CAMPBELL BIOLOGY IN FOCUS

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3

Carbon and the Molecular Diversity of Life

Lecture Presentations by Kathleen Fitzpatrick and Nicole Tunbridge, Simon Fraser University

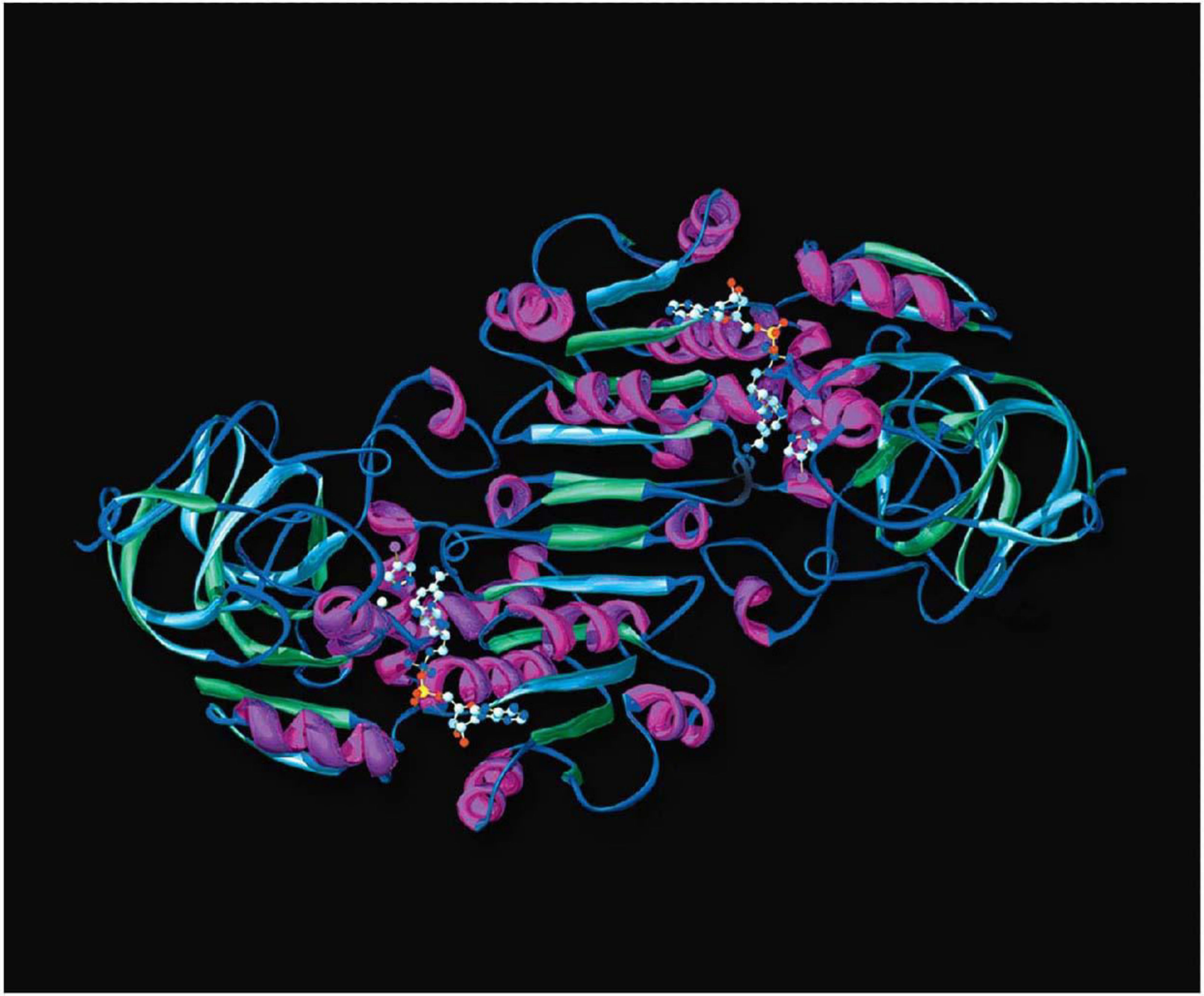
SECOND EDITION

Overview: Carbon Compounds and Life

- Aside from water, living organisms consist mostly of carbon-based compounds
- Carbon is unparalleled in its ability to form large, complex, and diverse molecules
- A compound containing carbon is said to be an **organic compound**

- Critically important molecules of all living things fall into four main classes
  - Carbohydrates
  - Lipids
  - Proteins
  - Nucleic acids
- The first three of these can form huge molecules called **macromolecules**

Figure 3.1



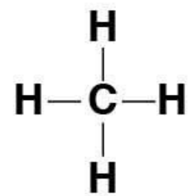
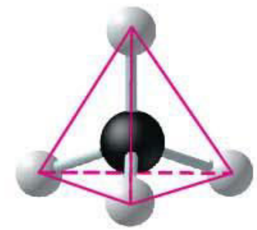
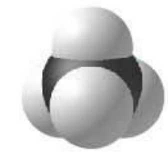
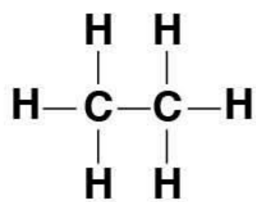
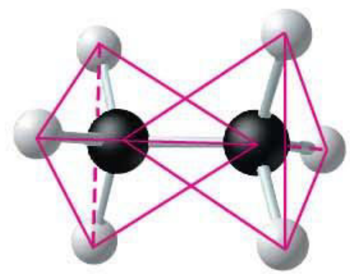
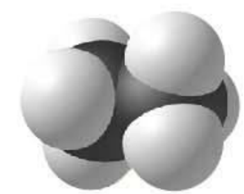
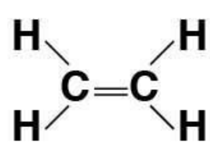
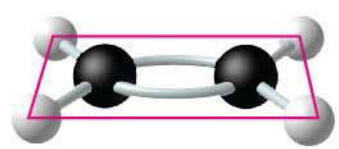
Concept 3.1: Carbon atoms can form diverse molecules by bonding to four other atoms

- An atom's electron configuration determines the kinds and number of bonds the atom will form with other atoms
- This is the source of carbon's versatility

The Formation of Bonds with Carbon

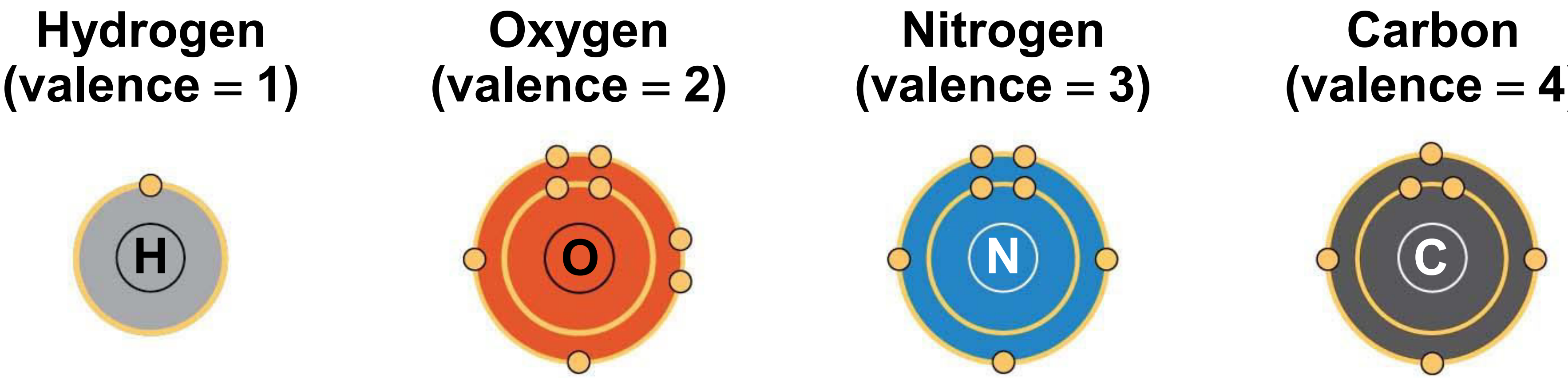
- With four **valence** electrons, carbon can form four covalent bonds with a variety of atoms
- This ability makes large, complex molecules possible
- In molecules with multiple carbons, each carbon bonded to four other atoms has a tetrahedral shape
- However, when two carbon atoms are joined by a double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

Figure 3.2

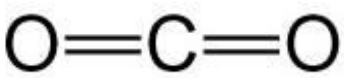
Molecular Shape	Molecular Formula	Structural Formula	Ball-and-Stick Model	Space-Filling Model
(a) Tetrahedral: methane	CH_4			
(b) More than one tetrahedral group: ethane	C_2H_6			
(c) Flat: ethene (ethylene)	C_2H_4			

- 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” that governs the architecture of living molecules

Figure 3.3


Hydrogen
(valence = 1)
H
Oxygen
(valence = 2)
O
Nitrogen
(valence = 3)
N
Carbon
(valence = 4)
C

- Carbon atoms can partner with atoms other than hydrogen; for example:
  - Carbon dioxide: CO_2



- A carbon atom can also form covalent bonds to other carbon atoms, linking the atoms into chains

Figure 3.UN01

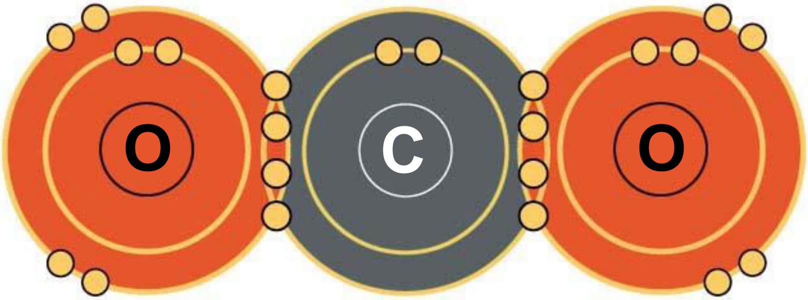
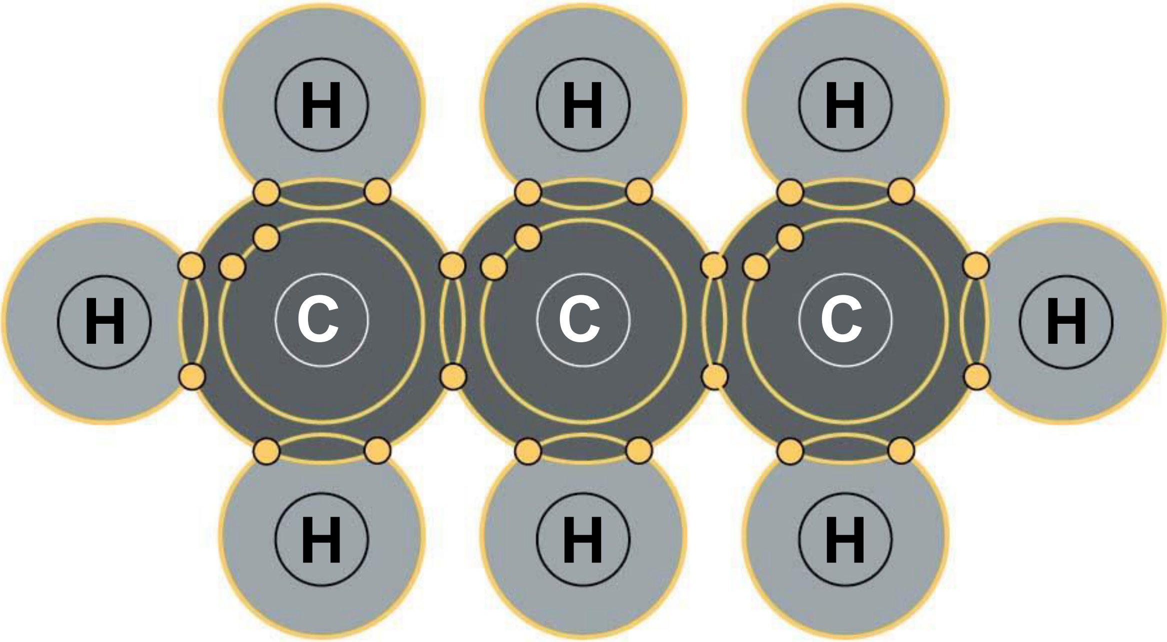


Figure 3.UN02



Molecular Diversity Arising from Variation in Carbon Skeletons

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

Animation: Carbon Skeletons

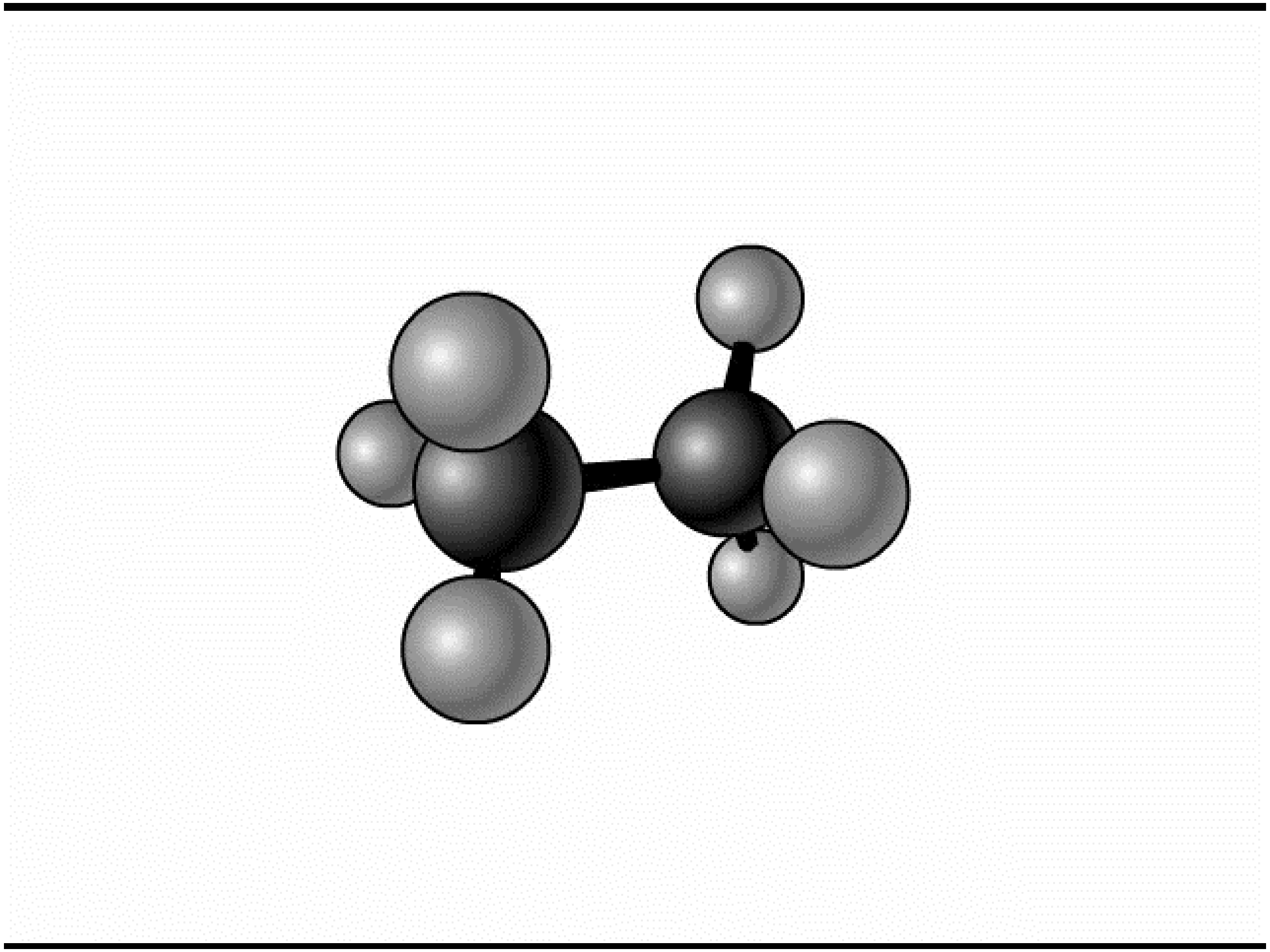
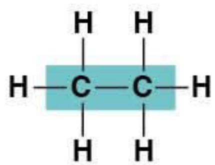
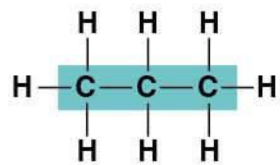


Figure 3.4

(a) Length

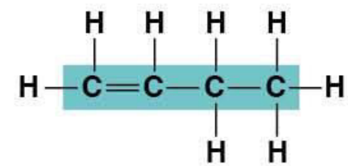


Ethane

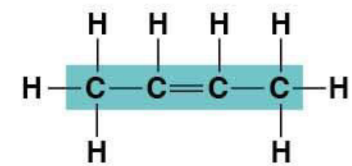


Propane

(c) Double bond position

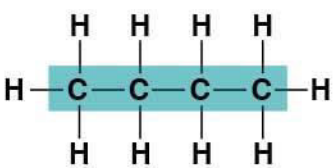


1-Butene

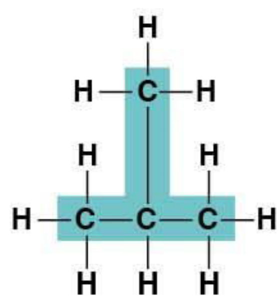


2-Butene

(b) Branching

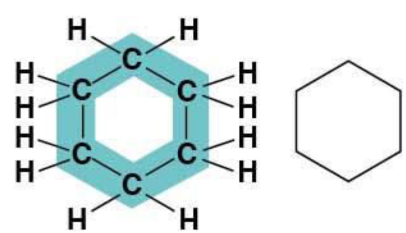


Butane

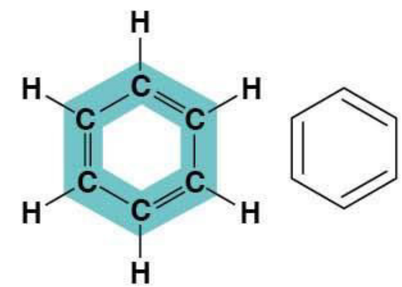


2-Methylpropane
(isobutane)

