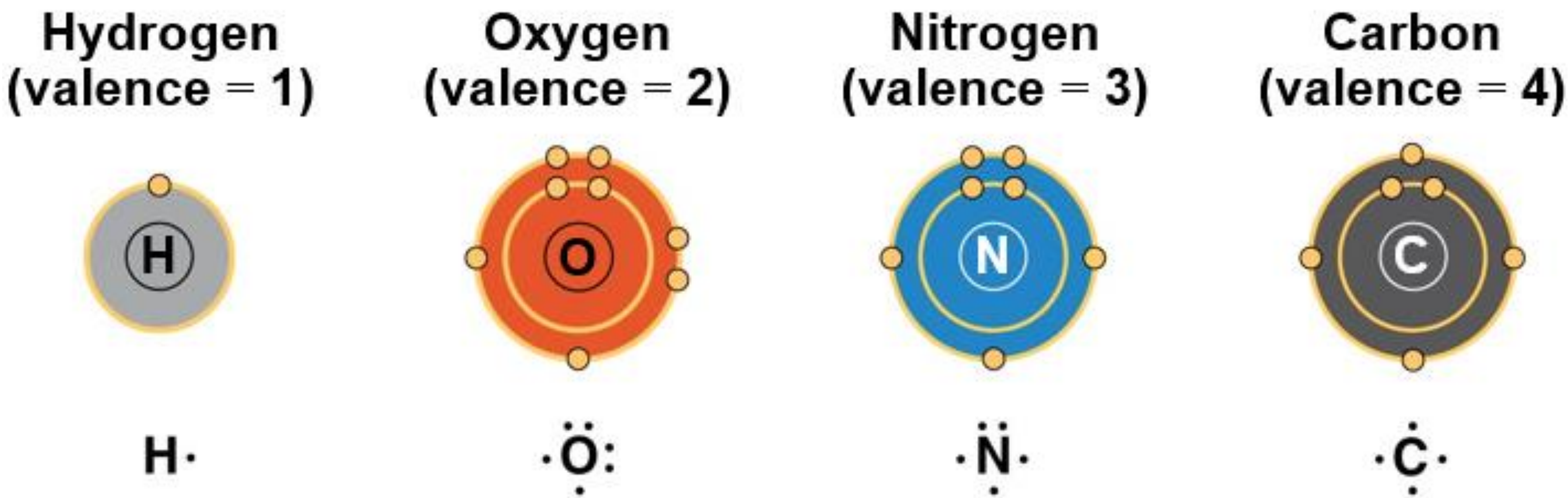
Figure 4.3 The Shapes of Three Simple Organic Molecules

Molecule	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			

The Formation of Bonds with Carbon, Continued

- 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 Valences of the Major Elements of Organic Molecules



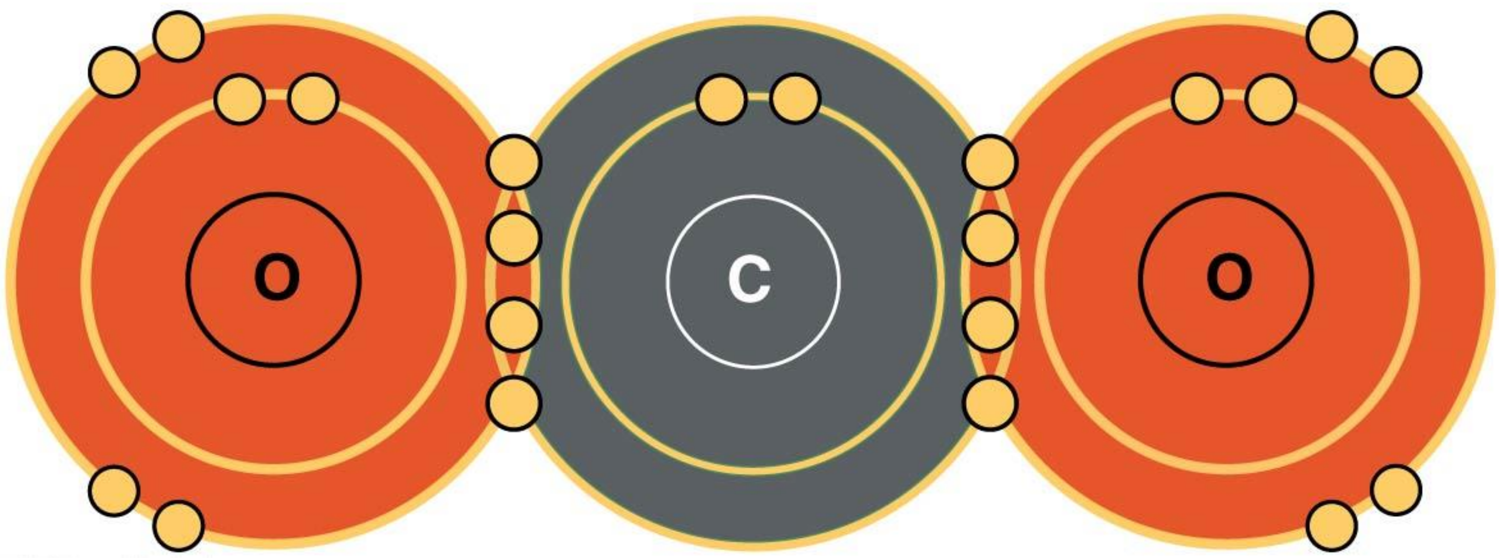
The Formation of Bonds with Carbon, Continued-1

- The electron configuration of carbon gives it covalent compatibility with many different elements
- The valences of carbon and its most frequent partners (hydrogen, oxygen, and nitrogen) are the building code for the architecture of living molecules

The Formation of Bonds with Carbon, Continued-2

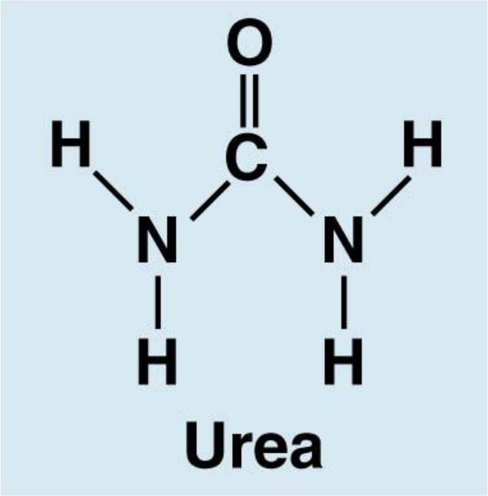
- Carbon atoms can partner with atoms other than hydrogen, such as the following:
  - Carbon dioxide: CO_2

$$O{=}C{=}O$$



The Formation of Bonds with Carbon, Continued-3

- Urea: $CO(NH_2)_2$



Molecular Diversity Arising from Variation in Carbon Skeletons

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

Figure 4.5 Four Ways that Carbon Skeletons can Vary

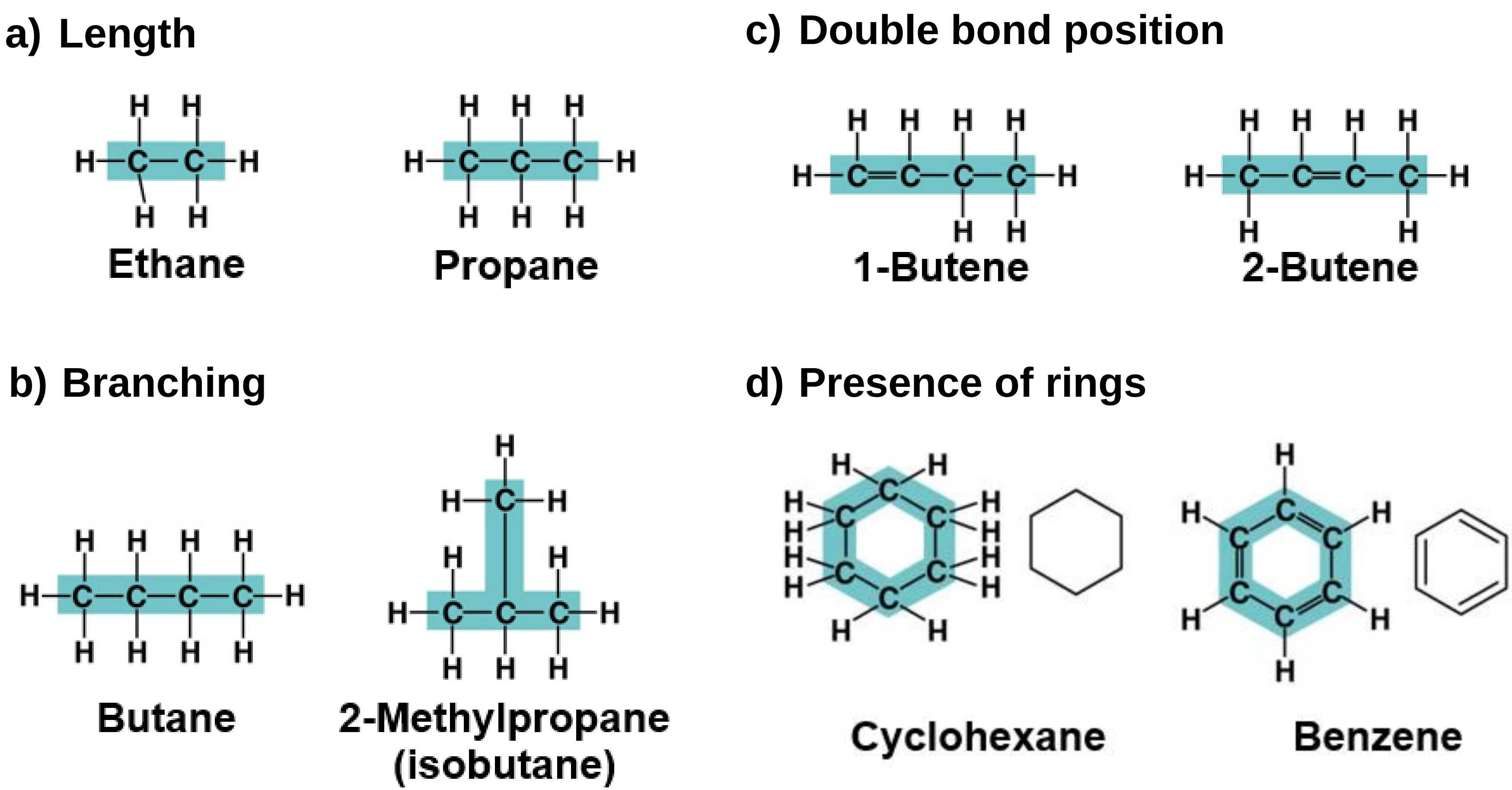


Figure 4.5a Four Ways that Carbon Skeletons can Vary (Part 1: Length)