(d) Presence of rings



Cyclohexane



Benzene

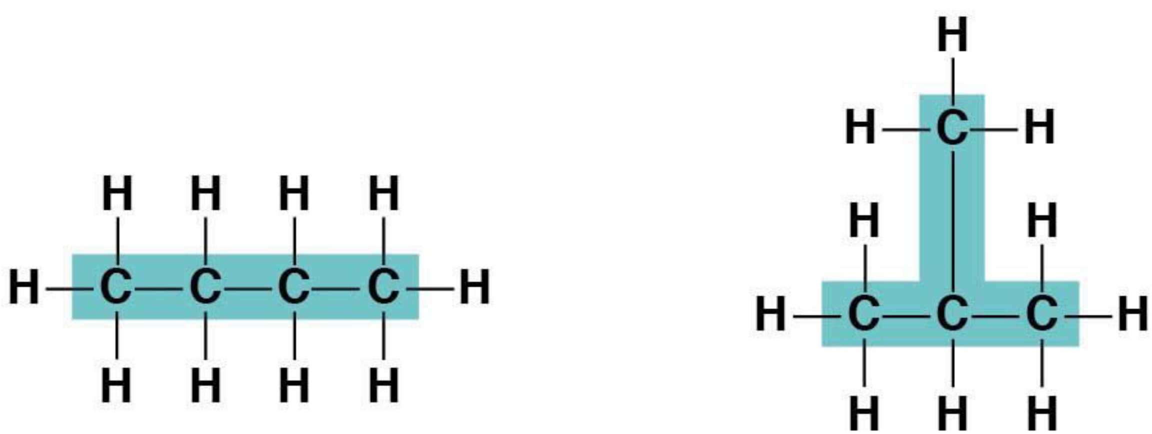
Figure 3.4-1

(a) Length

Ethane

Propane

(b) Branching

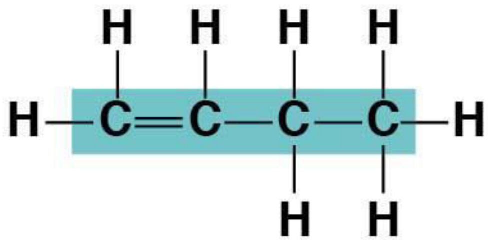


Butane

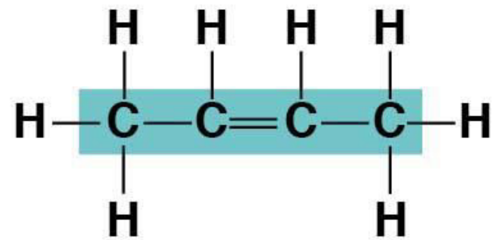
2-Methylpropane (isobutane)

Figure 3.4-2

(c) Double bond position

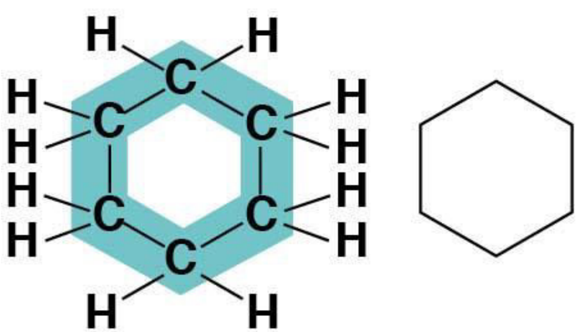


1-Butene

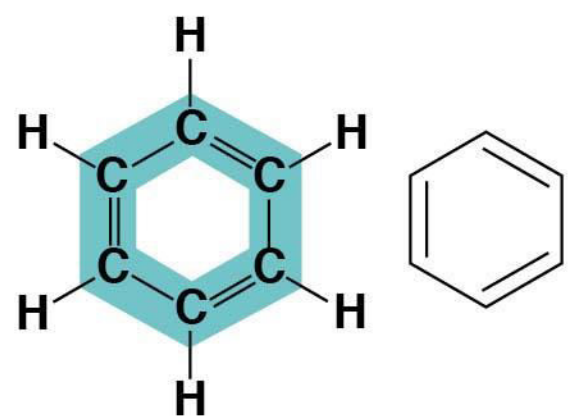


2-Butene

(d) Presence of rings



Cyclohexane



Benzene

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

Isomers

- **Isomers** are compounds that have the same number of atoms of the same elements but different structures and properties

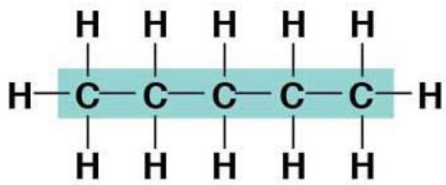
- **Structural isomers** differ in the covalent arrangement of their atoms
- The number of possible isomers increases as carbon skeletons increase in size

- In ***cis-trans*** **isomers**, carbons have covalent bonds to the same atoms, but the atoms differ in their spatial arrangement due to inflexibility of double bonds
- The subtle differences in shape between such isomers can greatly affect the activities of organic molecules

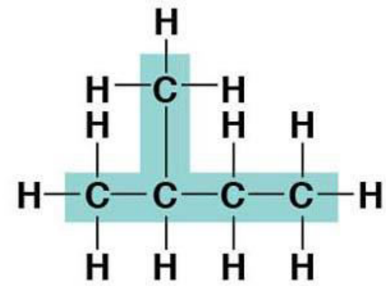
- **Enantiomers** are isomers that are mirror images of one another and differ in shape due to the presence of an asymmetric carbon
- Enantiomers are left-handed and right-handed versions of the same molecule
- Usually only one isomer is biologically active

Figure 3.5

(a) Structural isomers

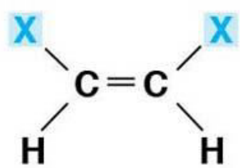


Pentane

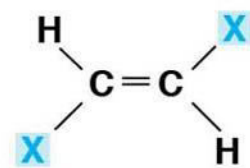


2-methyl butane

(b) *Cis-trans* isomers

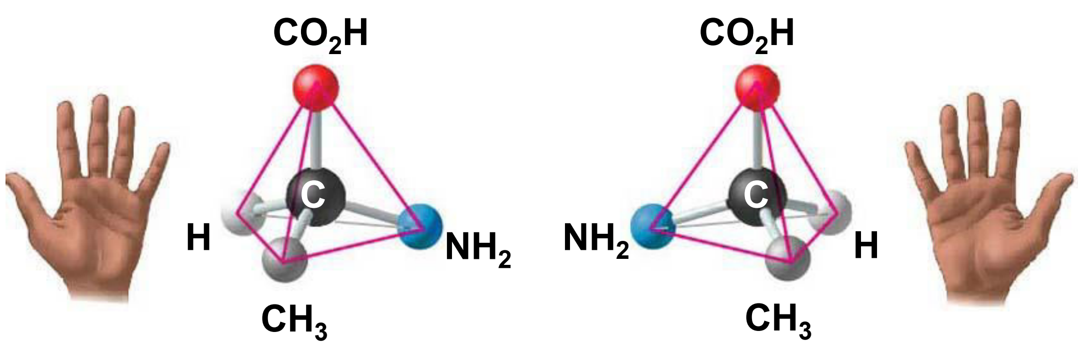


cis isomer: The two Xs are on the same side.



trans isomer: The two Xs are on opposite sides.

(c) Enantiomers



L isomer D isomer

Figure 3.5-1

(a) Structural isomers

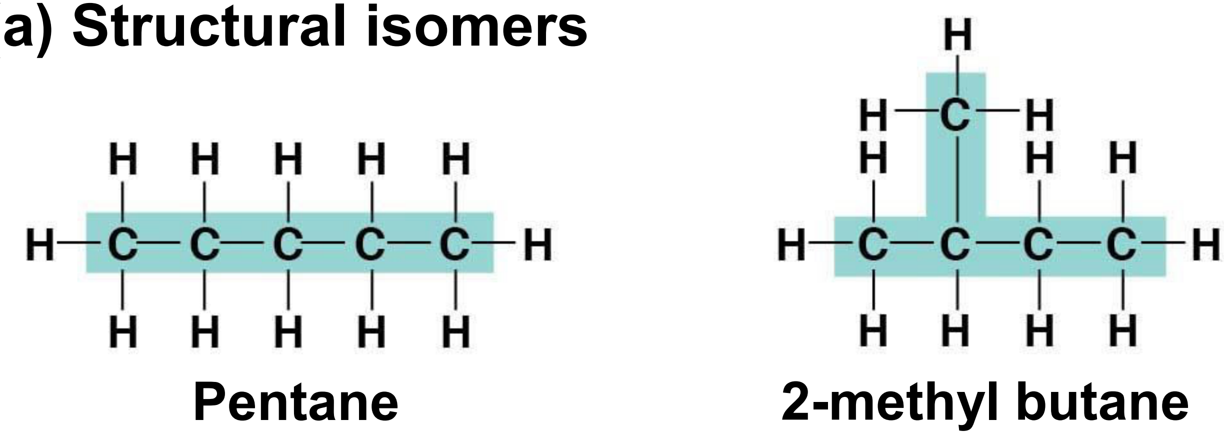
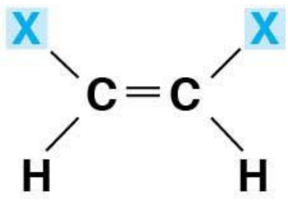
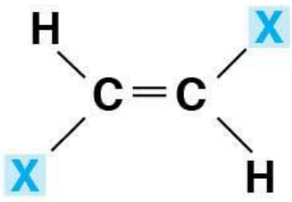


Figure 3.5-2

(b) *Cis-trans* isomers



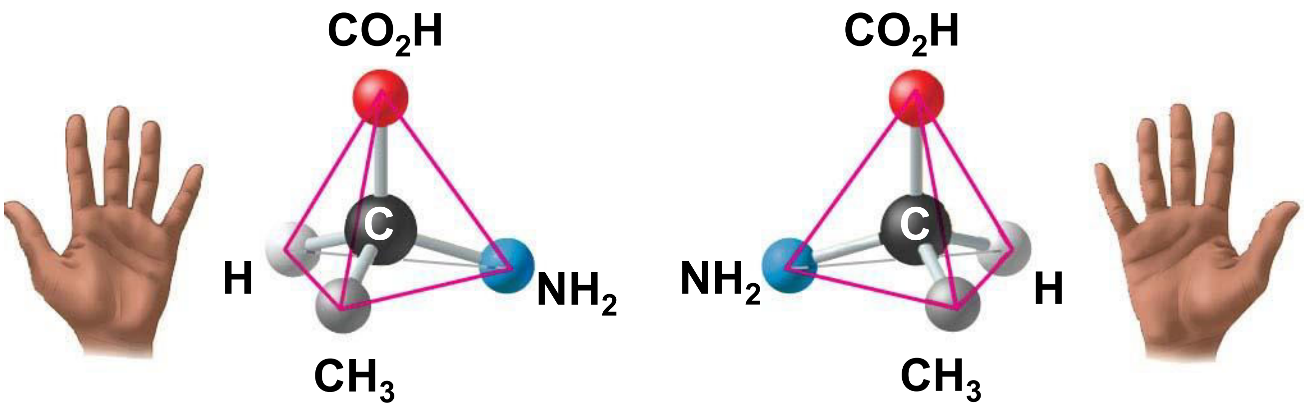
cis isomer: The two Xs are on the same side.



trans isomer: The two Xs are on opposite sides.

Figure 3.5-3

(c) Enantiomers

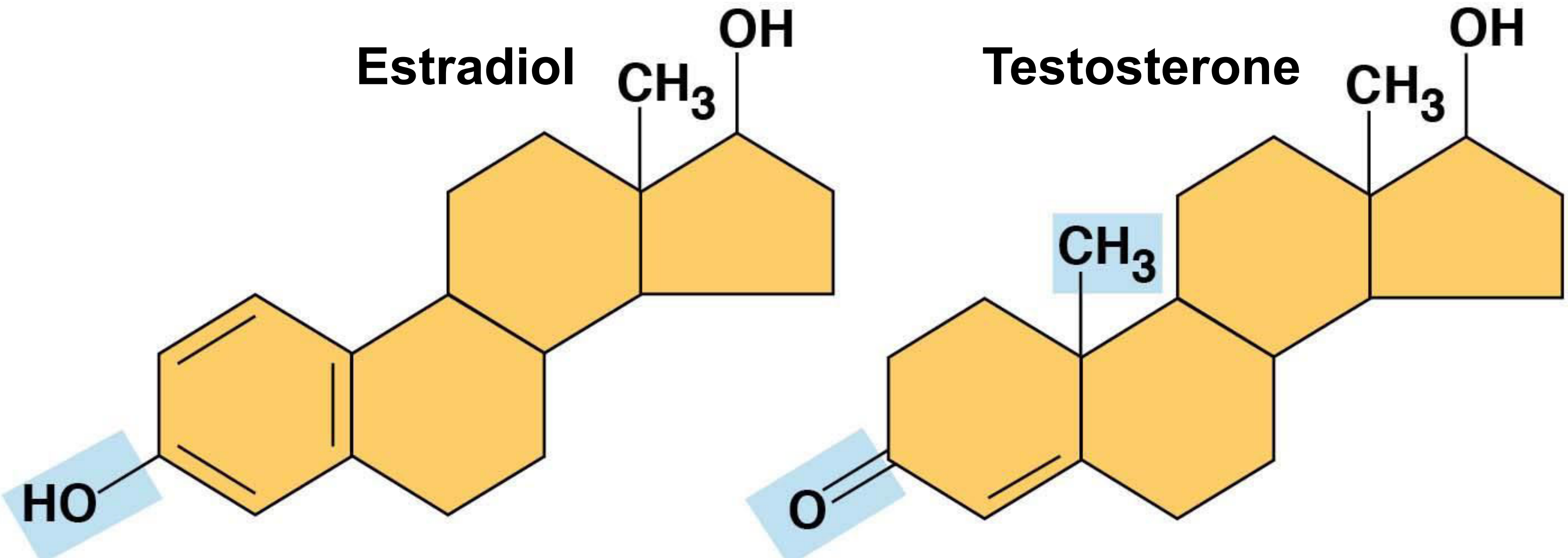


L isomer **D isomer**

The Chemical Groups Most Important to Life

- Chemical groups can replace one or more of the hydrogens bonded to the carbon skeleton of a hydrocarbon
- **Functional groups** are the chemical groups that affect molecular function by being directly involved in chemical reactions
- Each functional group participates in chemical reactions in a characteristic way

Figure 3.UN03



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

Figure 3.6

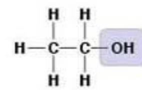
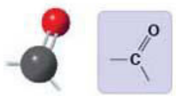
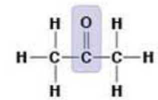
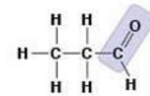
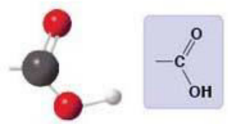
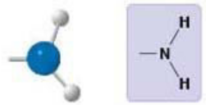
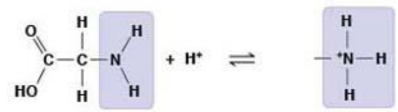
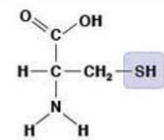
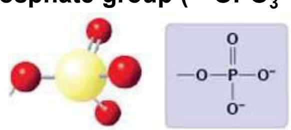
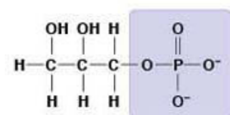
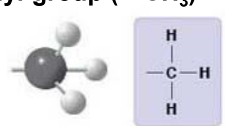
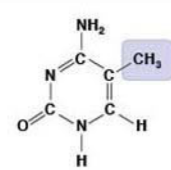
Chemical Group	Compound Name	Examples
Hydroxyl group (—OH)  (may be written HO—)	Alcohol	 Ethanol
Carbonyl group (>C=O) 	Ketone Aldehyde	 Acetone  Propanal
Carboxyl group (—COOH) 	Carboxylic acid, or organic acid	 Acetic acid ⇌ Ionized form of —COOH
Amino group (—NH_2) 	Amine	 Glycine + H^+ ⇌ Ionized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

Figure 3.6-1

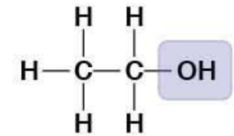
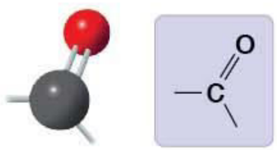
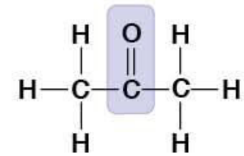
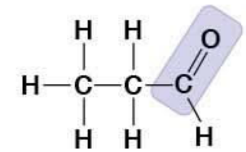
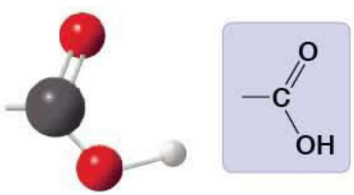
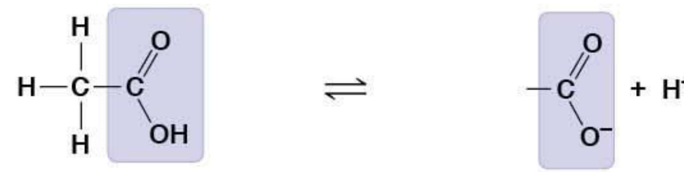
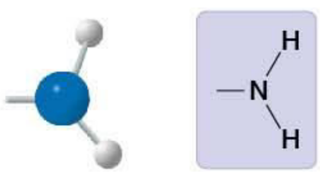
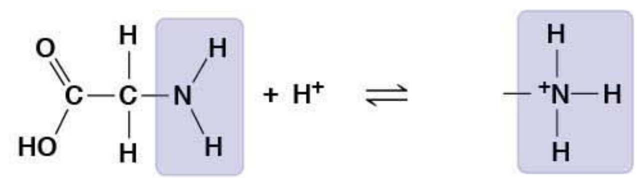
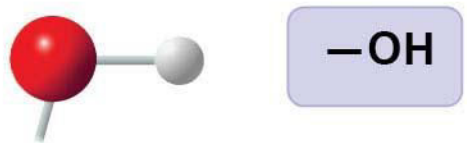
Chemical Group	Compound Name	Examples
Hydroxyl group (—OH)  (may be written HO—)	Alcohol	 Ethanol
Carbonyl group (>C=O) 	Ketone Aldehyde	 Acetone  Propanal
Carboxyl group (—COOH) 	Carboxylic acid, or organic acid	 Acetic acid; Ionized form of —COOH
Amino group ($—NH_2$) 	Amine	 Glycine; Ionized form of $—NH_2$

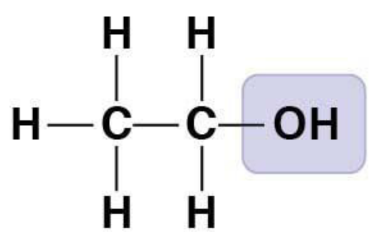
Figure 3.6-1a

Hydroxyl group (—OH)



(may be written HO—)

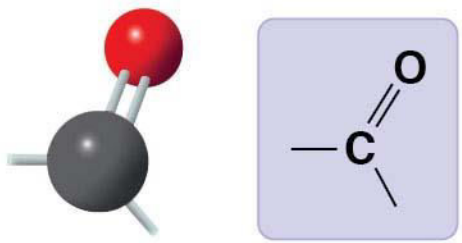
Alcohol
(The specific name usually ends in -*ol*.)



Ethanol, the alcohol present in alcoholic beverages

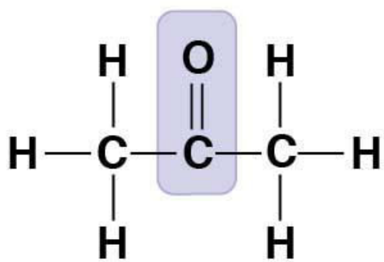
Figure 3.6-1b

Carbonyl group (>C═O)

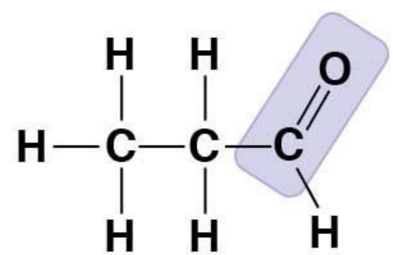


Ketone if the carbonyl group is within a carbon skeleton

Aldehyde if the carbonyl group is at the end of a carbon skeleton



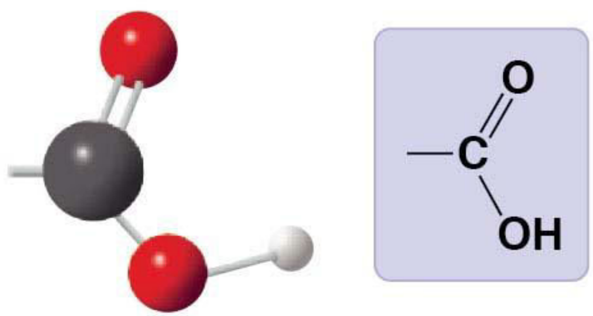
Acetone, the simplest ketone



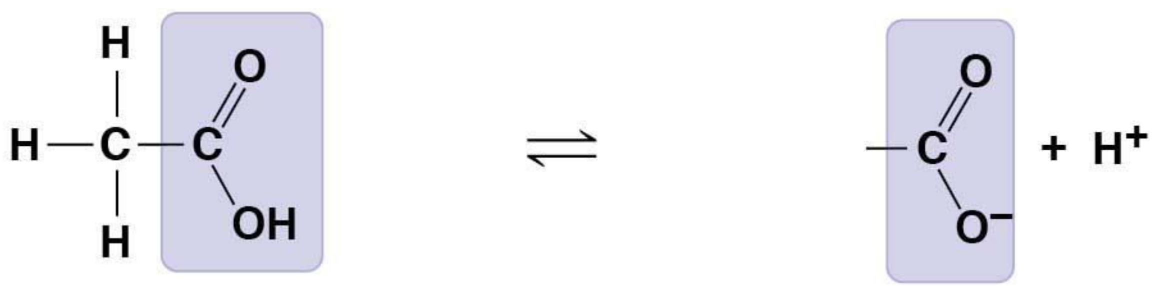
Propanal, an aldehyde

Figure 3.6-1c

Carboxyl group (—COOH)



Carboxylic acid, or organic acid



Acetic acid, which gives vinegar its sour taste

Ionized form of —COOH (carboxylate ion), found in cells

Figure 3.6-1d

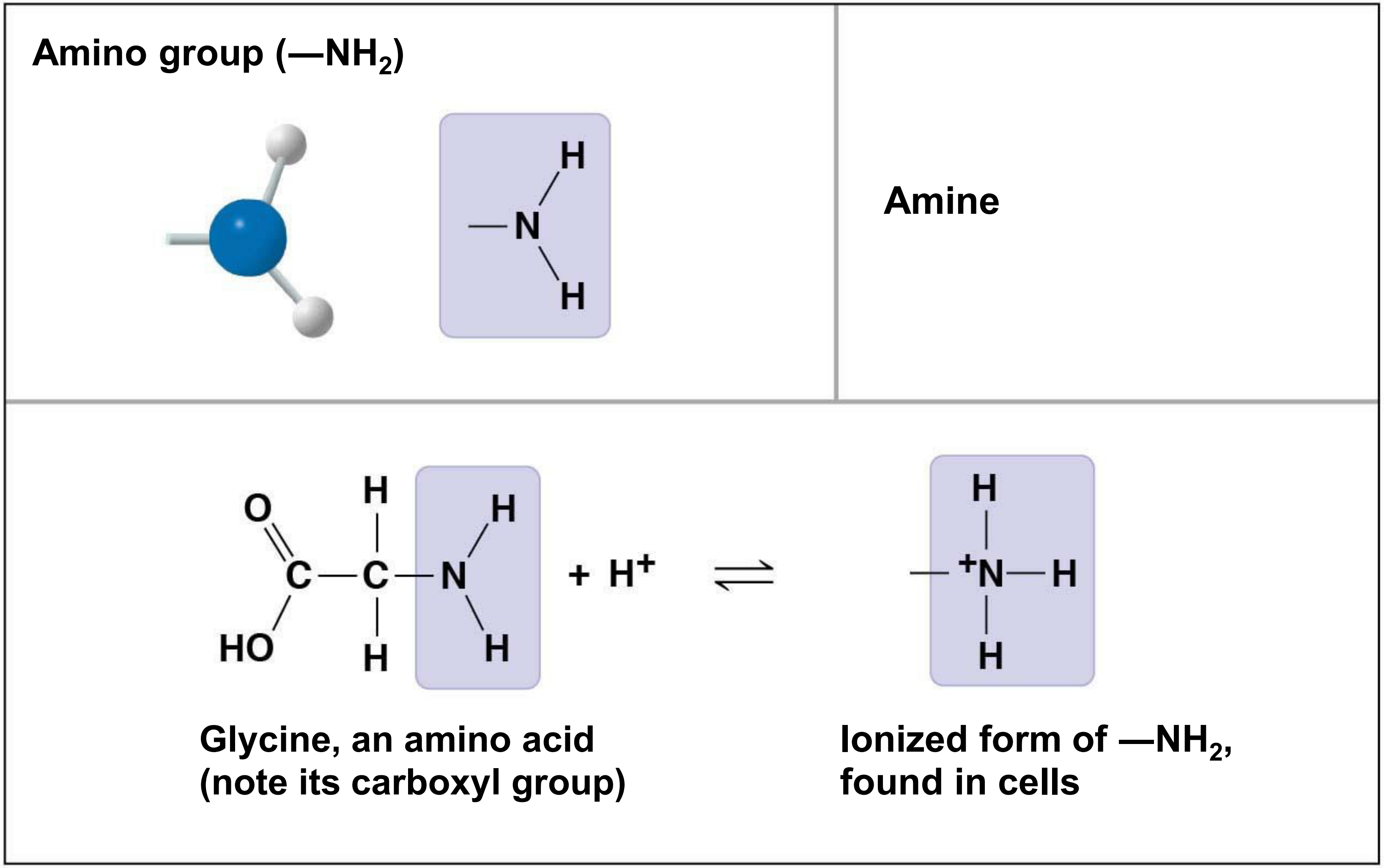

Amino group (—NH2)
Amine
+ H+
Glycine, an amino acid
(note its carboxyl group)
Ionized form of —NH2,
found in cells

Figure 3.6-2

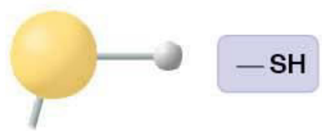
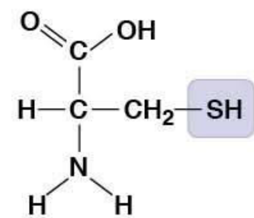
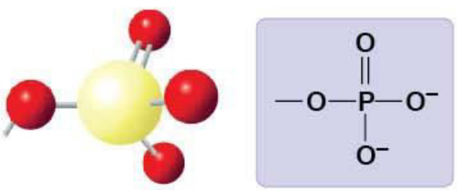
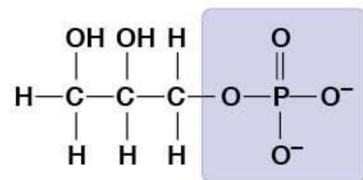
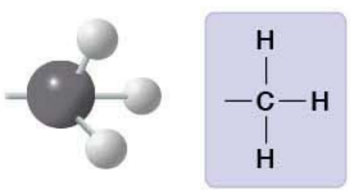
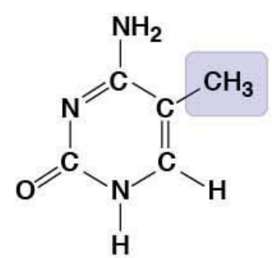
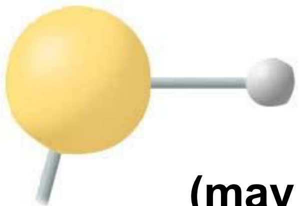
Chemical Group	Compound Name	Examples
Sulfhydryl group (—SH) 	Thiol	 Cysteine
Phosphate group ($—OPO_3^{2—}$) 	Organic phosphate	 Glycerol phosphate
Methyl group ($—CH_3$) 	Methylated compound	 5-Methyl cytosine

Figure 3.6-2a

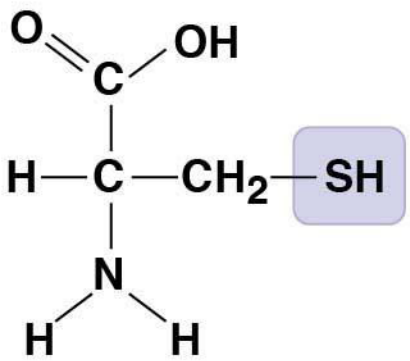
Sulfhydryl group (—SH)



—SH

(may be written HS—)

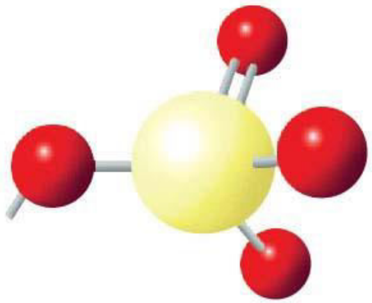
Thiol

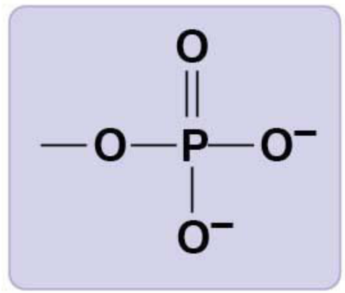


Cysteine, a sulfur-containing amino acid

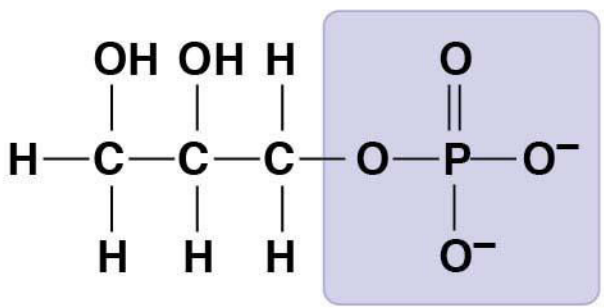
Figure 3.6-2b

Phosphate group (—OPO_3^{2-})





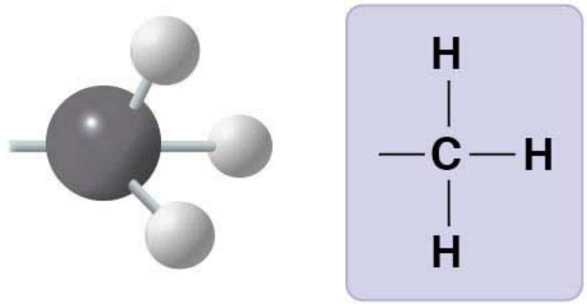
Organic phosphate



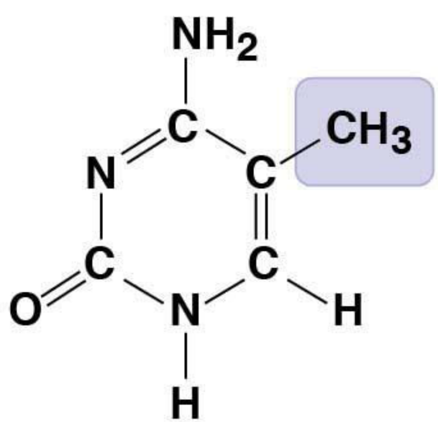
Glycerol phosphate, which takes part in many important chemical reactions in cells

Figure 3.6-2c

Methyl group ($—CH_3$)



Methylated compound

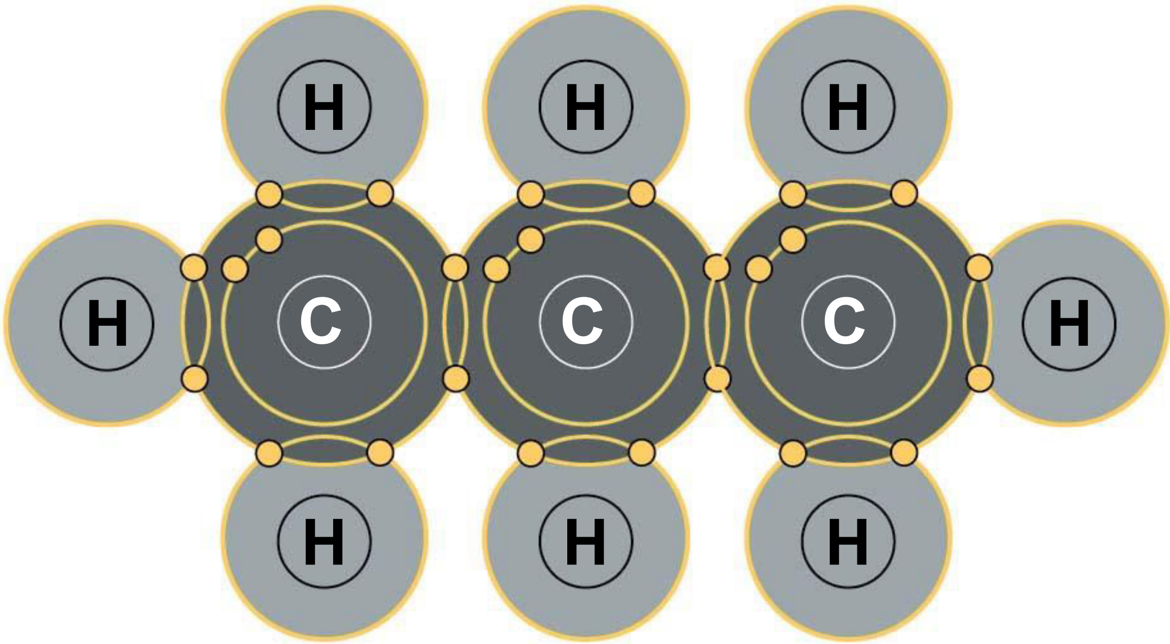


5-Methyl cytosine, a component of DNA that has been modified by addition of a methyl group

ATP: An Important Source of Energy for Cellular Processes

- An organic phosphate molecule, **adenosine triphosphate** (**ATP**), has an important function in the cell
- ATP consists of an organic molecule called adenosine attached to a string of three phosphate groups
- ATP stores the potential to react with water, releasing energy that can be used by the cell

Figure 3.UN02



Concept 3.2: Macromolecules are polymers, built from monomers

- A **polymer** is a long molecule consisting of many similar building blocks
- These small building-block molecules are called **monomers**
- Some molecules that serve as monomers also have other functions of their own

The Synthesis and Breakdown of Polymers

- Cells make and break down polymers by the same mechanisms
- A **dehydration reaction** occurs when two monomers bond together through the loss of a water molecule
- Polymers are disassembled to monomers by **hydrolysis**, a reaction that is essentially the reverse of the dehydration reaction
- These processes are facilitated by **enzymes**, which speed up chemical reactions