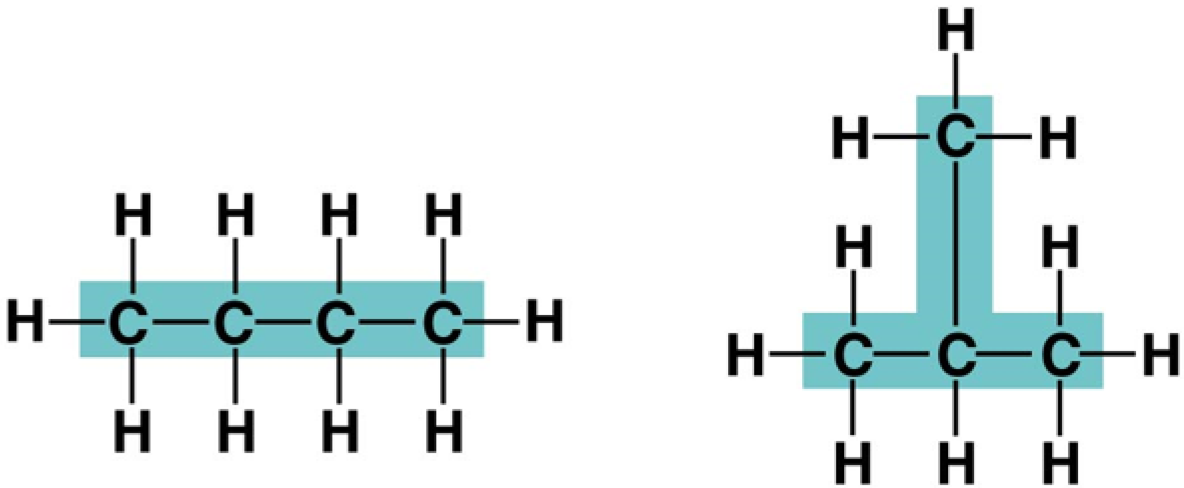
a) Length

Ethane

Propane

Figure 4.5b Four Ways that Carbon Skeletons can Vary (Part 2: Branching)

b) Branching



Butane

2-Methylpropane (isobutane)

Figure 4.5c Four Ways that Carbon Skeletons can Vary (Part 3: Double Bond Position)

c) Double bond position

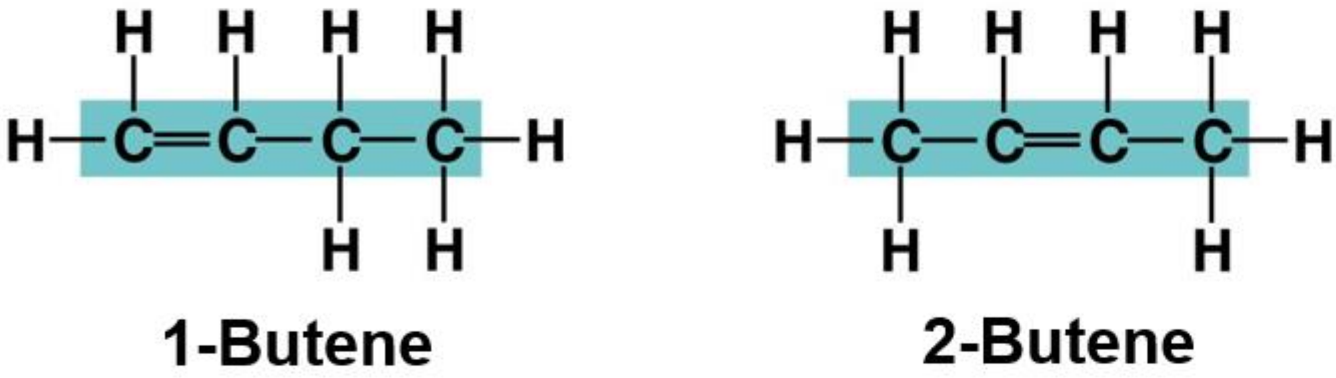
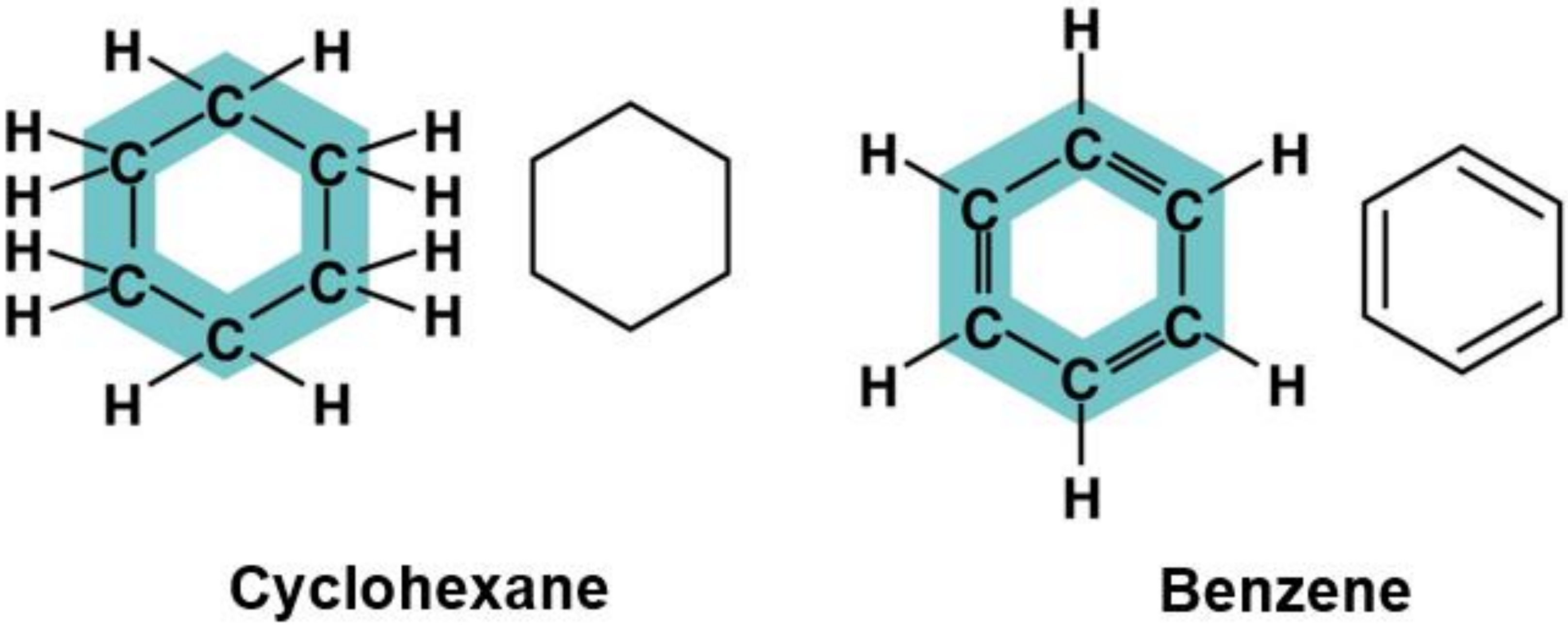
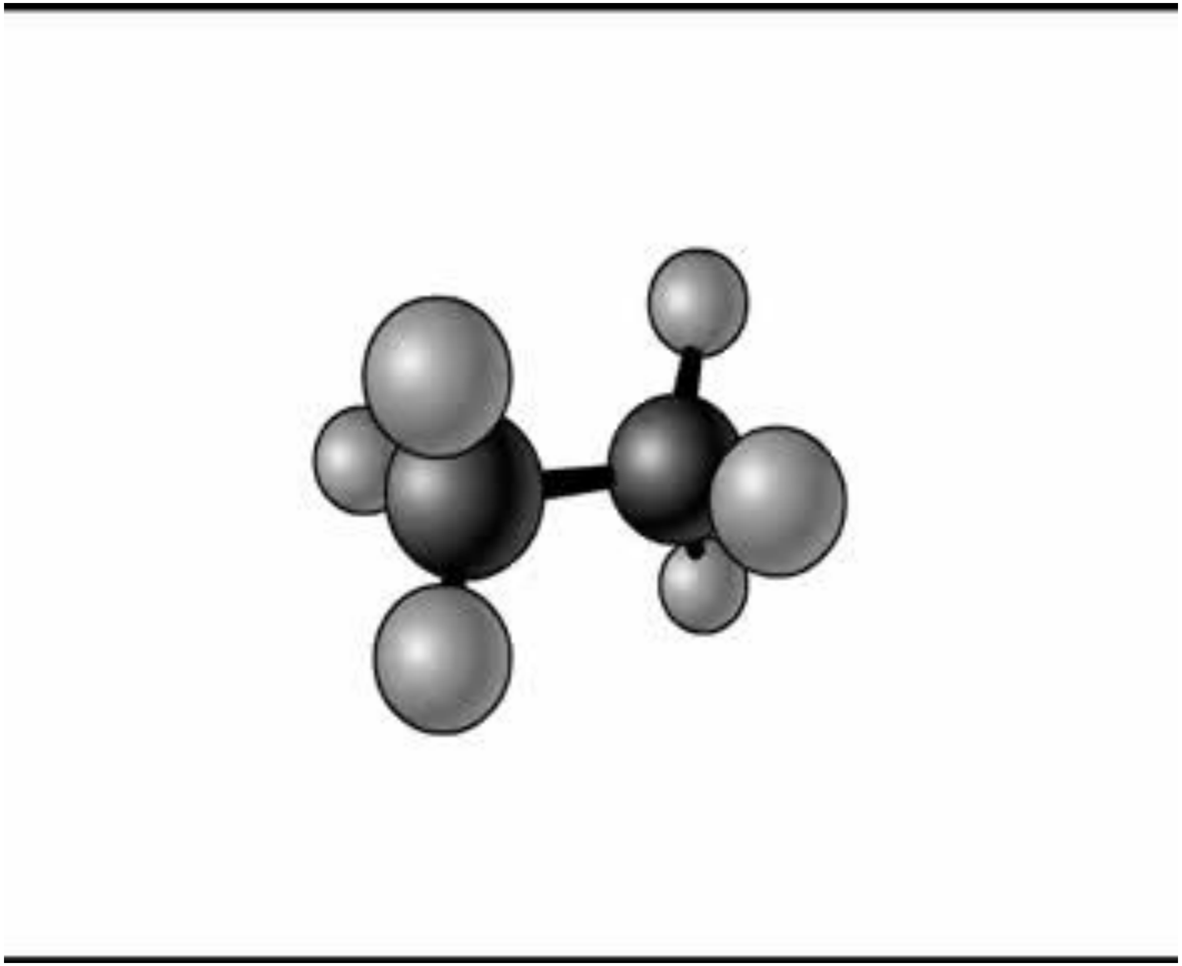