Animation: Polymers

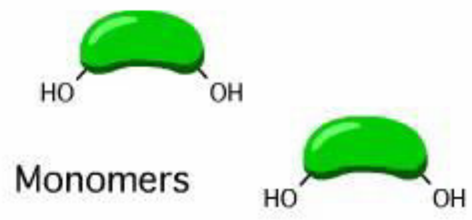


Figure 3.7

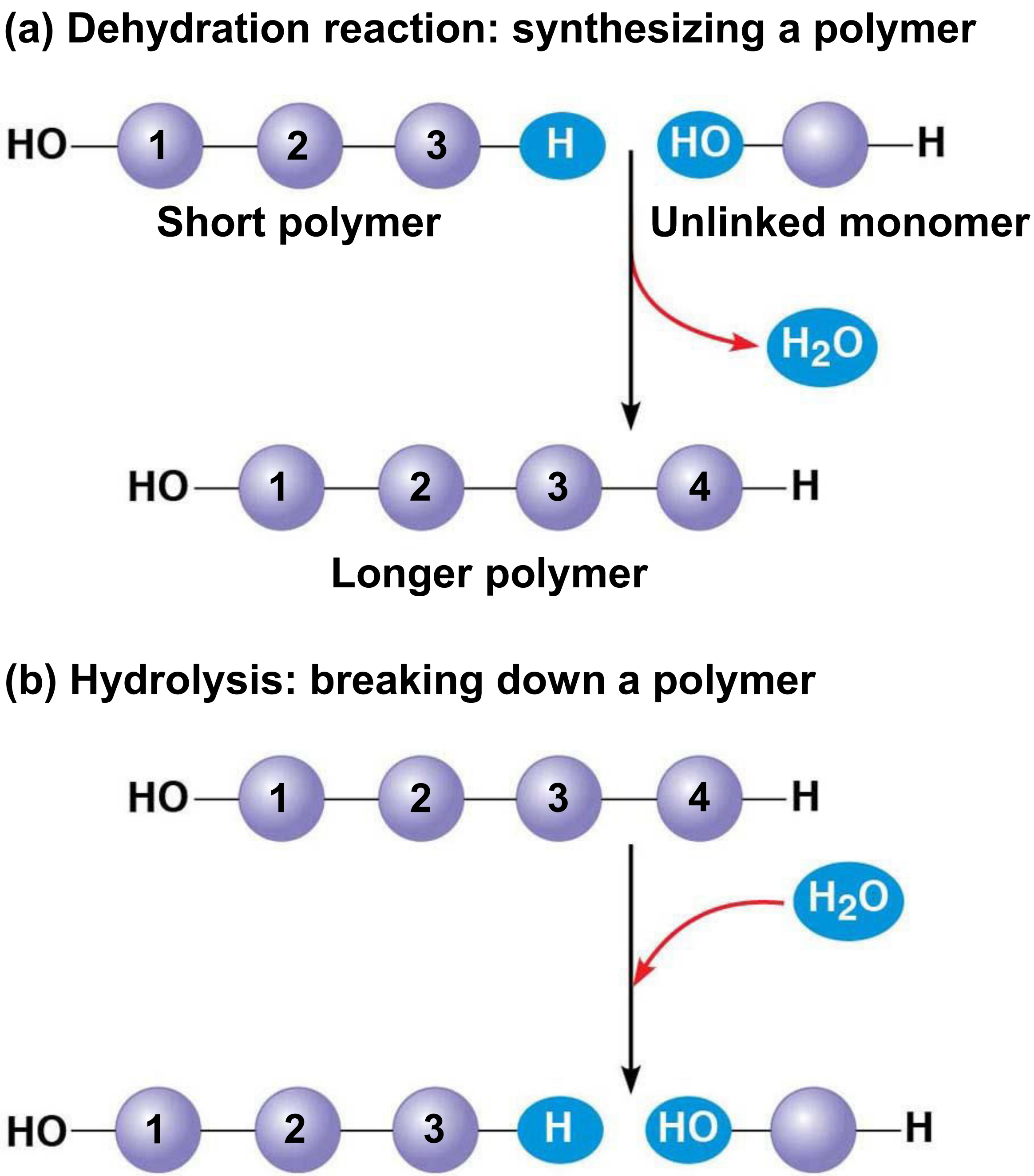

(a) Dehydration reaction: synthesizing a polymer
HO 1 2 3 H
HO H
Short polymer
Unlinked monomer
H_2O
HO 1 2 3 4 H
Longer polymer
(b) Hydrolysis: breaking down a polymer
HO 1 2 3 4 H
H_2O
HO 1 2 3 H
HO H

Figure 3.7-1

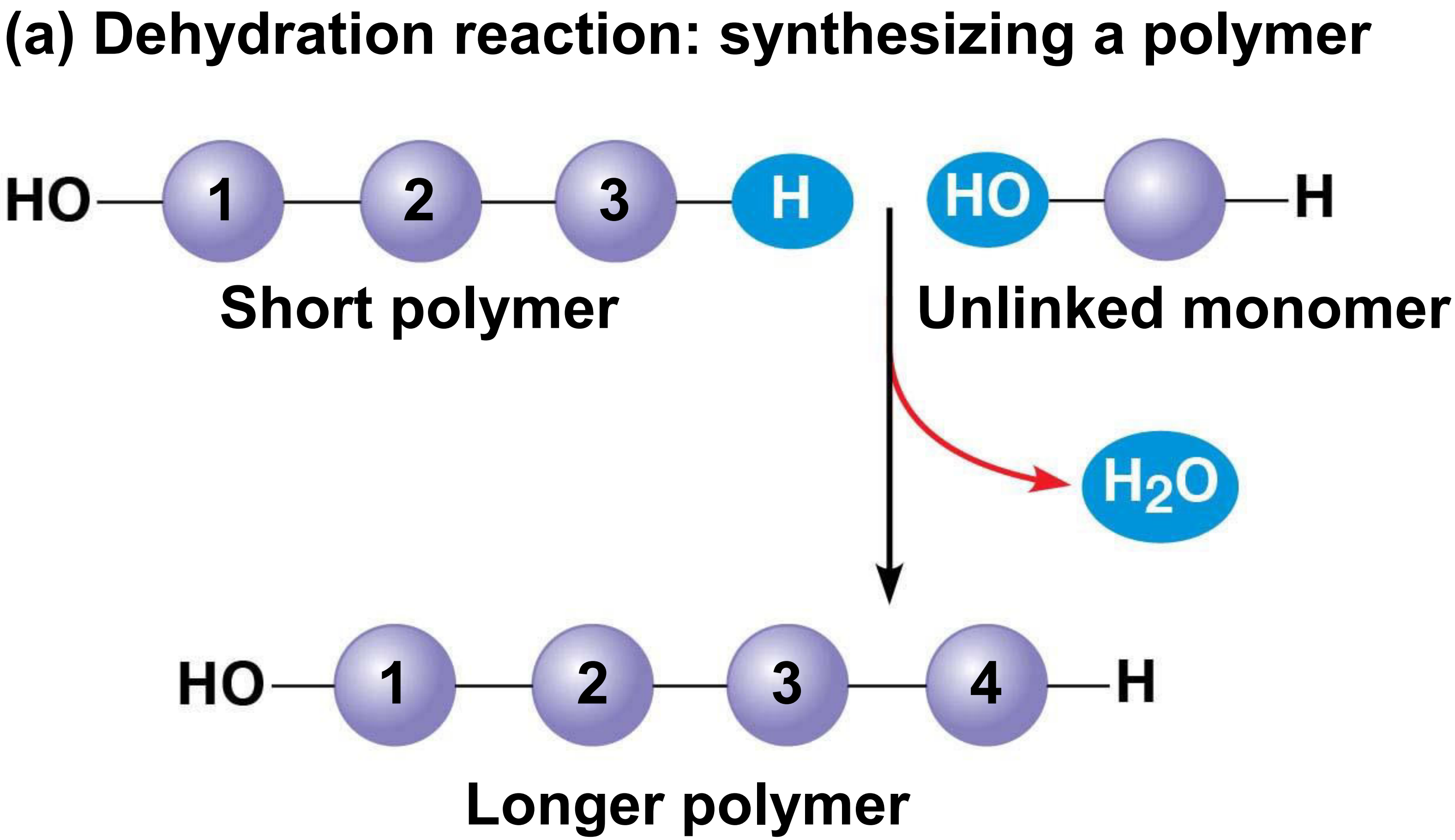
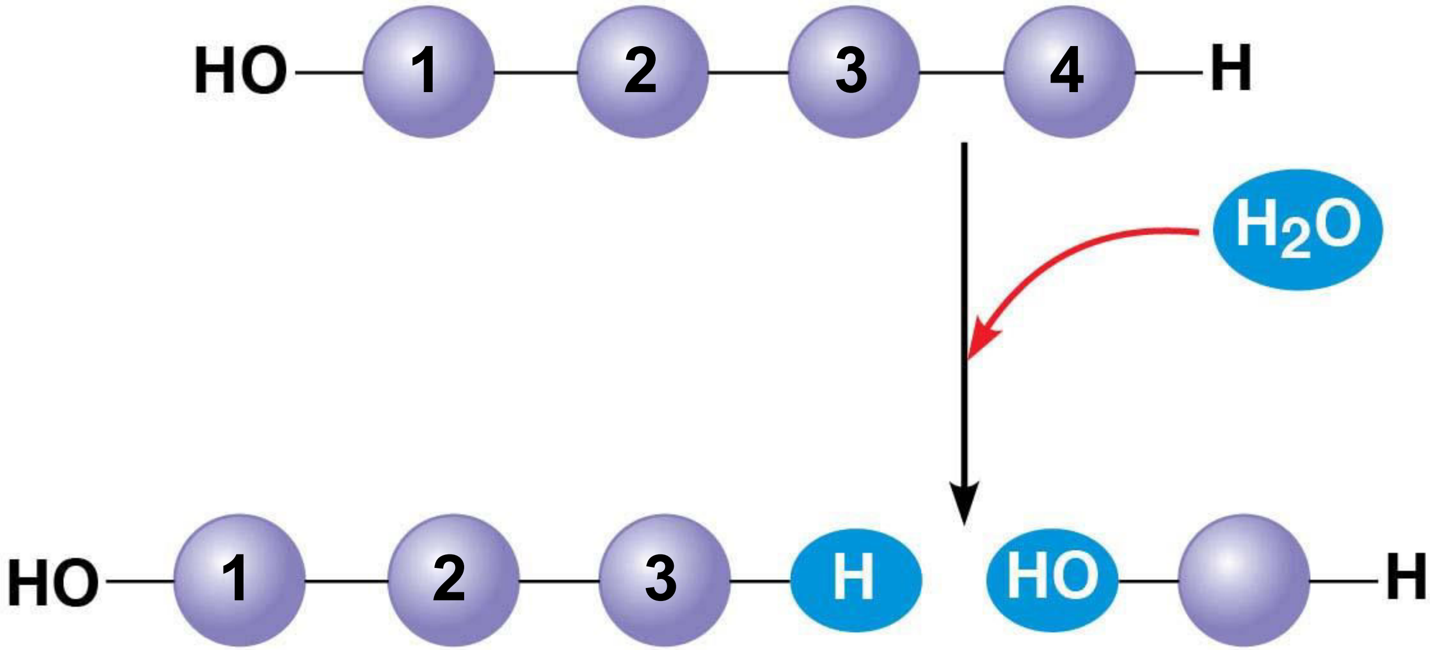

(a) Dehydration reaction: synthesizing a polymer
HO
1
2
3
H
HO
H
Short polymer
Unlinked monomer
H_2O
HO
1
2
3
4
H
Longer polymer

Figure 3.7-2

(b) Hydrolysis: breaking down a polymer



The Diversity of Polymers

- Each cell has thousands of different macromolecules
- Macromolecules vary among cells of an organism, vary more within a species, and vary even more between species
- An immense variety of polymers can be built from a small set of monomers

Concept 3.3: Carbohydrates serve as fuel and building material

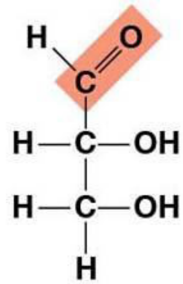
- **Carbohydrates** include sugars and the polymers of sugars
- The simplest carbohydrates are monosaccharides, or simple sugars
- Carbohydrate macromolecules are polysaccharides, polymers composed of many sugar building blocks

Sugars

- **Monosaccharides** have molecular formulas that are usually multiples of CH_2O
- Glucose ($C_6H_{12}O_6$) is the most common monosaccharide
- Monosaccharides are classified by the number of carbons in the carbon skeleton and the placement of the carbonyl group ($C{=}O$)

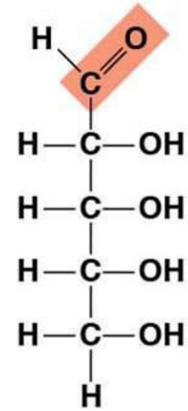
Figure 3.8

Triose: three-carbon sugar ($C_3H_6O_3$)



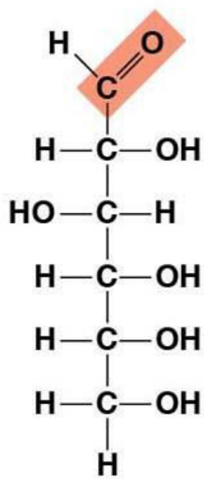
Glyceraldehyde
An initial breakdown product of glucose in cells

Pentose: five-carbon sugar ($C_5H_{10}O_5$)

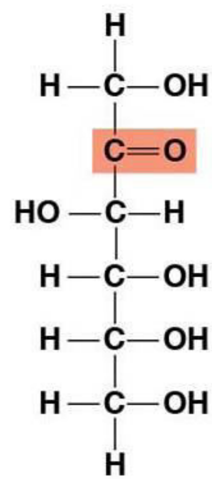


Ribose
A component of RNA

Hexoses: six-carbon sugars ($C_6H_{12}O_6$)



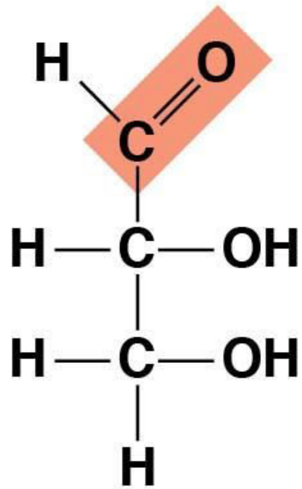
Glucose



Fructose

Energy sources for organisms

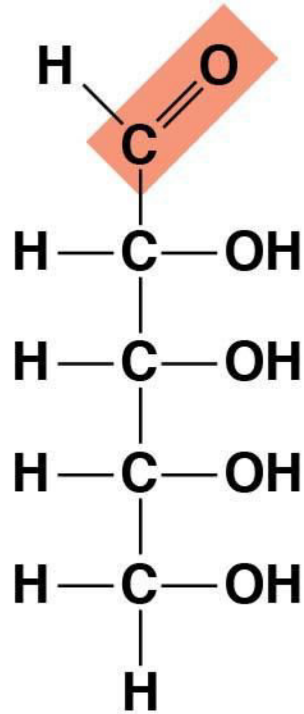
Triose: three-carbon sugar ($C_3H_6O_3$)



Glyceraldehyde
An initial breakdown product of glucose in cells

Figure 3.8-2

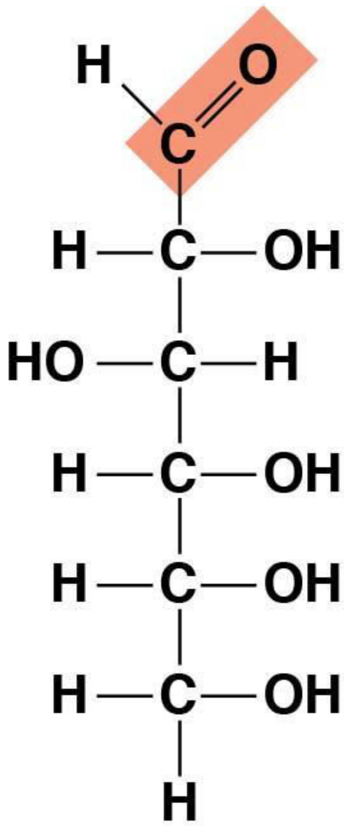
Pentose: five-carbon sugar ($C_5H_{10}O_5$)



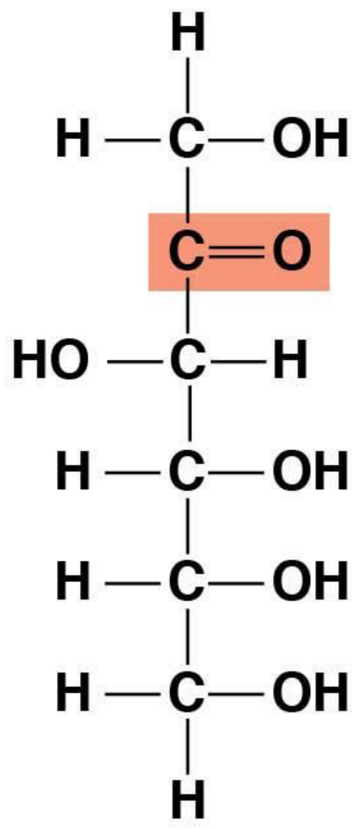
Ribose
A component of RNA

Figure 3.8-3

Hexoses: six-carbon sugars ($C_6H_{12}O_6$)



Glucose

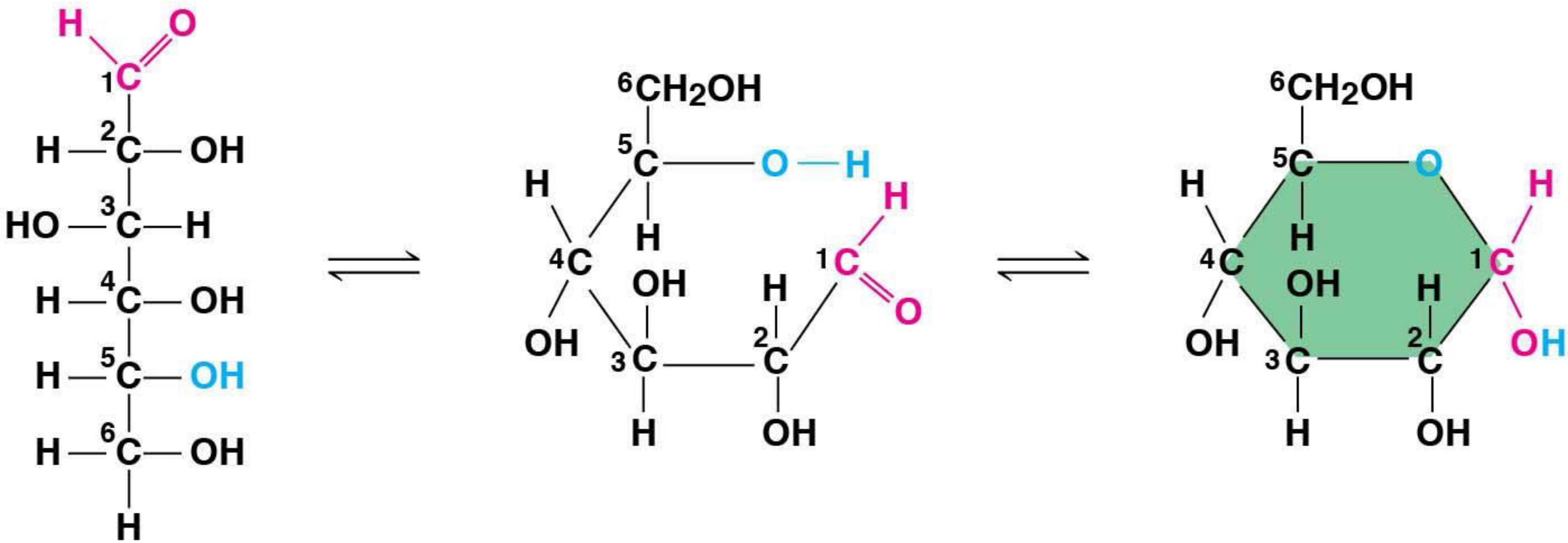


Fructose

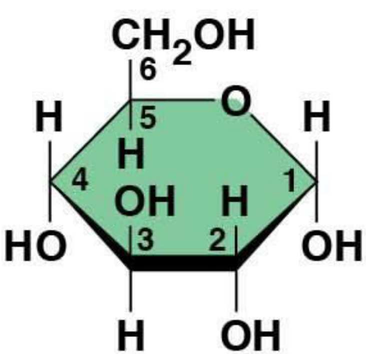
Energy sources for organisms

- Though often drawn as linear skeletons, in aqueous solutions many sugars form rings
- Monosaccharides serve as a major nutrients for cells and as raw material for building molecules

Figure 3.9



(a) Linear and ring forms



(b) Abbreviated ring structure

- A **disaccharide** is formed when a dehydration reaction joins two monosaccharides
- This covalent bond is called a **glycosidic linkage**

Figure 3.10-s1

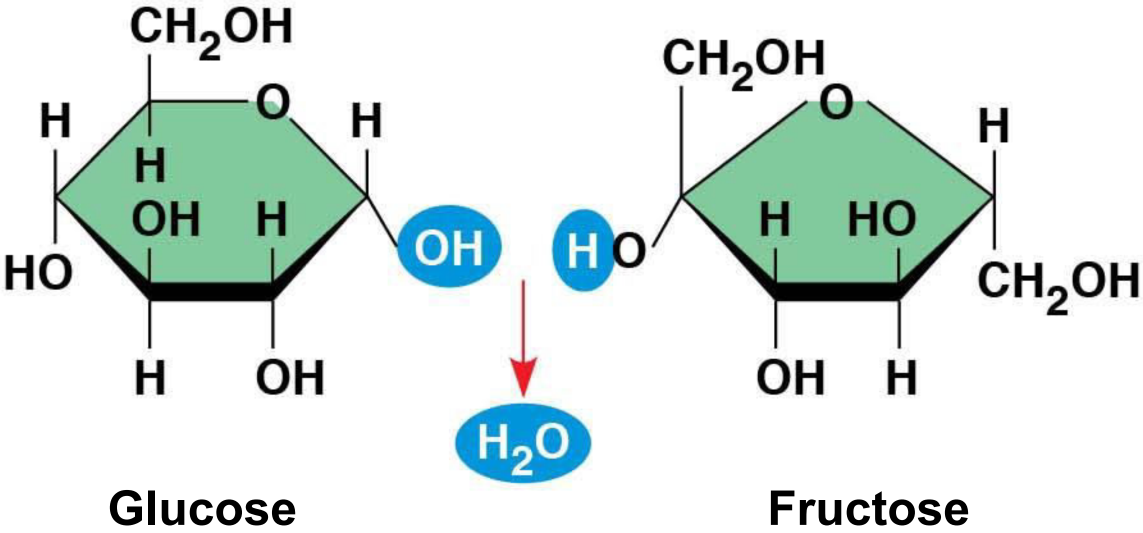
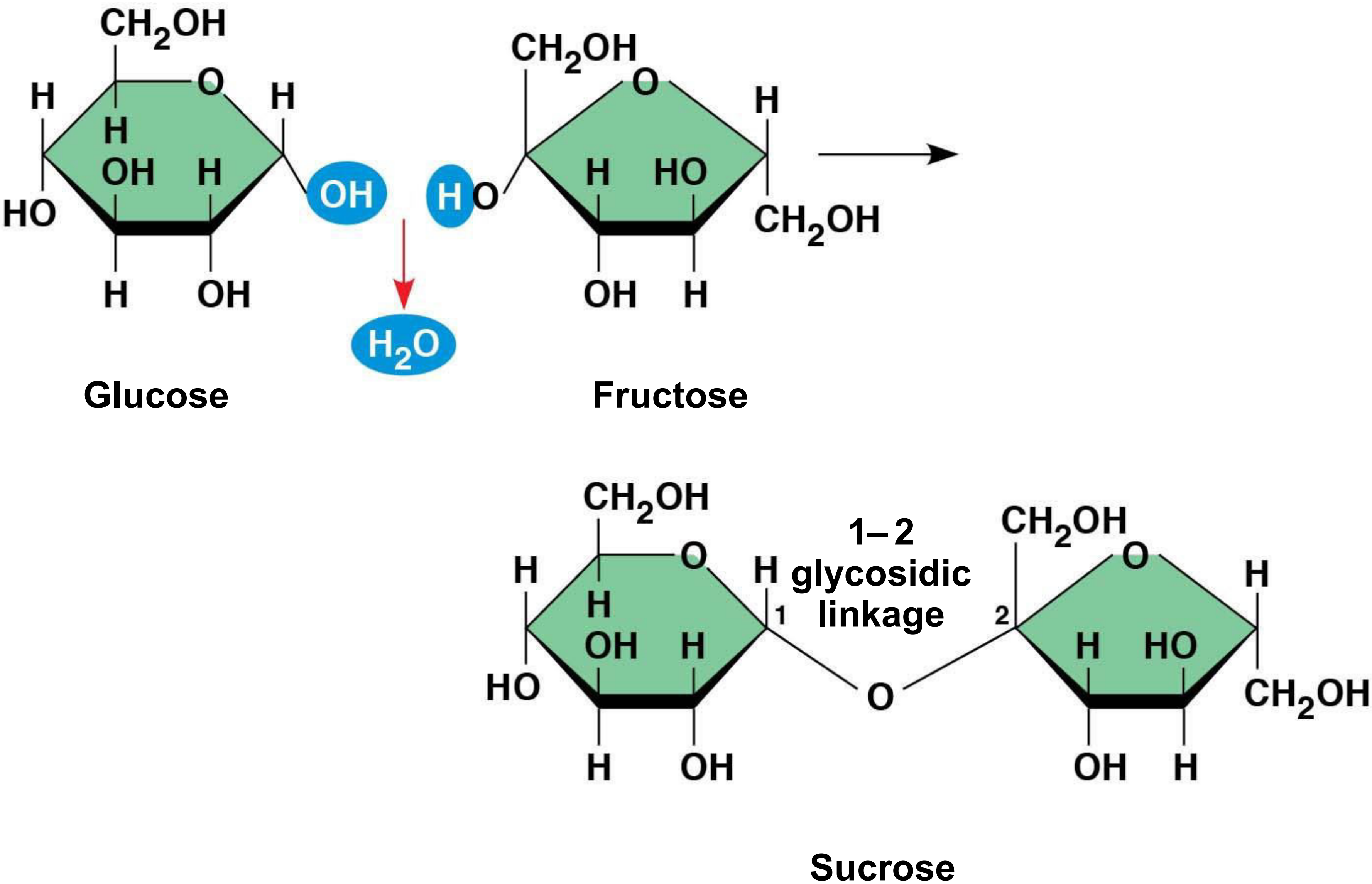


Figure 3.10-s2



Polysaccharides

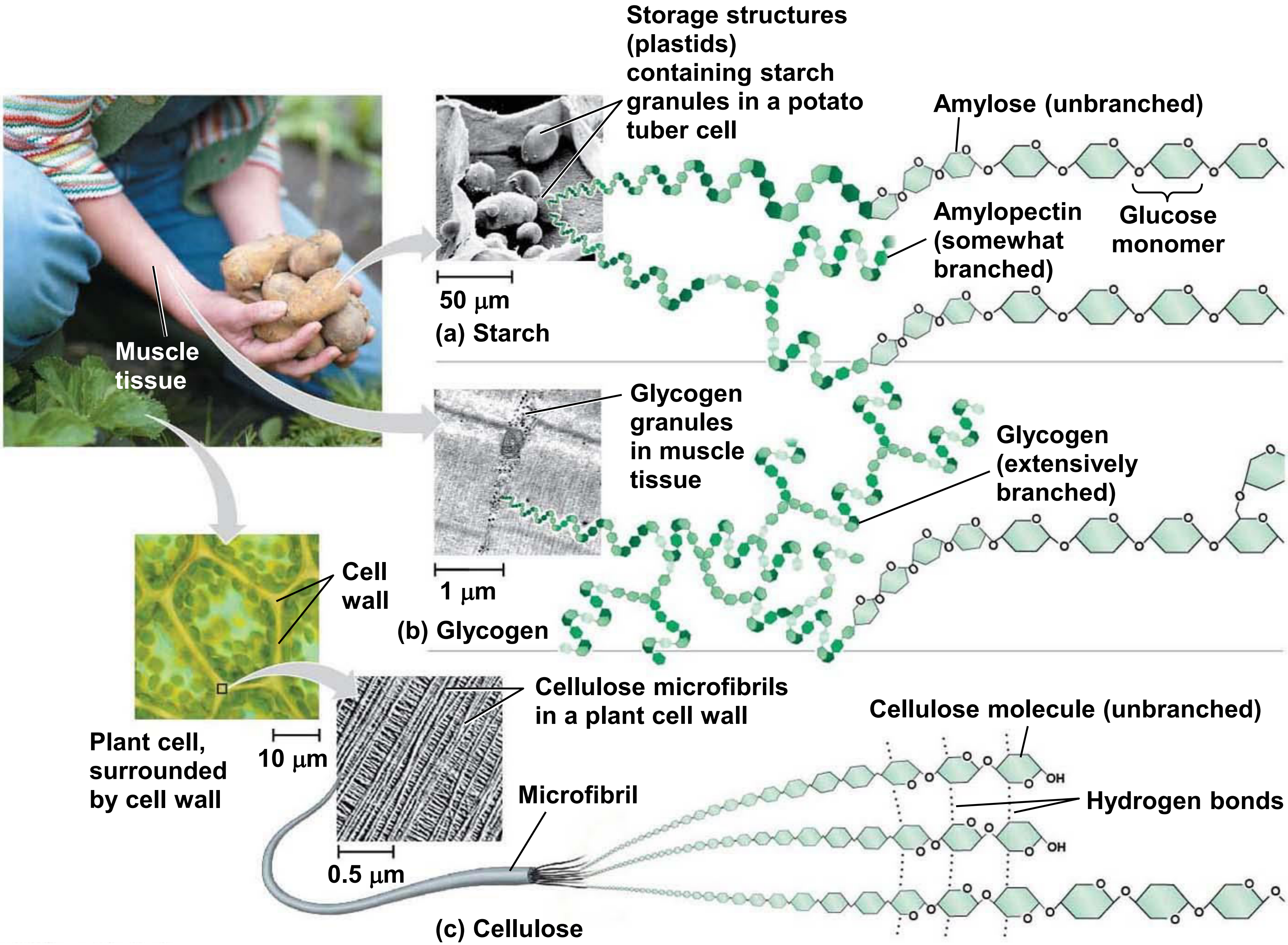
- **Polysaccharides**, the polymers of sugars, have storage and structural roles
- The structure and function of a polysaccharide are determined by its sugar monomers and the positions of glycosidic linkages

Storage Polysaccharides

- **Starch**, a storage polysaccharide of plants, consists entirely of glucose monomers
- Plants store surplus starch as granules
- Most animals have enzymes that can hydrolyze plant start, making glucose available as a nutrient

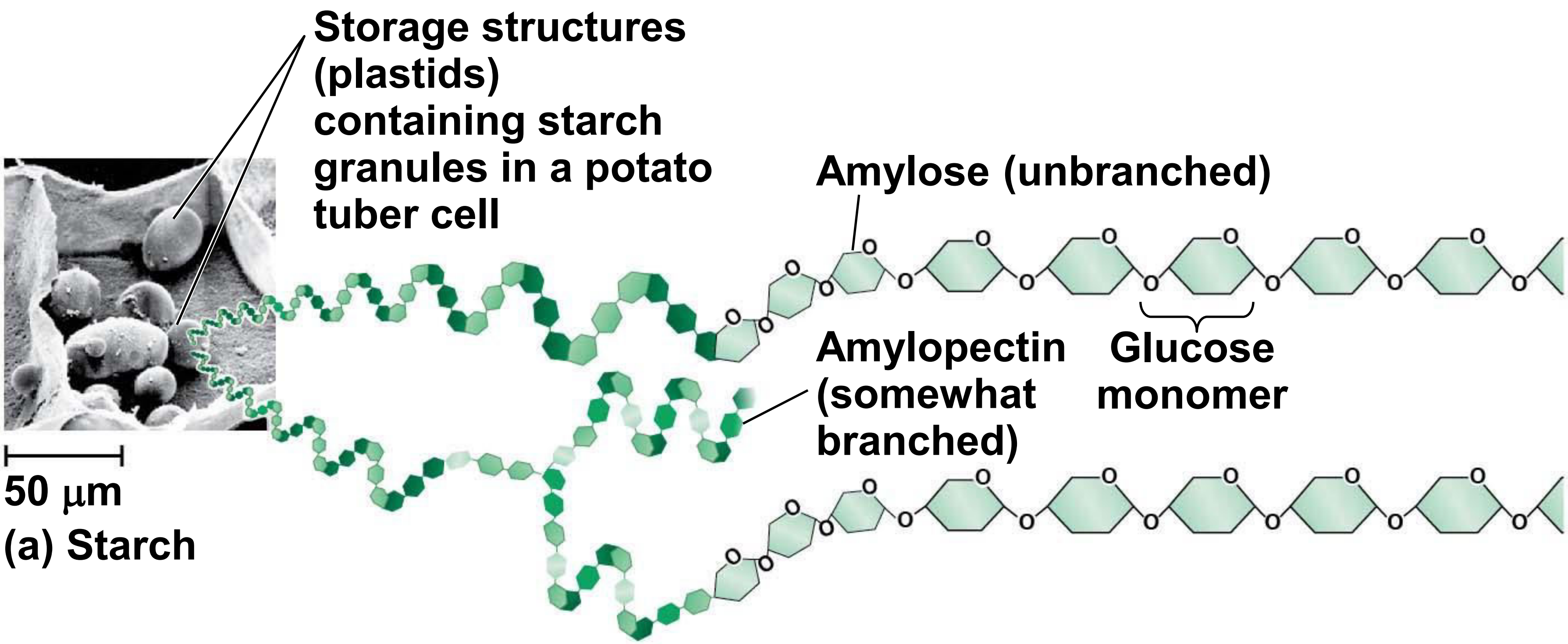
- **Glycogen** is a storage polysaccharide in animals
- Humans and other vertebrates store glycogen mainly in liver and muscle cells

Figure 3.11



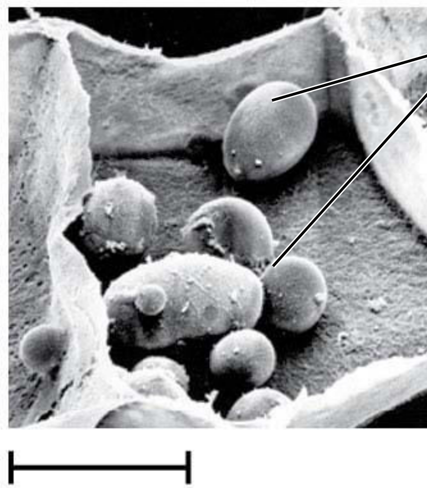
Storage structures (plastids) containing starch granules in a potato tuber cell
Amylose (unbranched)
Amylopectin (somewhat branched)
Glucose monomer
50 μm
(a) Starch
Muscle tissue
Glycogen granules in muscle tissue
Glycogen (extensively branched)
1 μm
(b) Glycogen
Cell wall
Plant cell, surrounded by cell wall
10 μm
Cellulose microfibrils in a plant cell wall
Cellulose molecule (unbranched)
Microfibril
Hydrogen bonds
0.5 μm
OH
OH
(c) Cellulose