Figure 4.5d Four Ways that Carbon Skeletons can Vary (Part 4: Presence of Rings)

d) Presence of rings



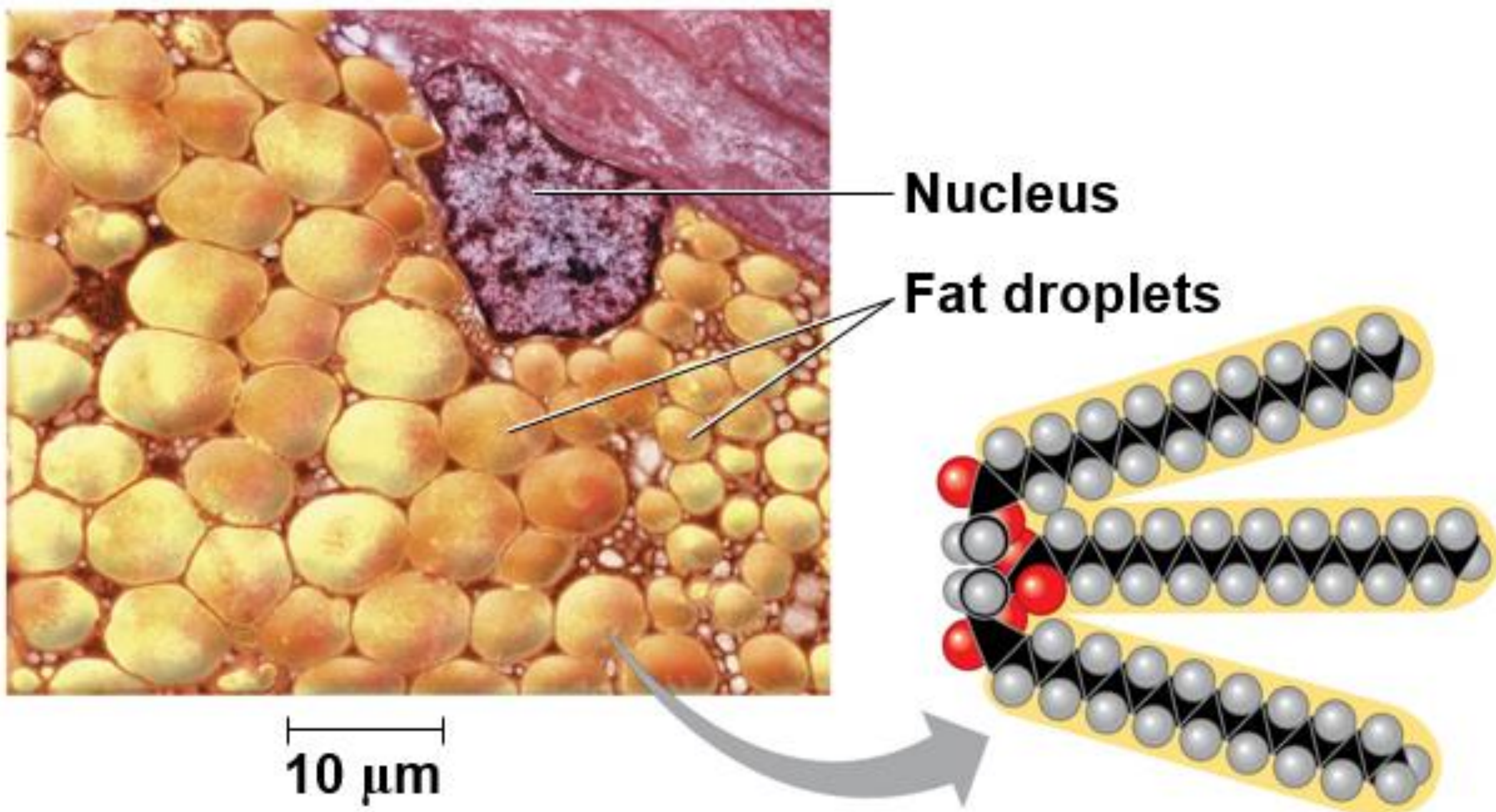
Animation: Carbon Skeletons



Hydrocarbons

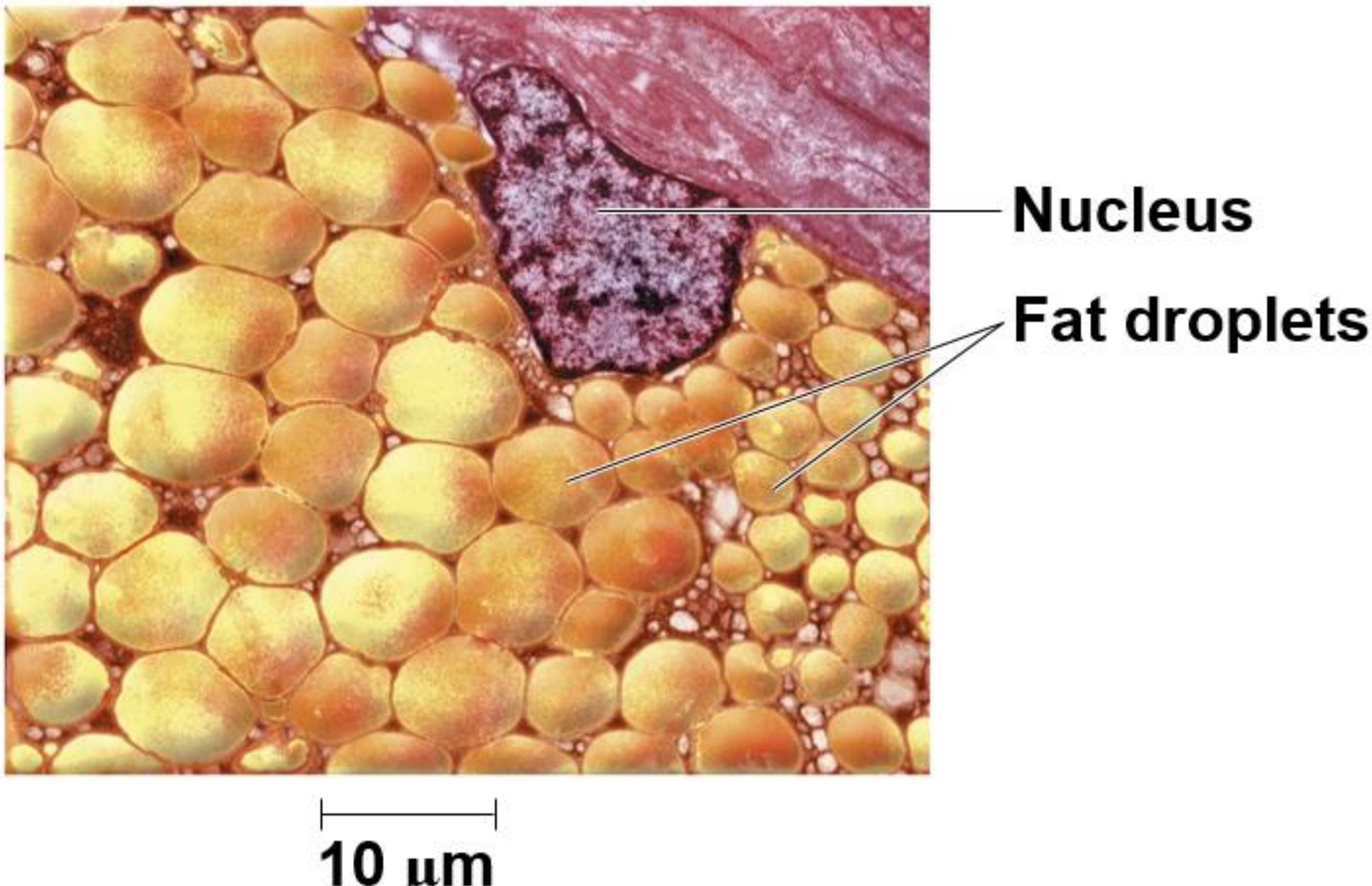
- **Hydrocarbons** are organic molecules consisting of only carbon and hydrogen
- Many organic molecules, such as fats, have hydrocarbon components
- Hydrocarbons can undergo reactions that release a large amount of energy

Figure 4.6 The Role of Hydrocarbons in Fats



(a) Part of a human adipose cell (b) A fat molecule

Figure 4.6a The Role of Hydrocarbons in Fats (Part 1: Micrograph)



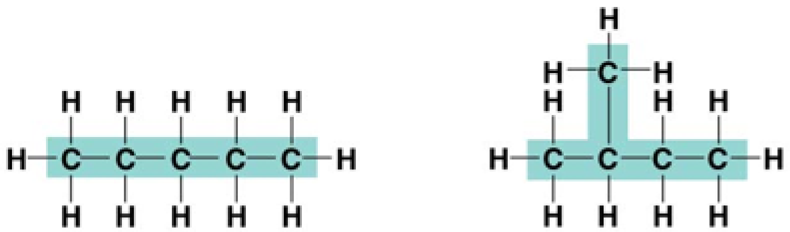
a) Part of a human adipose cell

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** have the same covalent bonds but differ in their spatial arrangements
  - **Enantiomers** are isomers that are mirror images of each other

Figure 4.7 Three Types of Isomers

a) Structural isomers



Pentane

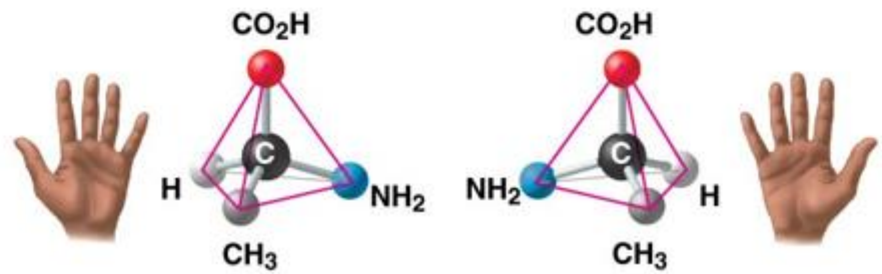
2-Methylbutane

b) *Cis-trans* isomers

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

trans **isomer:**
The two Xs are on opposite sides.

c) Enantiomers



L isomer

D isomer

Figure 4.7a Three Types of Isomers (Part 1: Structural Isomers)