Figure 3.11-1

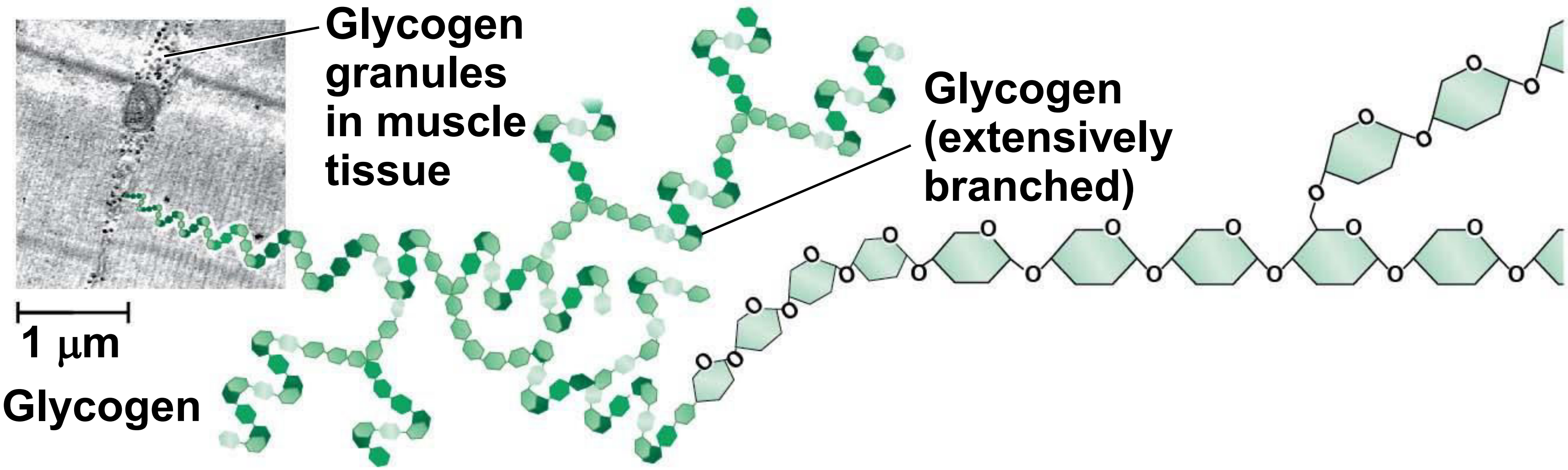


(a) Starch

Figure 3.11-1a



Storage structures (plastids) containing starch granules in a potato tuber cell


Glycogen granules in muscle tissue
1 μm
Glycogen (extensively branched)
O

(b) Glycogen

Figure 3.11-2a

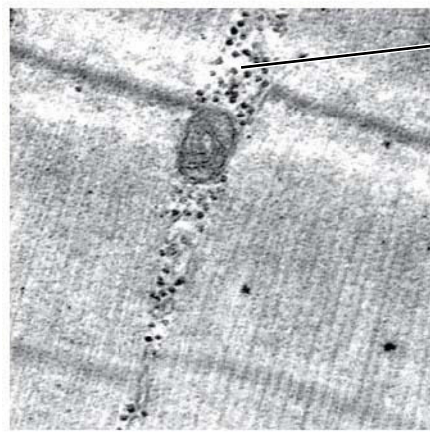
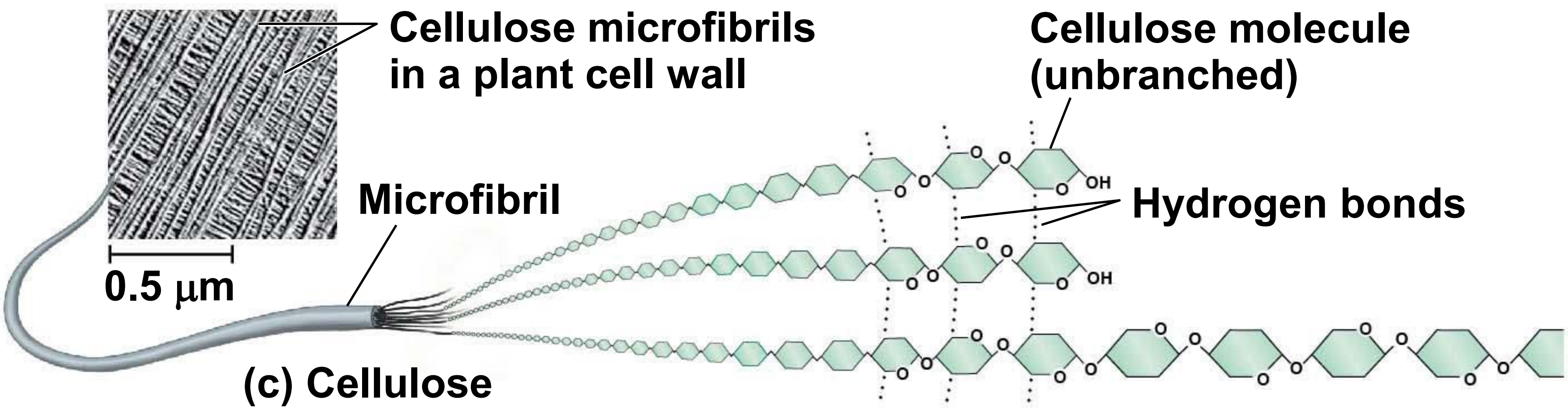
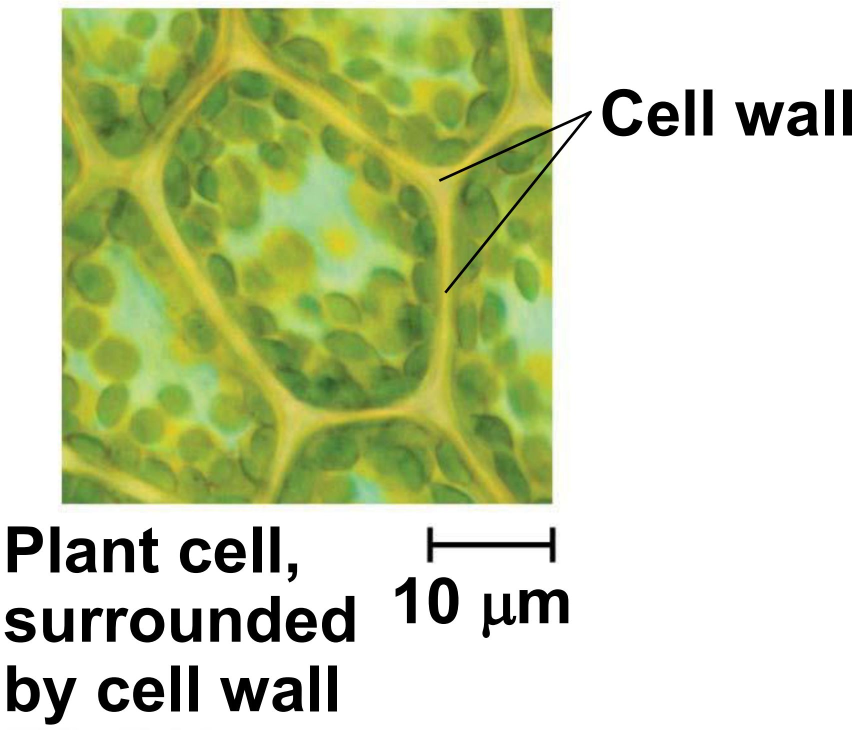


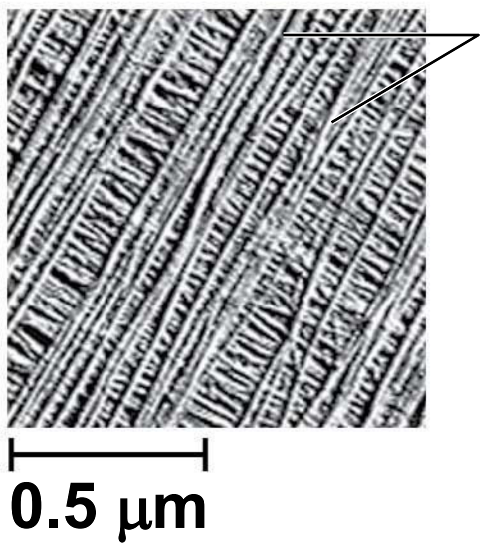
Figure 3.11-3



(c) Cellulose

Figure 3.11-3a



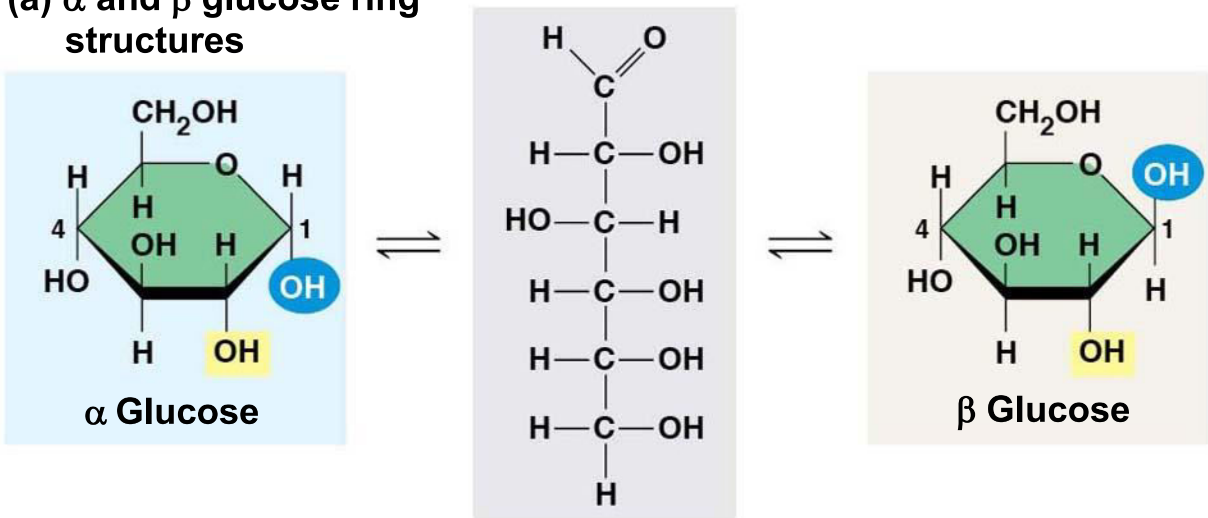

Cellulose microfibrils
in a plant cell wall
0.5 μm

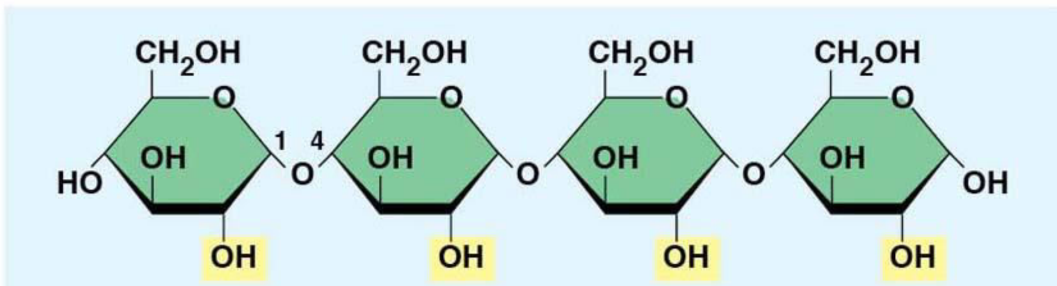
Structural Polysaccharides

- The polysaccharide **cellulose** is a major component of the tough wall of plant cells
- Like starch and glycogen, cellulose is a polymer of glucose, but the glycosidic linkages in cellulose differ
- The difference is based on two ring forms for glucose

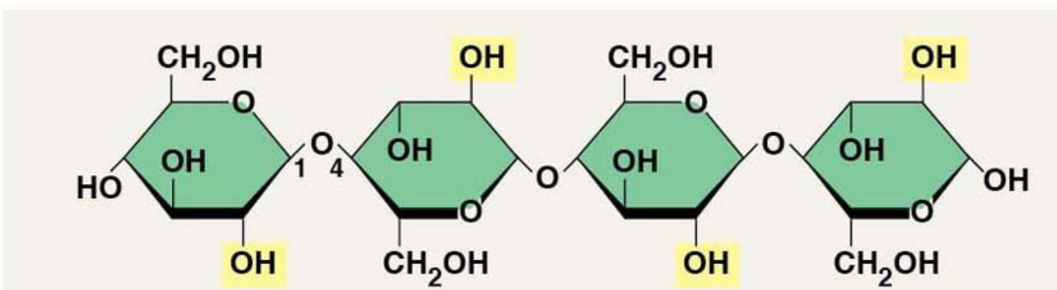
Figure 3.12

(a) α and β glucose ring structures





(b) Starch: 1–4 linkage of α glucose monomers



(c) Cellulose: 1–4 linkage of β glucose monomers

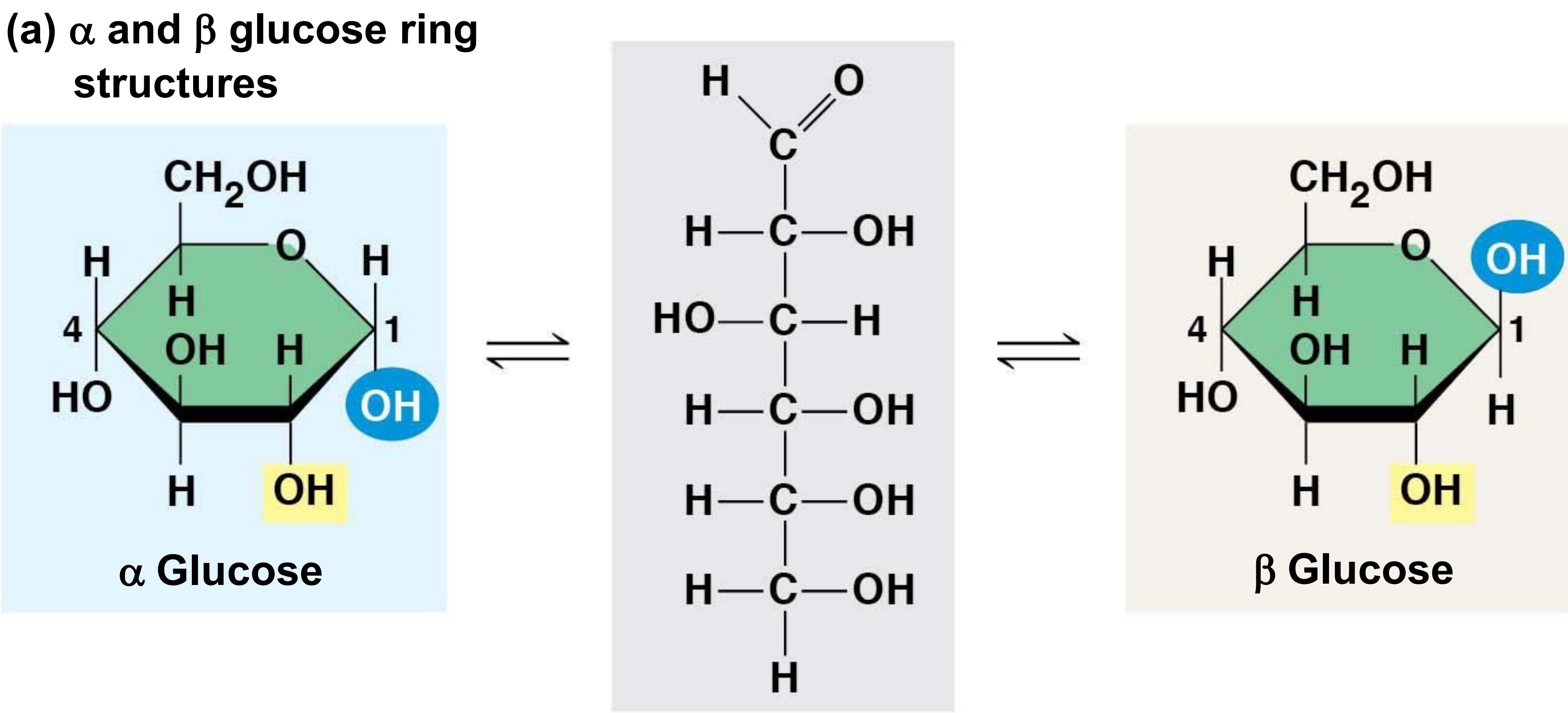
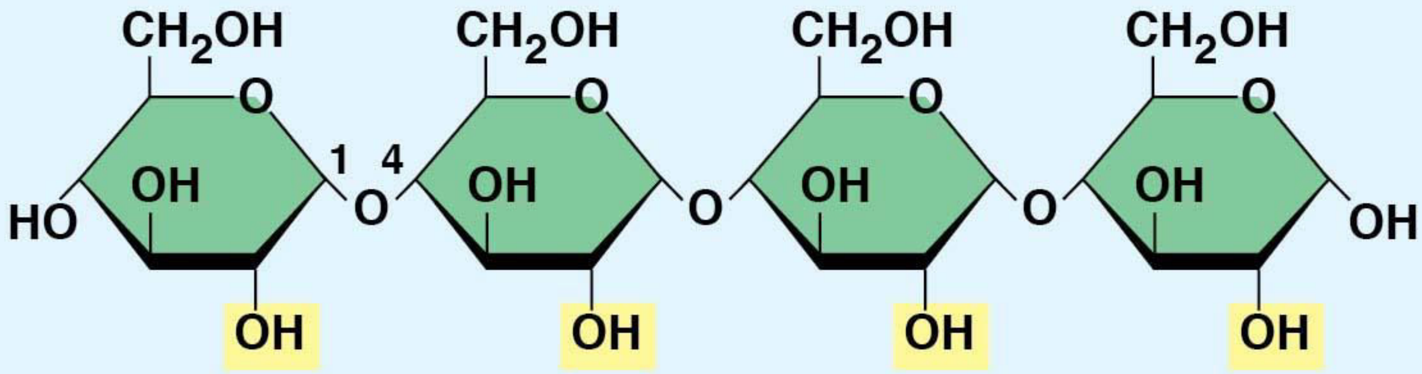
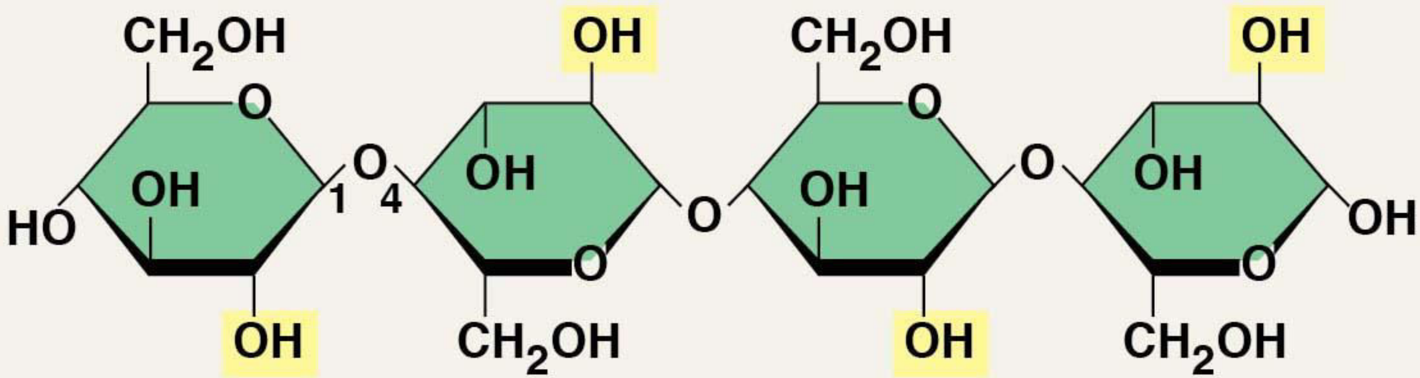

(a) α and β glucose ring structures
CH2OH
O
H
H
4
1
H
OH
H
HO
OH
H
OH
α Glucose
H
O
C
H—C—OH
HO—C—H
H—C—OH
H—C—OH
H—C—OH
H
CH2OH
O
OH
H
4
1
H
OH
H
HO
H
H
OH
β Glucose

Figure 3.12-2



(b) Starch: 1–4 linkage of α glucose monomers

Figure 3.12-3



(c) Cellulose: 1–4 linkage of β glucose monomers

- In starch, the glucose monomers are arranged in the alpha (α) conformation
- Starch (and glycogen) are largely helical
- In cellulose, the monomers are arranged in the beta (β) conformation
- Cellulose molecules are relatively straight

- In cellulose, some hydroxyl groups on its glucose monomers can hydrogen-bond with hydroxyl groups of other cellulose molecules
- Parallel cellulose molecules held together this way are grouped into microfibrils, which form strong building materials for plants