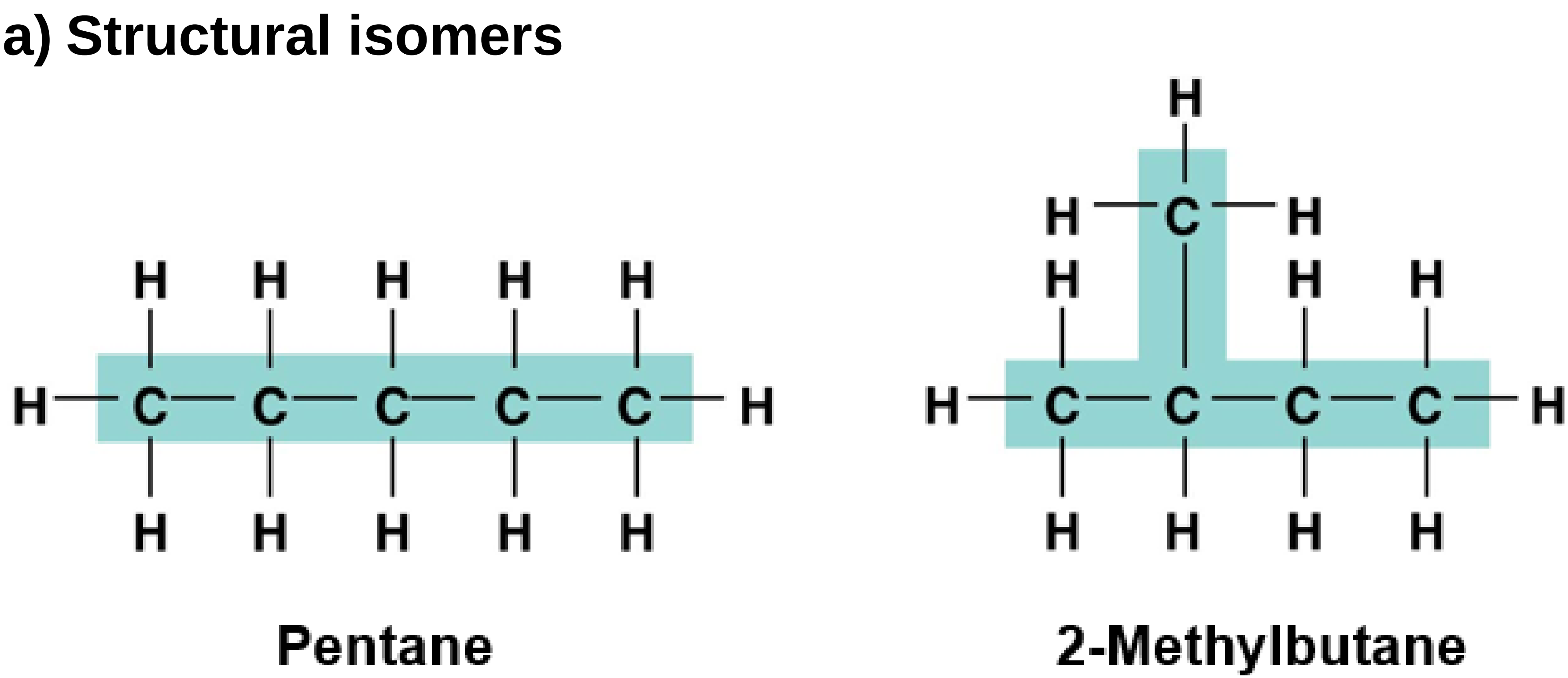
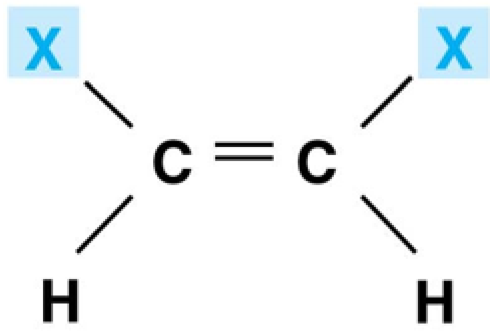
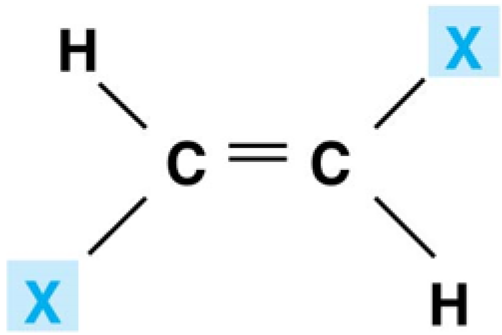


Figure 4.7b Three Types of Isomers (Part 2: *Cis-trans* Isomers)

b) *Cis-trans* isomers

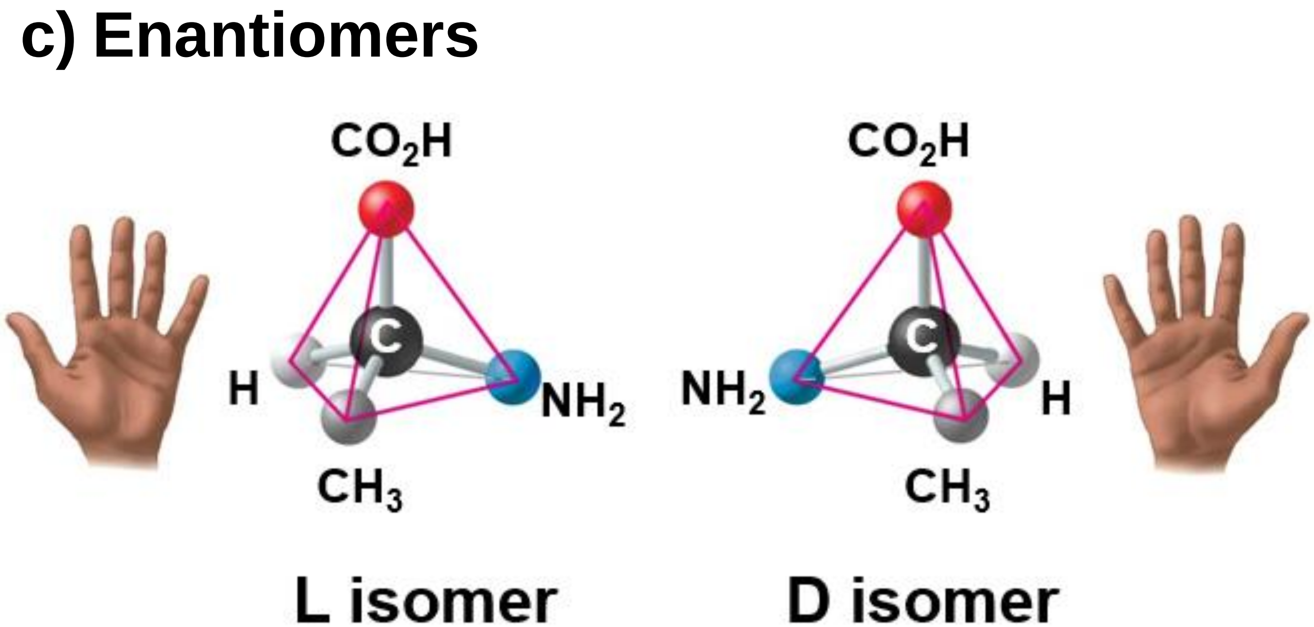


cis **isomer: The two Xs are on the same side.**

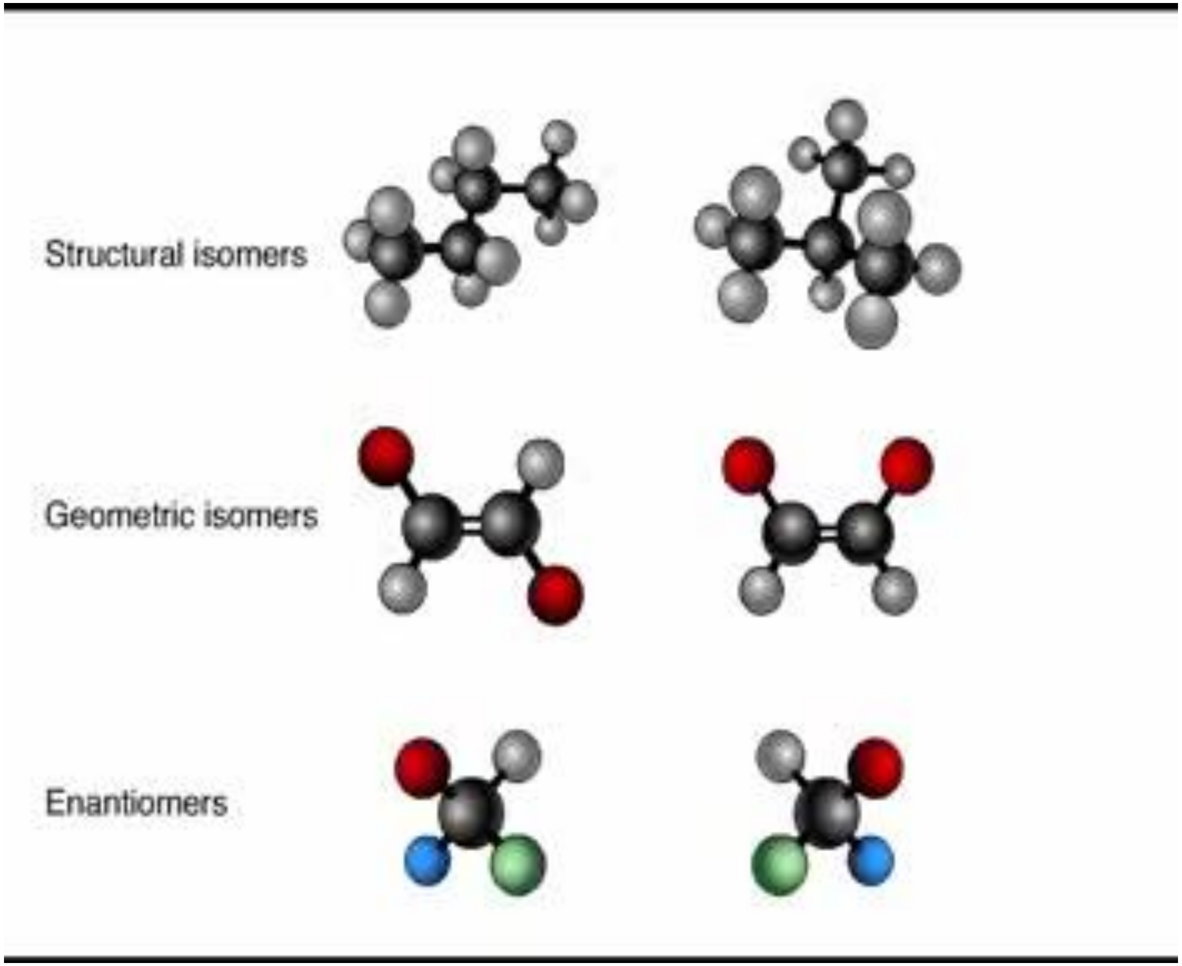


trans **isomer: The two Xs are on opposite sides.**

Figure 4.7c Three Types of Isomers (Part 3: Enantiomers)



Animation: Isomers



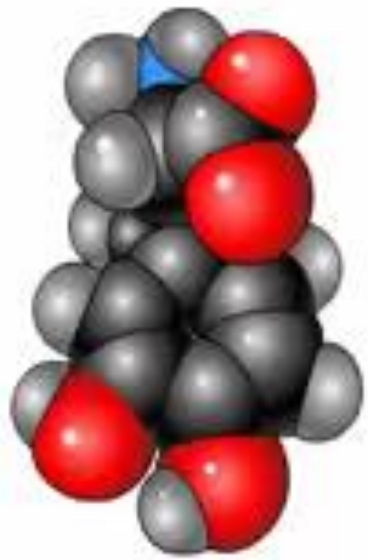
Isomers, Continued

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

Figure 4.8 The Pharmacological Importance of Enantiomers

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

Animation: L-Dopa



$C_9H_{11}NO_4$

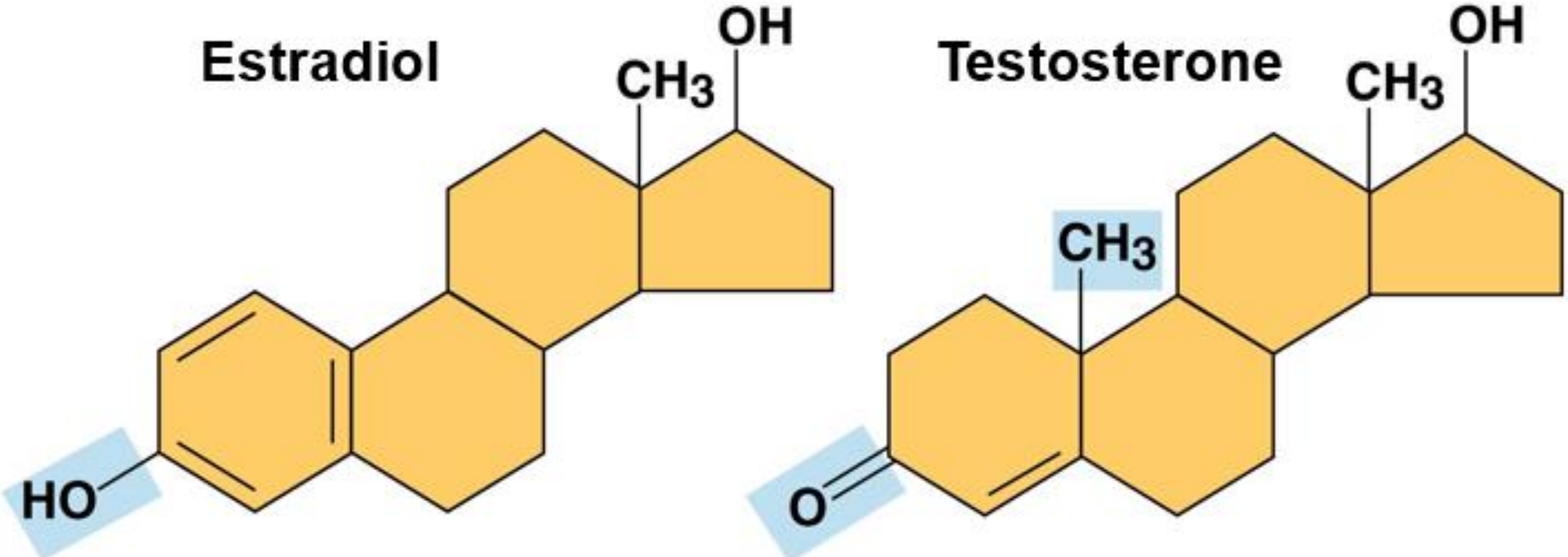
Concept 4.3: A few chemical groups are key to molecular function

- Distinctive properties of organic molecules depend on the carbon skeleton and on the chemical groups attached to it
- A number of characteristic groups can replace the hydrogens attached to skeletons of organic molecules

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

Figure 4.UN04 In-text Figure, Sex Hormones, P. 62



The Chemical Groups Most Important in the Processes of Life, Continued

- **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 Chemical Groups Most Important in the Processes of Life, Continued-1

- 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 Some Biologically Important Chemical Groups

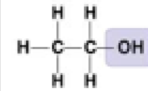
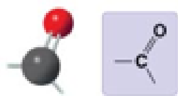
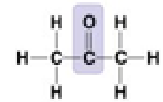
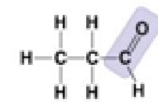
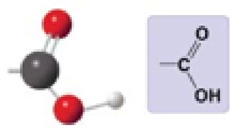
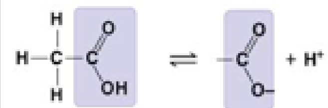
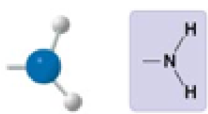
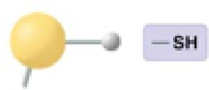
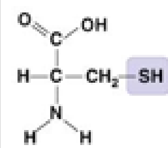
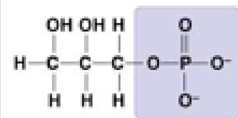
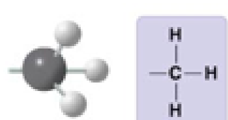
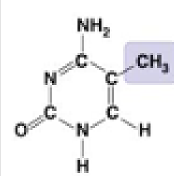
Chemical Group	Group Properties	Examples
Hydroxyl group (—OH) 	Alcohol	 Ethanol
Carbonyl group (>C = O) 	Ketone Aldehyde	 Acetone  Propanal
Carboxyl group (—COOH) 	Carboxylic acid or organic acid	 Acetic acid
Amino group (—NH_2) 	Amine	 Glycine
Sulfhydryl group (—SH) 	Thiol	 Cysteine
Phosphate group (—OPO_3^{2-}) 	Organic phosphate	 Glycerol phosphate
Methyl group (—CH_3) 	Methylated compound	 5-Methylcytosine

Figure 4.9a Some Biologically Important Chemical Groups (Part 1)

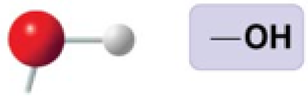
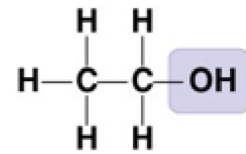
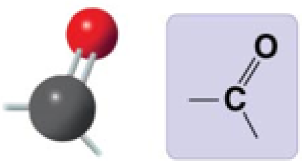
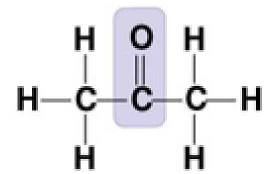
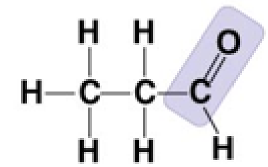
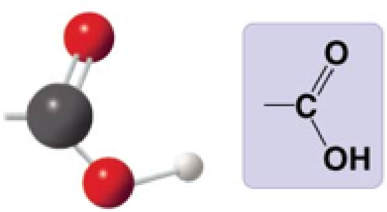
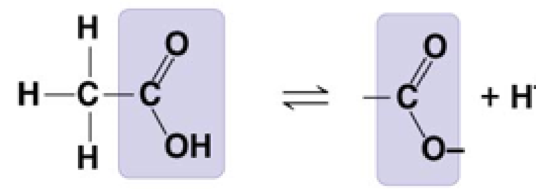
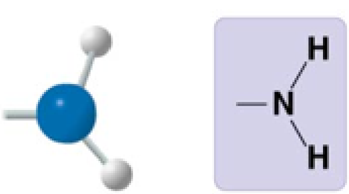
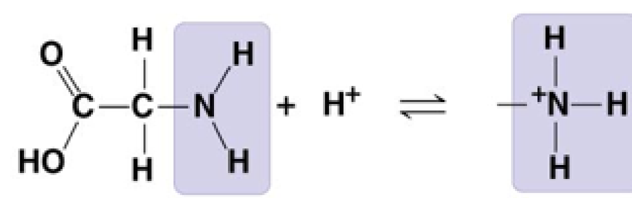
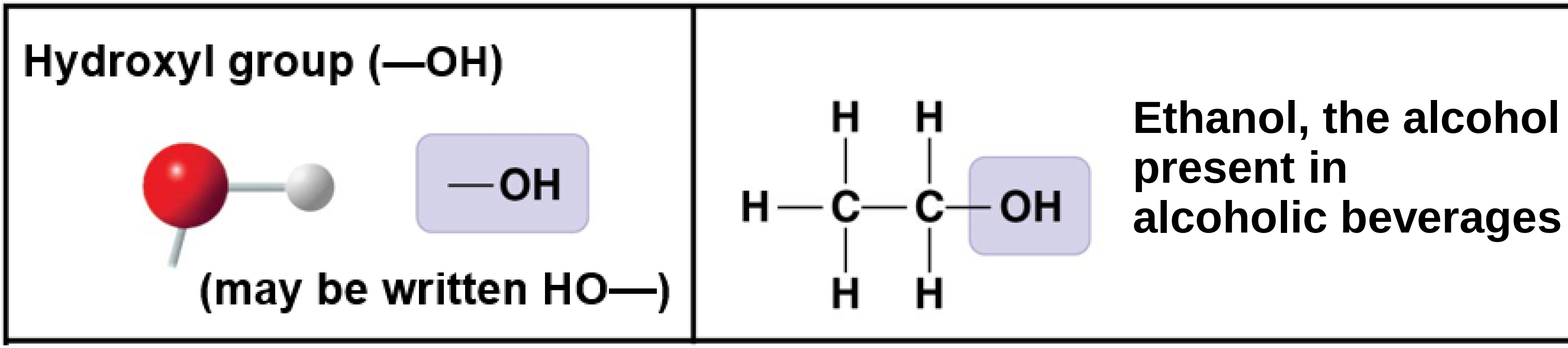
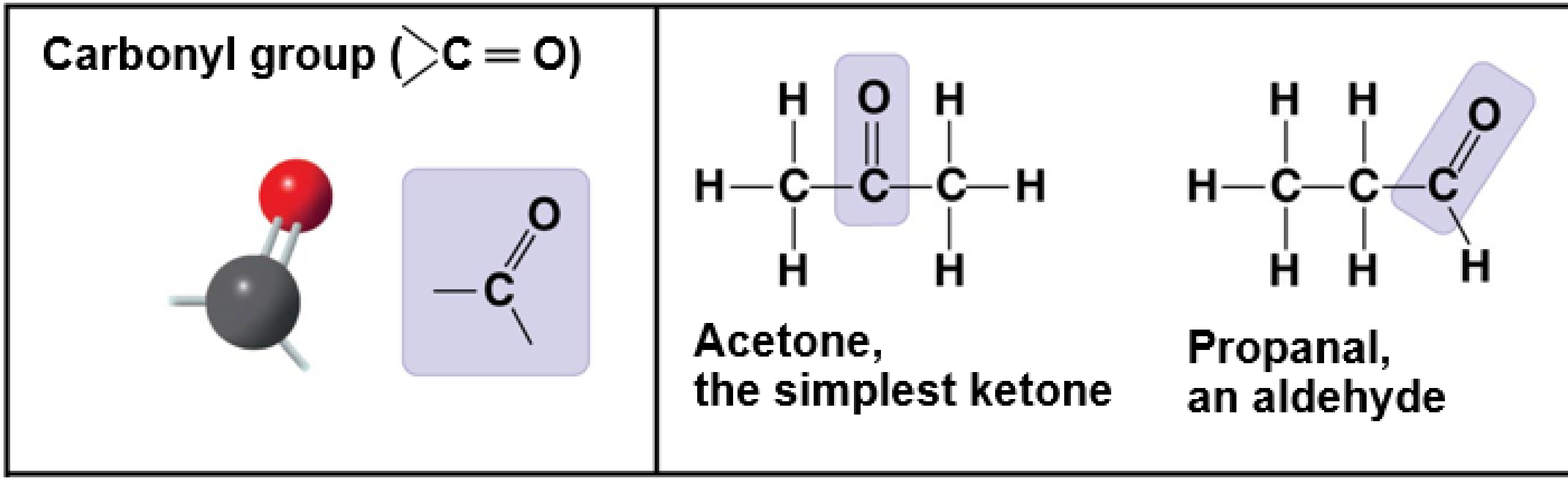
Chemical Group	Compound Name	Examples
Hydroxyl group (—OH) 	Alcohol	 Ethanol
Carbonyl group (>C = O) 	Ketone Aldehyde	 Acetone  Propanal
Carboxyl group (—COOH) 	Carboxylic acid or organic acid	 Acetic acid
Amino group ($—NH_2$) 	Amine	 Glycine