- Enzymes that digest starch by hydrolyzing α linkages can't hydrolyze β linkages in cellulose
- Cellulose in human food passes through the digestive tract as insoluble fiber
- Some microbes use enzymes to digest cellulose
- Many herbivores, from cows to termites, have symbiotic relationships with these microbes

- **Chitin**, another structural polysaccharide, is found in the exoskeleton of arthropods
- Chitin also provides structural support for the cell walls of many fungi

Concept 3.4: Lipids are a diverse group of hydrophobic molecules

- **Lipids** do not form true polymers
- The unifying feature of lipids is having little or no affinity for water
- Lipids are hydrophobic because they consist mostly of hydrocarbons, which form nonpolar covalent bonds
- The most biologically important lipids are fats, phospholipids, and steroids

Fats

- **Fats** are constructed from two types of smaller molecules: glycerol and fatty acids
- Glycerol is a three-carbon alcohol with a hydroxyl group attached to each carbon
- A **fatty acid** consists of a carboxyl group attached to a long carbon skeleton

Animation: Fats

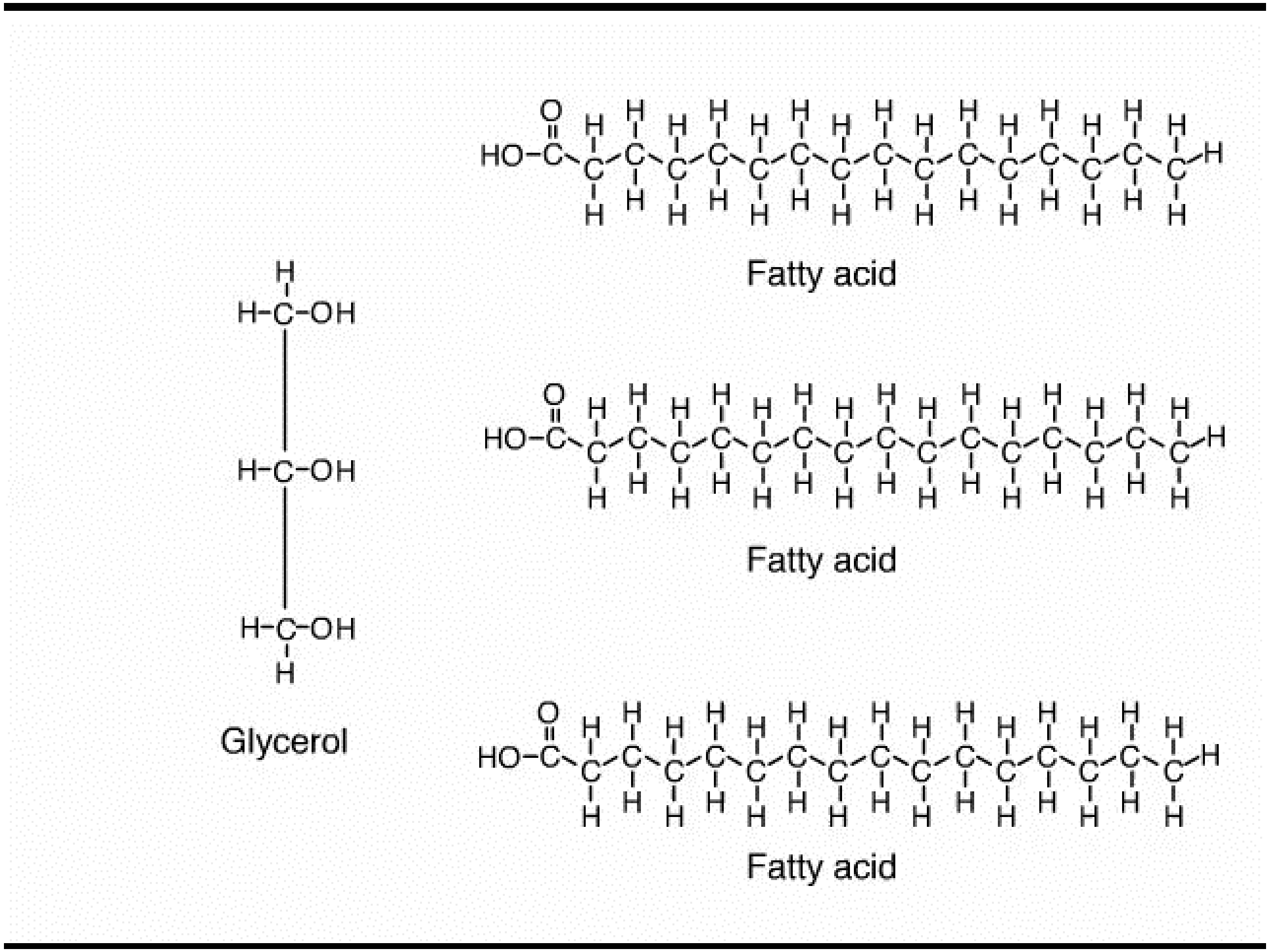
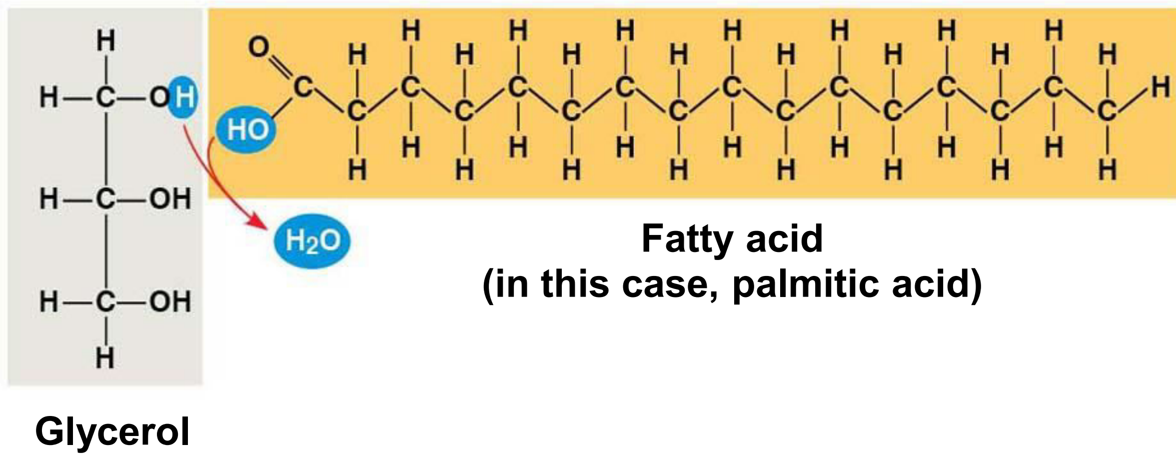
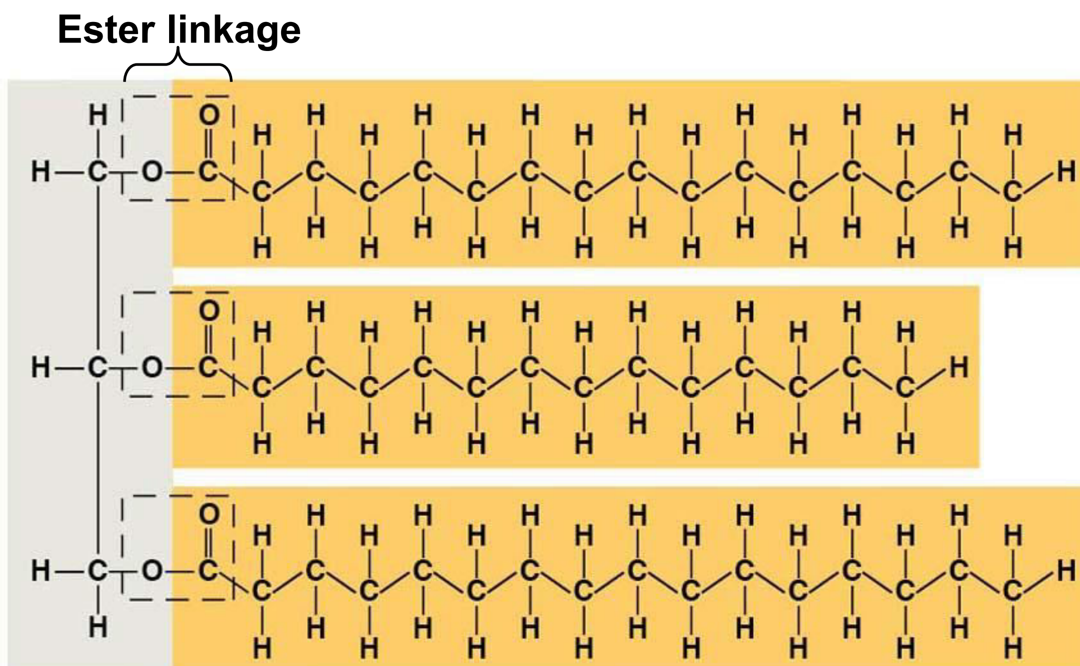


Figure 3.13

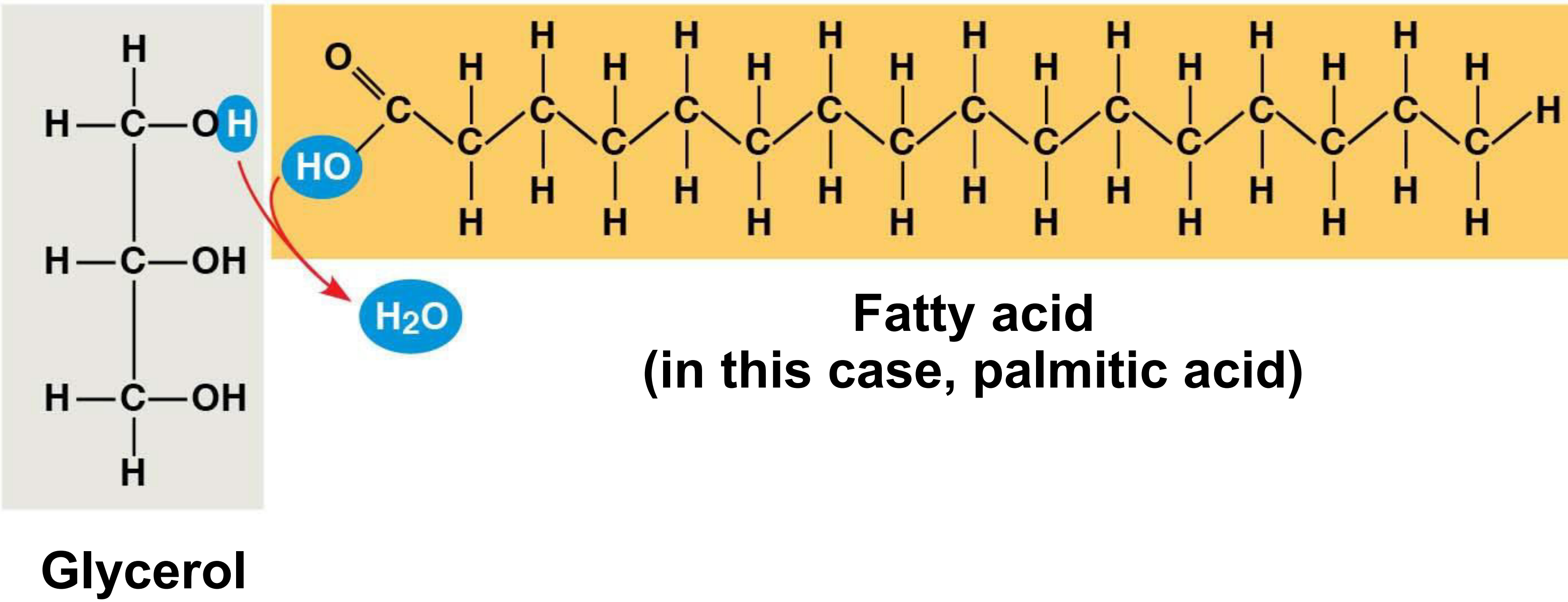


(a) One of three dehydration reactions in the synthesis of a fat



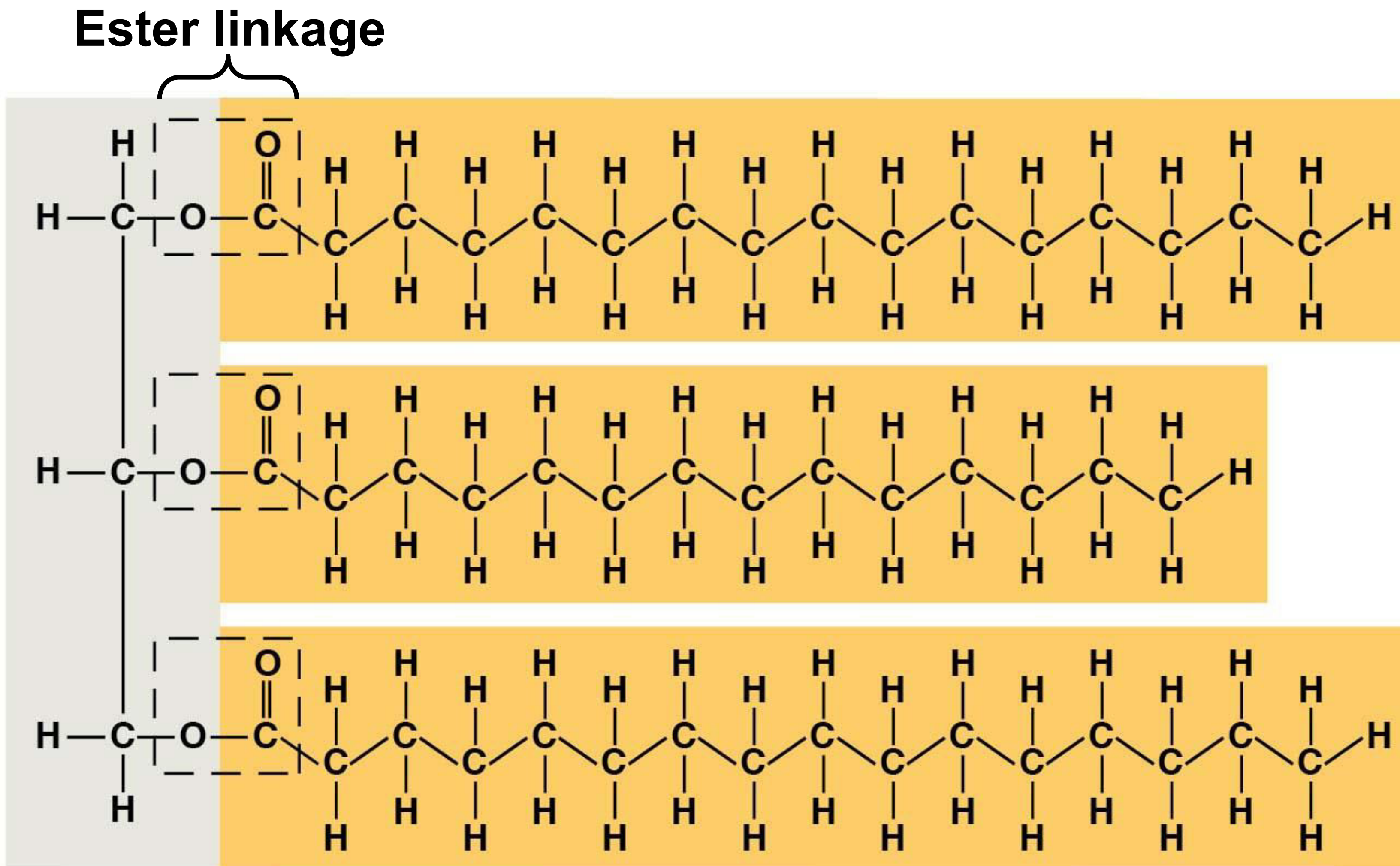
(b) Fat molecule (triacylglycerol)

Figure 3.13-1



(a) One of three dehydration reactions in the synthesis of a fat

Figure 3.13-2



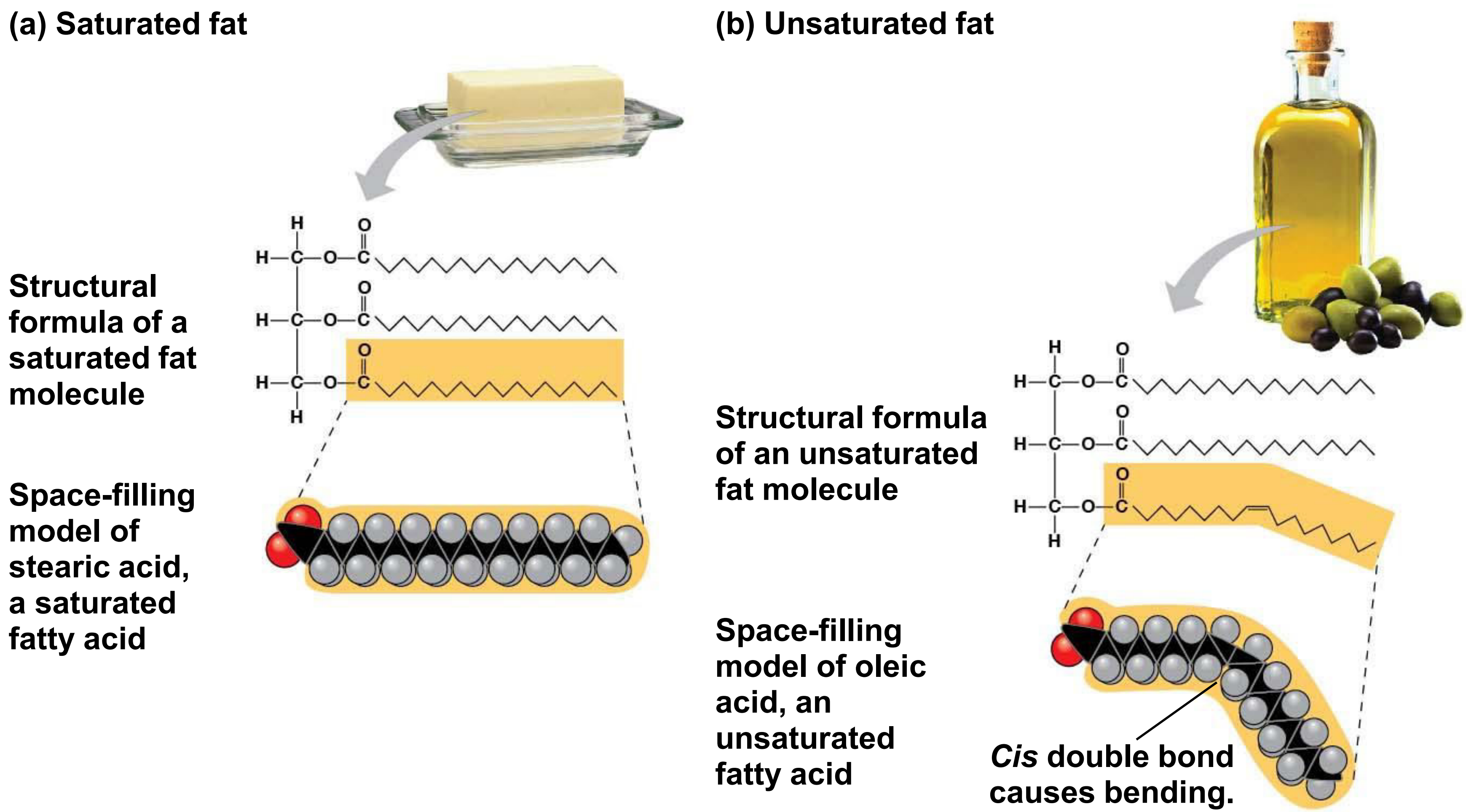
(b) Fat molecule (triacylglycerol)