Figure 4.9aa Some Biologically Important Chemical Groups (Part 1a: Hydroxyl Group)



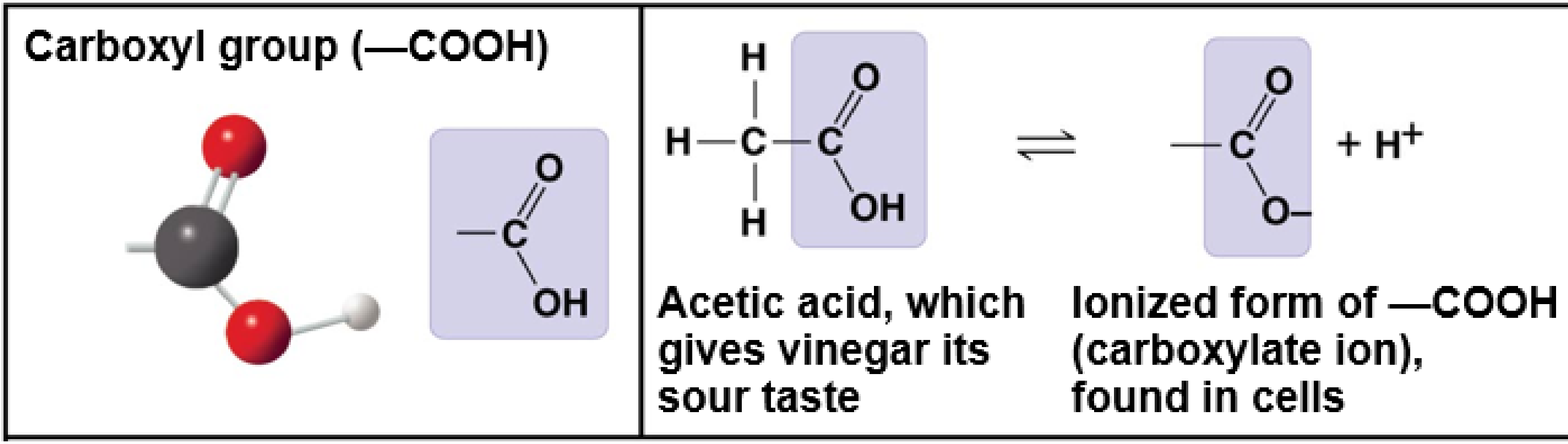
Polar due to electronegative oxygen. Forms hydrogen bonds with water.
Compound name: Alcohol

Figure 4.9ab Some Biologically Important Chemical Groups (Part 1b: Carbonyl Group)



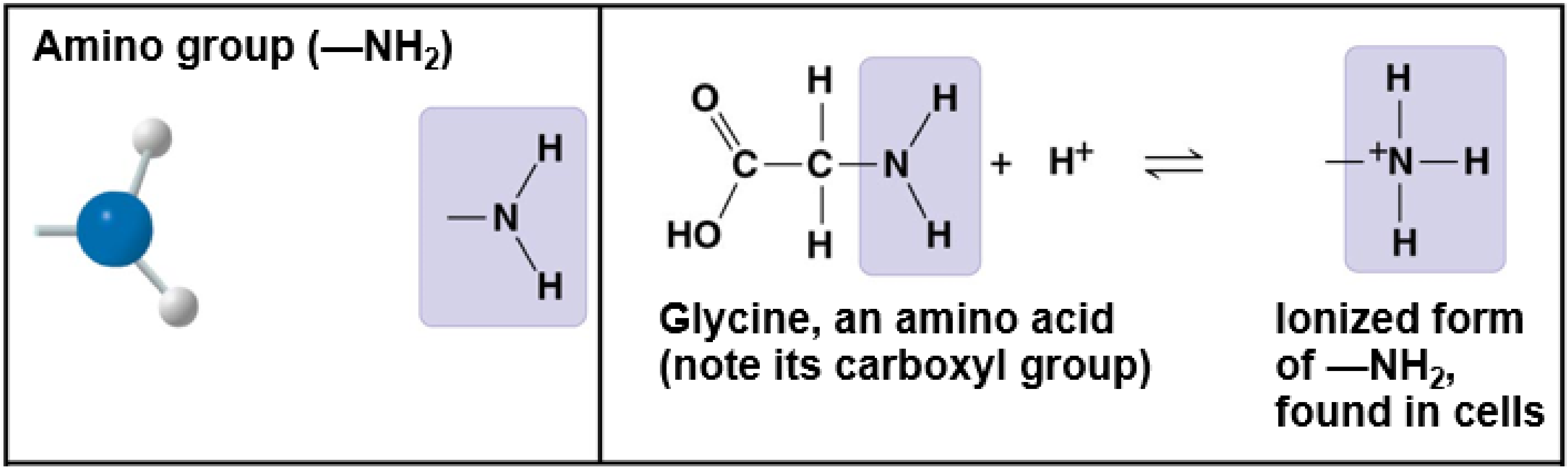
Sugars with ketone groups are called ketoses; those with aldehydes are called aldoses.
Compound name: Ketone or aldehyde

Figure 4.9ac Some Biologically Important Chemical Groups (Part 1c: Carboxyl Group)



Acts as an acid.
Compound name: Carboxylic acid, or organic acid

Figure 4.9ad Some Biologically Important Chemical Groups (Part 1d: Amino Group)



Acts as a base.
Compound name: Amine

Figure 4.9b Some Biologically Important Chemical Groups (Part 2)

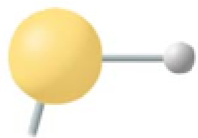
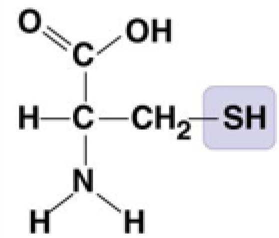
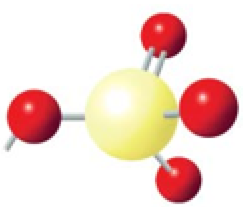
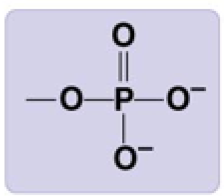
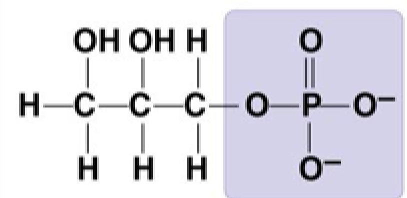
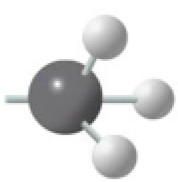
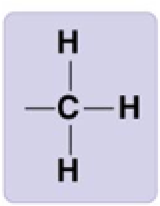
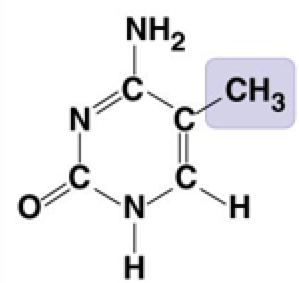
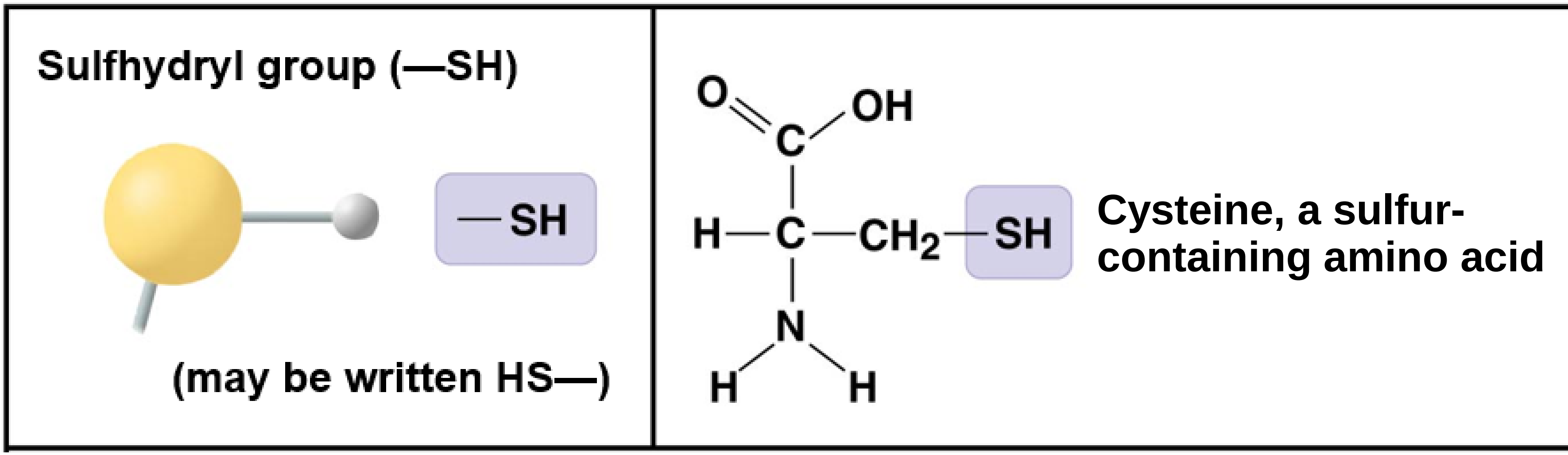
Chemical Group	Compound Name	Examples
Sulfhydryl group (—SH)  —SH	Thiol	 Cysteine
Phosphate group ($—OPO_3^{2-}$)  	Organic phosphate	 Glycerol phosphate
Methyl group ($—CH_3$)  	Methylated compound	 5-Methylcytosine

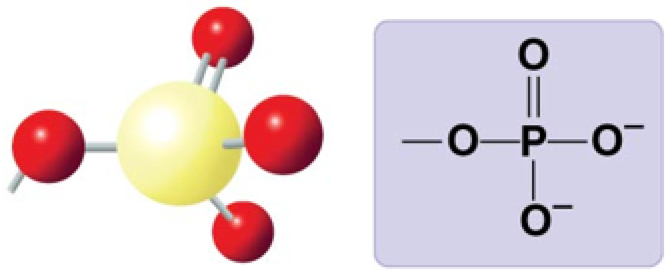
Figure 4.9ba Some Biologically Important Chemical Groups (Part 2a: Sulfhydryl Group)

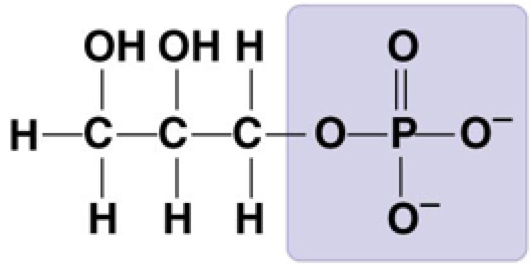


Two —SH groups can react, forming a “cross-link” that helps stabilize protein structure.
Compound name: Thiol

Figure 4.9bb Some Biologically Important Chemical Groups (Part 2b: Phosphate Group)

Phosphate group (—OPO_3^{2-})

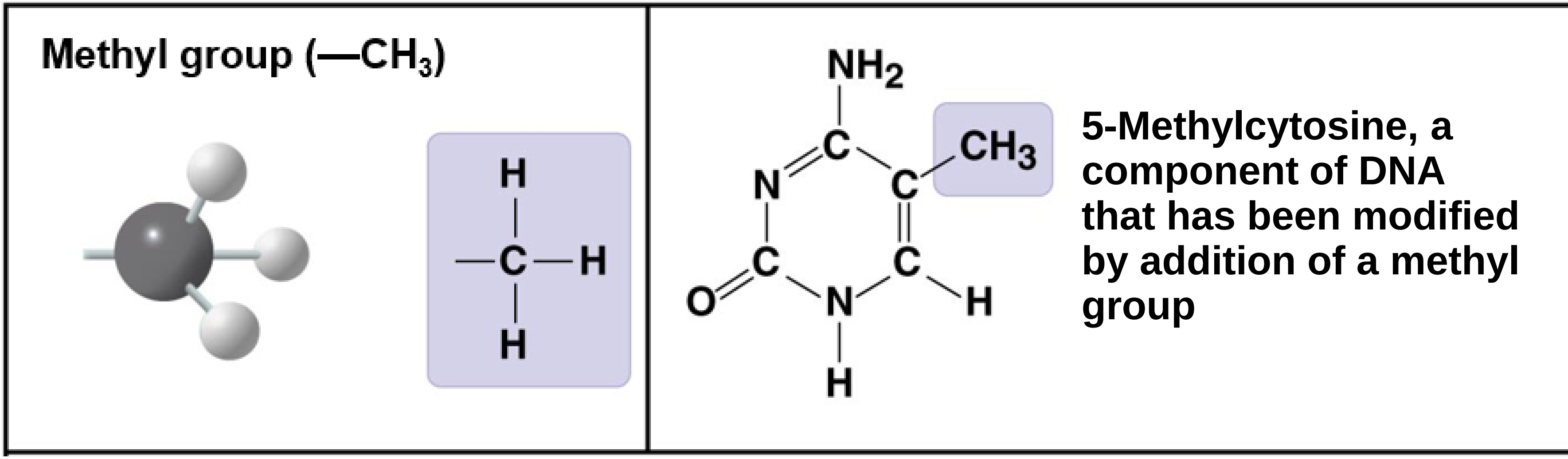




Glycerol phosphate, which takes part in many important chemical reactions in cells

Contributes negative charge. When attached, confers on a molecule the ability to react with water, releasing energy.
Compound name: Organic phosphate

Figure 4.9bc Some Biologically Important Chemical Groups (Part 2c: Methyl Group)



Affects the expression of genes. Affects the shape and function of sex hormones.
Compound name: Methylated compound

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

Figure 4.UN05 In-text Figure, ATP Phosphate Chain, P. 64

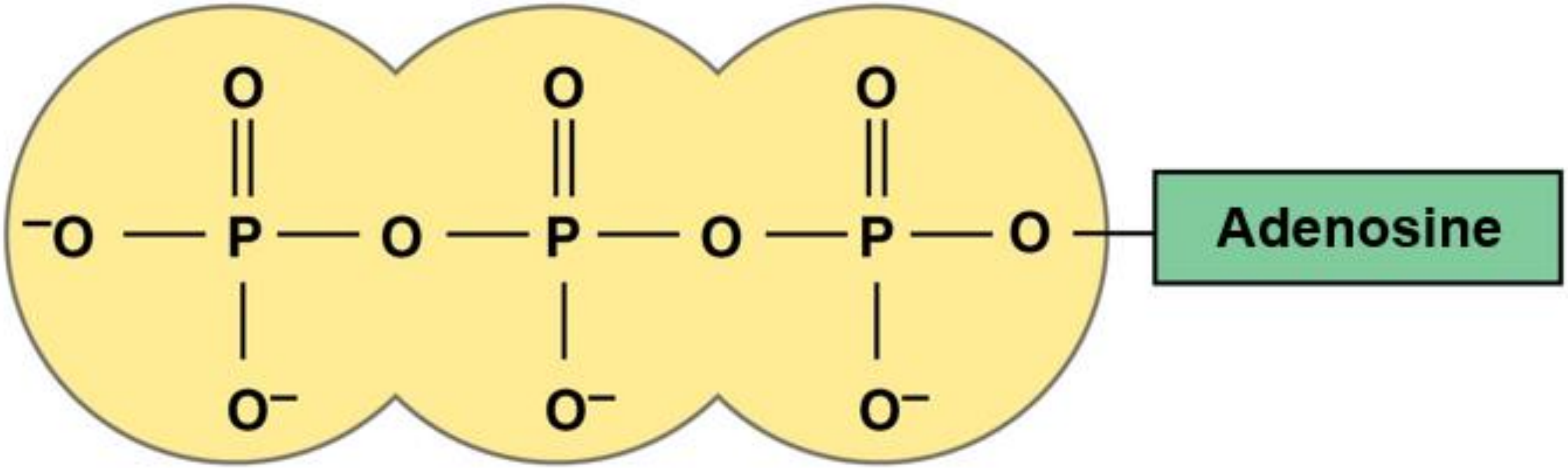
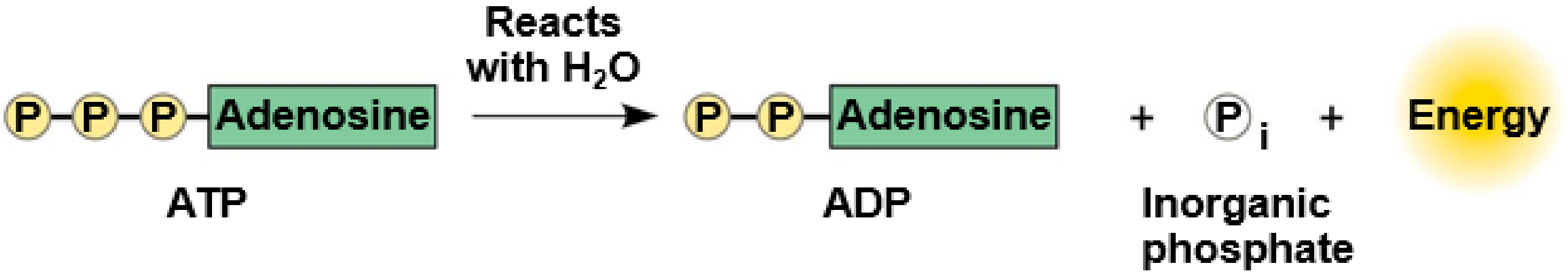


Figure 4.UN06 In-text Figure, ATP to ADP Reaction, P. 64



The Chemical Elements of Life: *A Review*

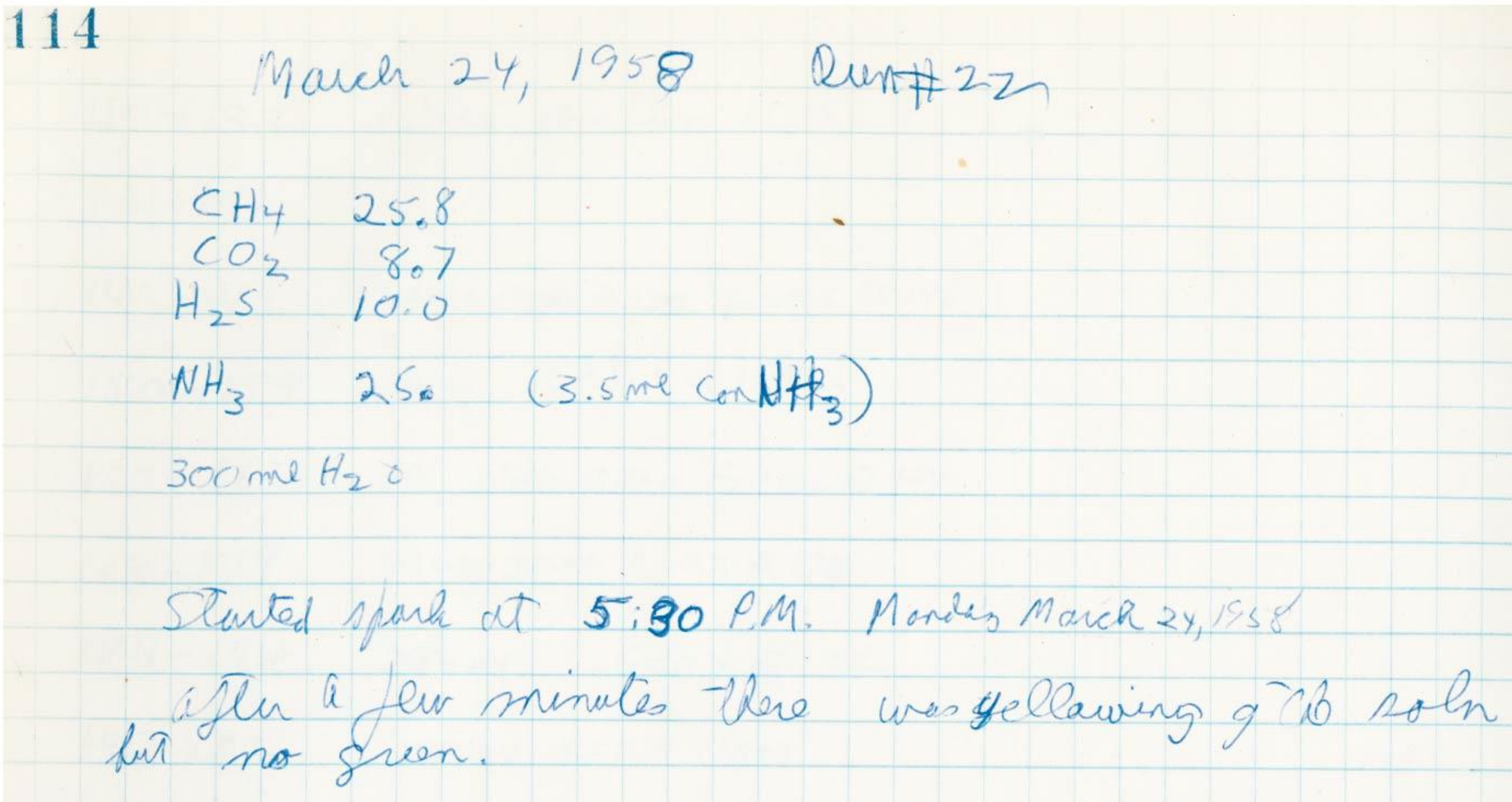
- The versatility of carbon makes possible the great diversity of organic molecules
- Variation at the molecular level lies at the foundation of all biological diversity

Figure 4.UN01a Working with Moles and Molar Ratios (Part 1: Experiment Data)

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 Science USA* 108:5526-5531 (2011). www.pnas.org/cgi/doi/10.1073/pnas.1019191108.

Figure 4.UN01b Working with Moles and Molar Ratios (Part 2: Miller's Notes)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March 24, 1958 Run #22

CH_4 25.8
CO_2 8.7
H_2S 10.0
NH_3 25.0 (3.5 ml Conc 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.UN01c Working with Moles and Molar Ratios (Part 3: Miller's Original Vials)

Figure 4.UN08 Test Your Understanding, Question 2 (Functional Groups)

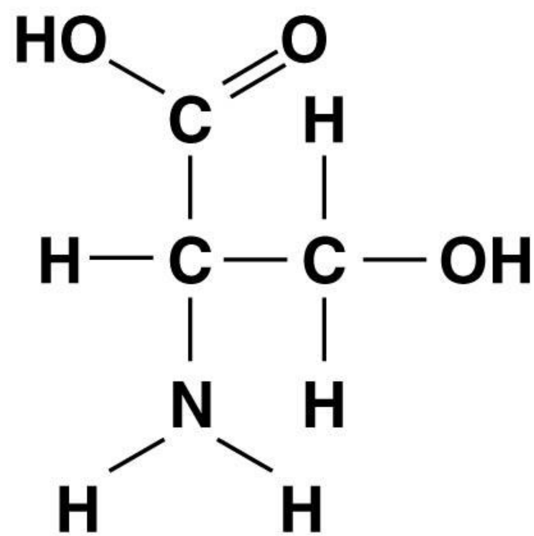


Figure 4.UN09 Test Your Understanding, Question 5 (Sugar Molecules)

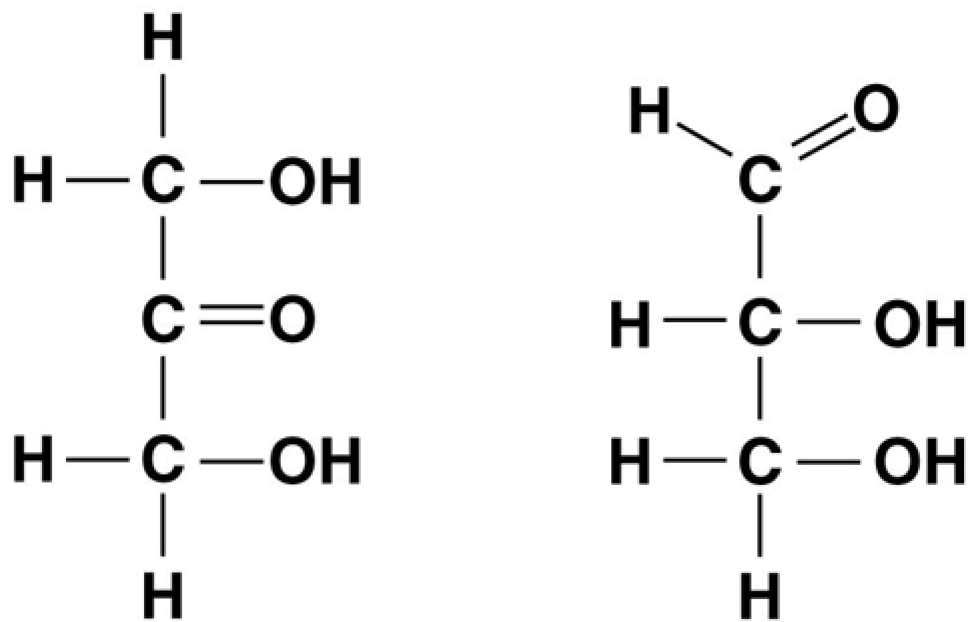


Figure 4.UN10 Test Your Understanding, Question 6 (Asymmetric Carbon)

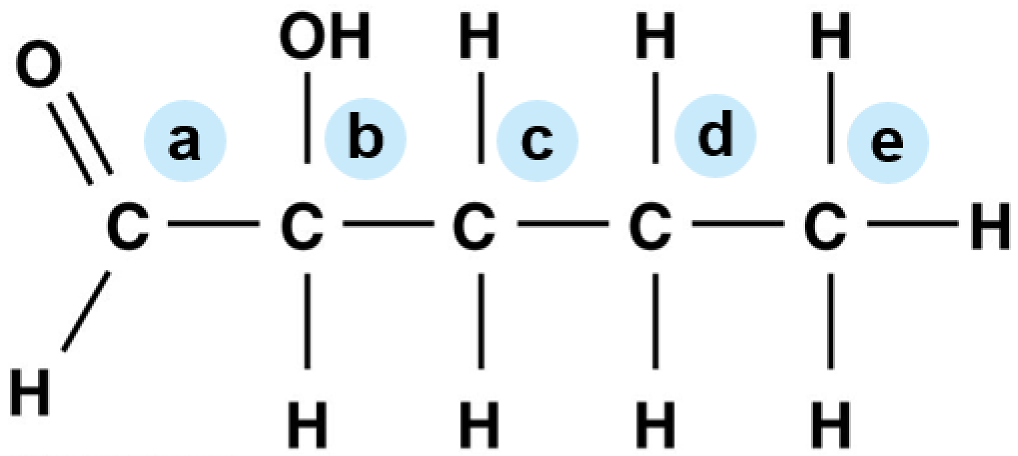
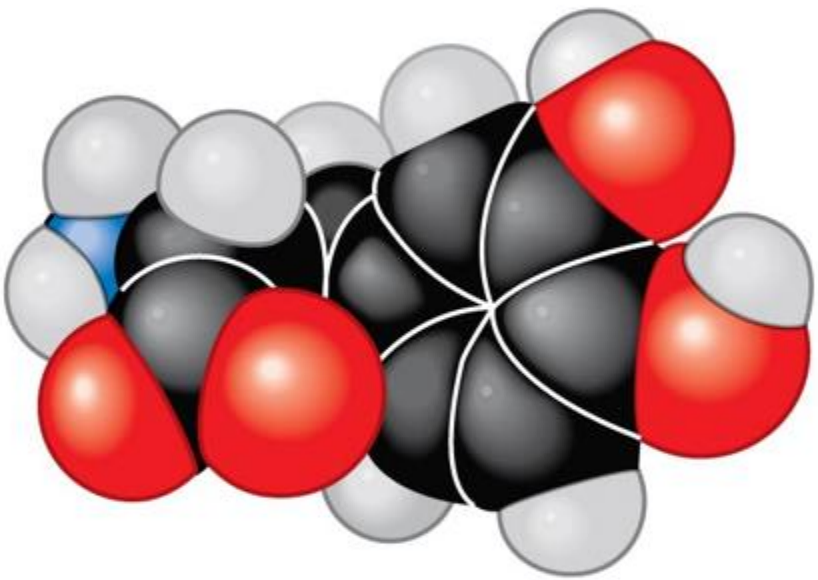
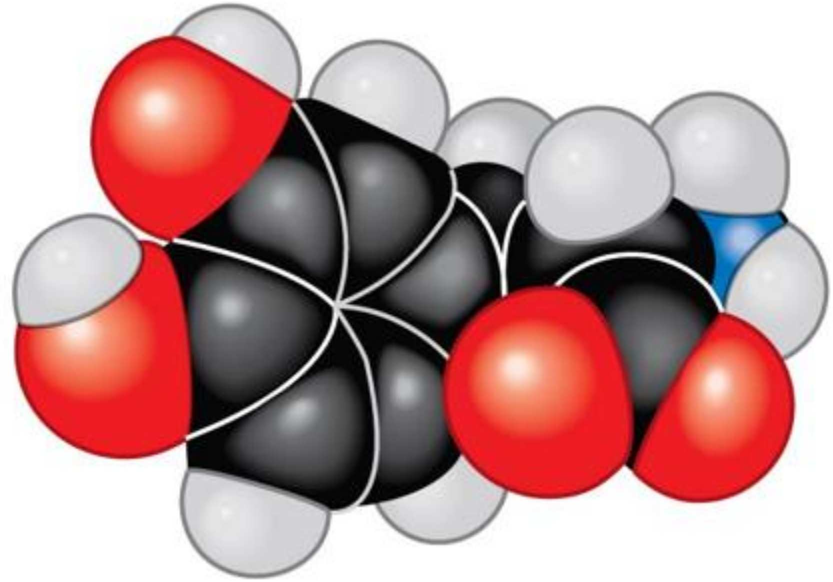


Figure 4.UN11 Test Your Understanding, Question 11 (Enantiomers)



L-dopa



D-dopa

Figure 4.UN12 Test Your Understanding, Question 12 (Male and Female Lions)