- Fats separate from water because water molecules hydrogen-bond to each other and exclude the fats
- In a fat, three fatty acids are joined to glycerol by an ester linkage, creating a **triacylglycerol**, or triglyceride

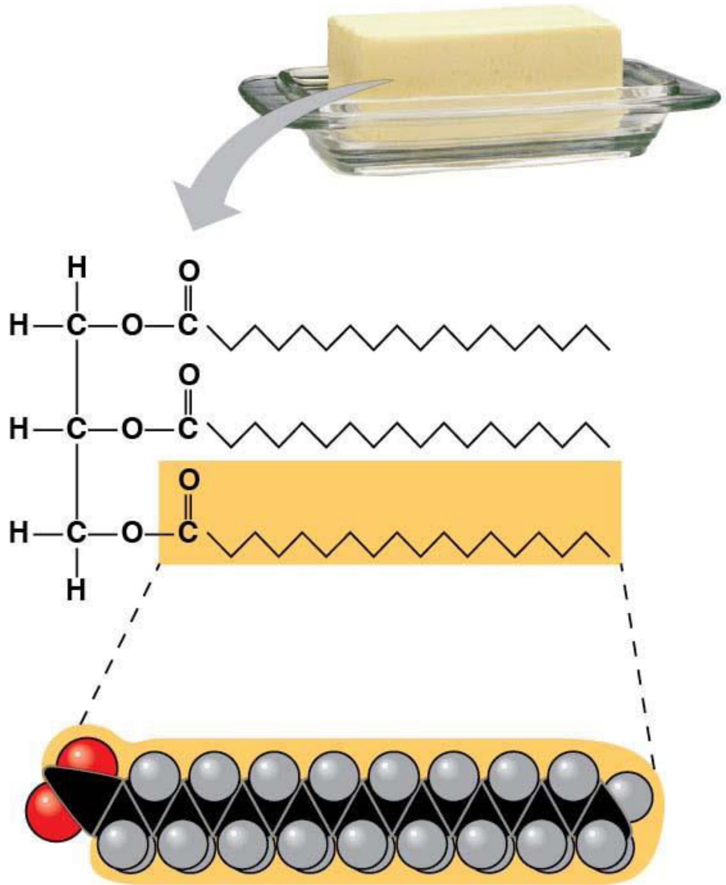
- Fatty acids vary in length (number of carbons) and in the number and locations of double bonds
- **Saturated fatty acids** have the maximum number of hydrogen atoms possible and no double bonds
- **Unsaturated fatty acids** have one or more double bonds

- Fats made from saturated fatty acids are called saturated fats and are solid at room temperature
- Most animal fats are saturated
- Plant fats and fish fats are usually unsaturated
- Fats made from unsaturated fatty acids, called unsaturated fats or oils, are liquid at room temperature

Figure 3.14


(a) Saturated fat
Structural formula of a saturated fat molecule
H
H—C—O—C
O
H—C—O—C
O
H—C—O—C
O
H
Space-filling model of stearic acid, a saturated fatty acid
(b) Unsaturated fat
Structural formula of an unsaturated fat molecule
Space-filling model of oleic acid, an unsaturated fatty acid
Cis double bond causes bending.

(a) Saturated fat



Structural formula of a saturated fat molecule

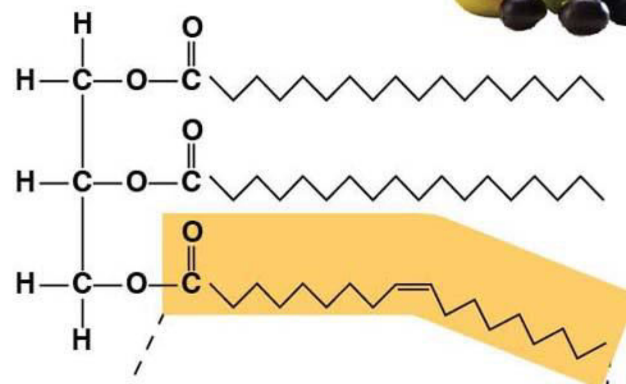
Space-filling model of stearic acid, a saturated fatty acid

Figure 3.14-1a

Figure 3.14-2

(b) Unsaturated fat

Structural formula of an unsaturated fat molecule



Space-filling model of oleic acid, an unsaturated fatty acid

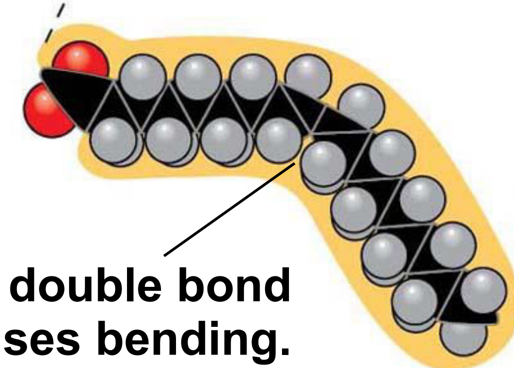
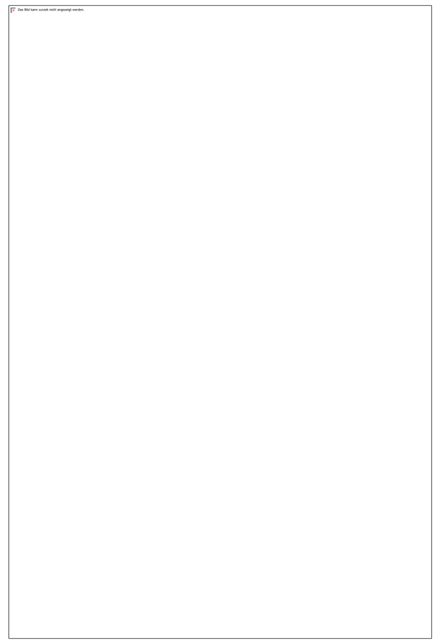


Figure 3.14-2a

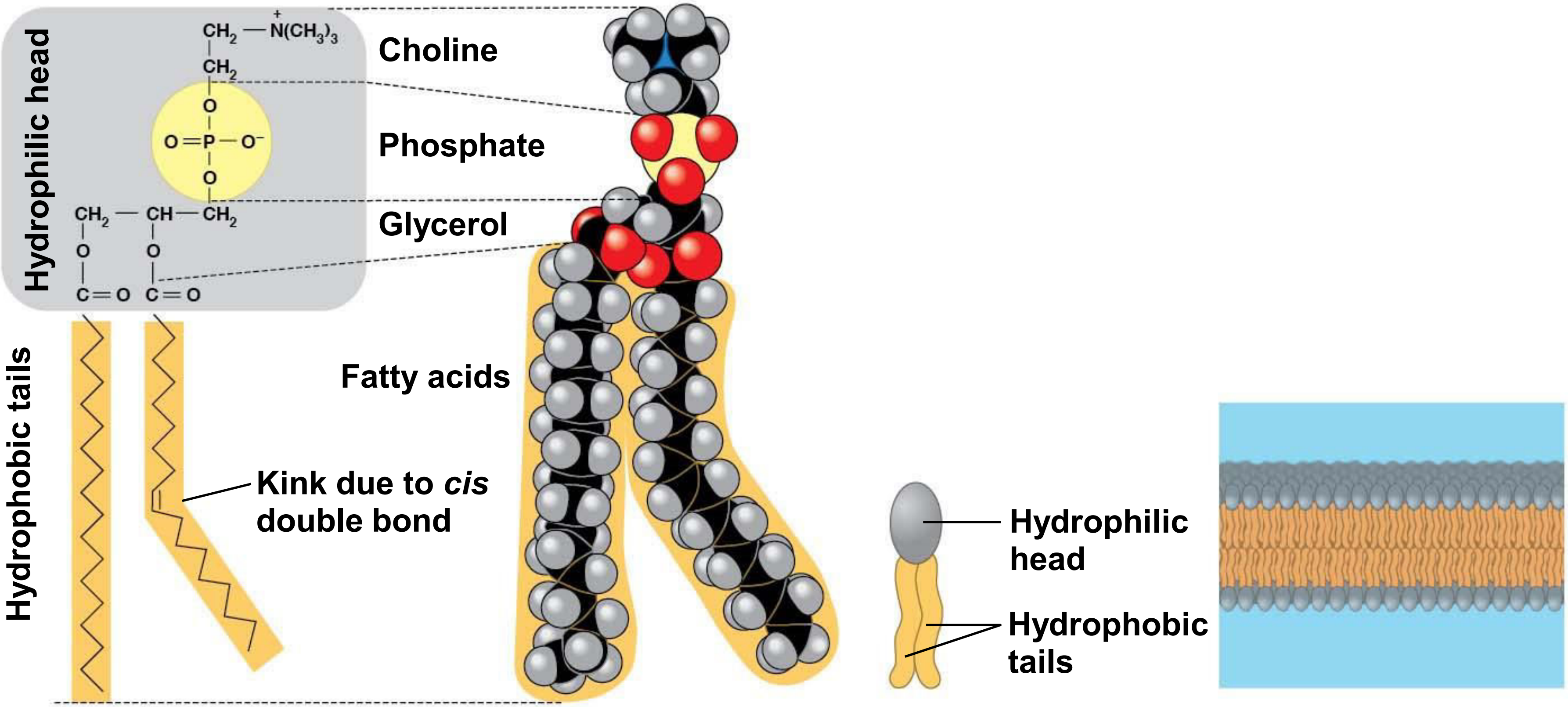


- The major function of fats is energy storage
- Fat is a compact way for animals to carry their energy stores with them

Phospholipids

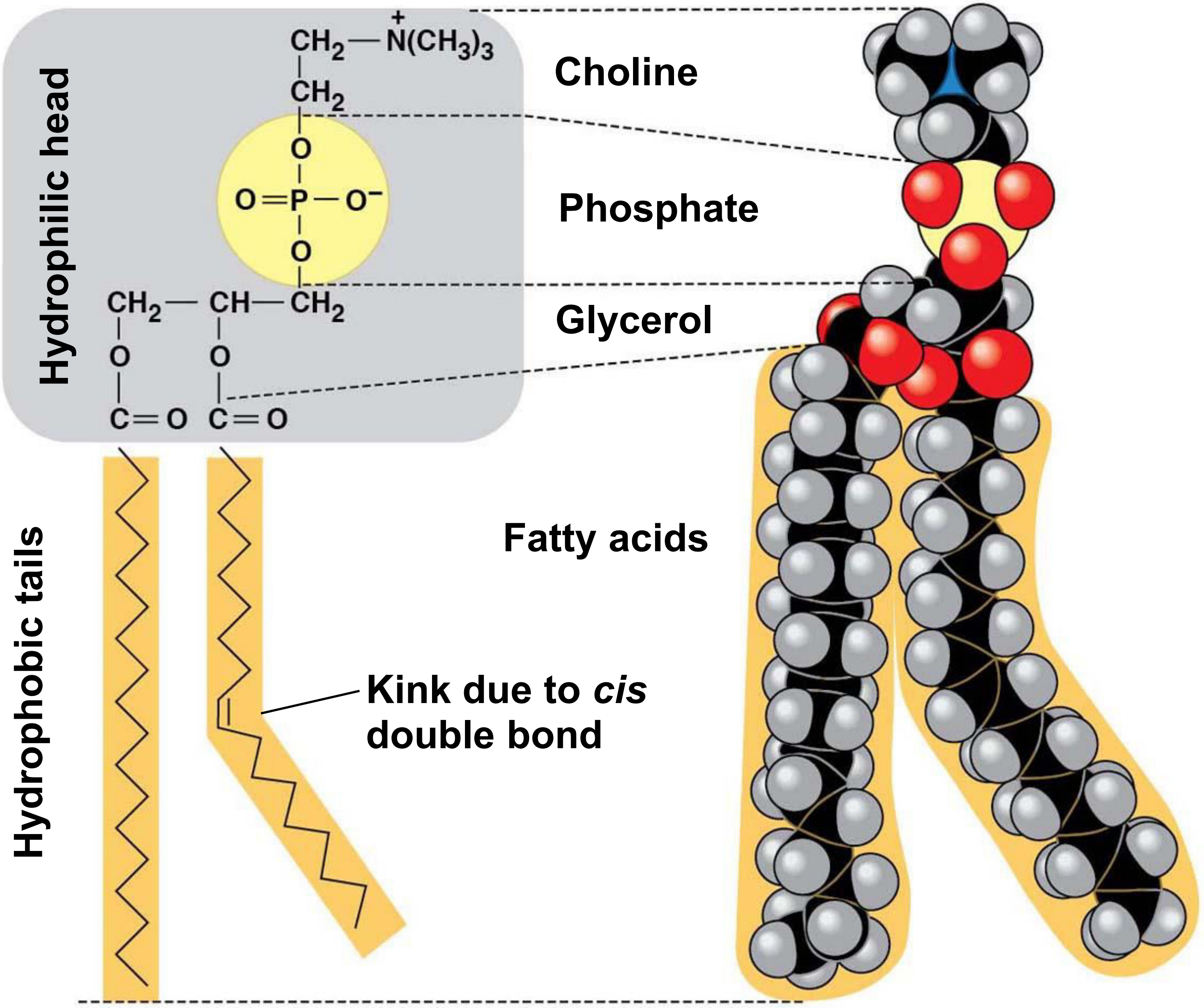
- In a **phospholipid**, two fatty acids and a phosphate group are attached to glycerol
- The two fatty acid tails are hydrophobic, but the phosphate group and its attachments form a hydrophilic head
- Phospholipids are major constituents of cell membranes

Figure 3.15



(a) Structural formula **(b) Space-filling model** **(c) Phospholipid symbol** **(d) Phospholipid bilayer**

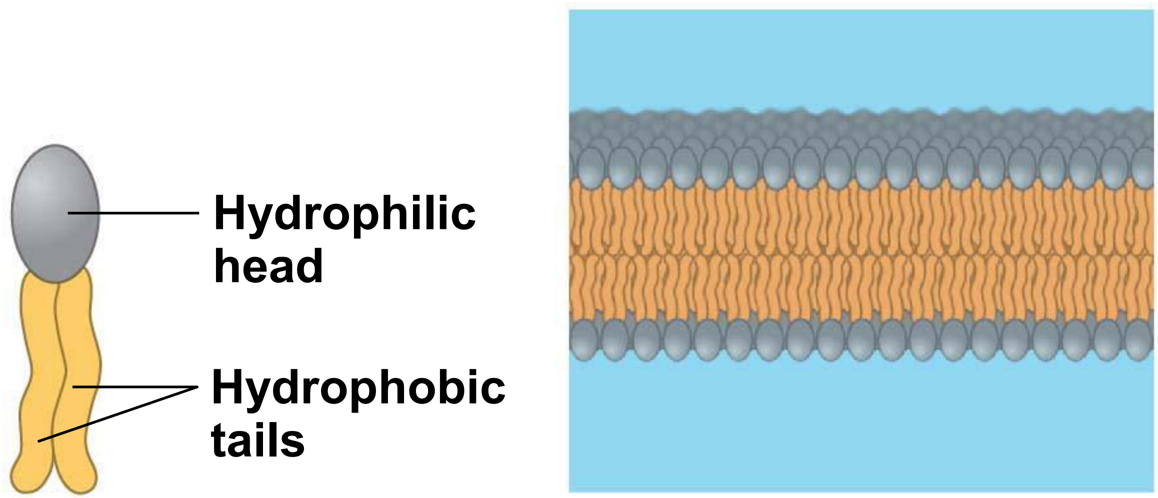
Figure 3.15-1



(a) Structural formula

(b) Space-filling model

Figure 3.15-2



(c) Phospholipid symbol

(d) Phospholipid bilayer

- When phospholipids are added to water, they self-assemble into a bilayer, with the hydrophobic tails pointing toward the interior
- This feature of phospholipids results in the bilayer arrangement found in cell membranes
- The phospholipid bilayer forms a boundary between a cell and its external environment

Steroids

- **Steroids** are lipids characterized by a carbon skeleton consisting of four fused rings
- **Cholesterol**, an important steroid, is a component in animal cell membranes
- Although cholesterol is essential in animals, high levels in the blood may contribute to atherosclerosis

Figure 3.16

Das Bild kann zurzeit nicht angezeigt werden.

Concept 3.5: Proteins include a diversity of structures, resulting in a wide range of functions

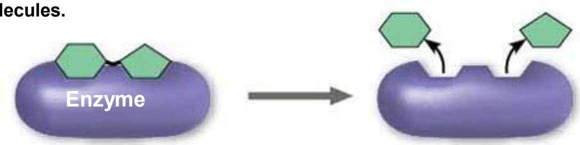
- Proteins account for more than 50% of the dry mass of most cells
- Protein functions include defense, storage, transport, cellular communication, movement, and structural support

Figure 3.17

Enzymatic proteins

Function: Selective acceleration of chemical reactions

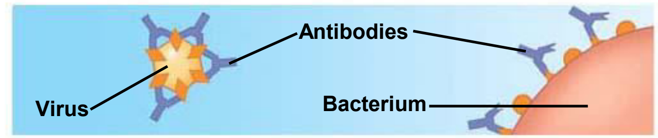
Example: Digestive enzymes catalyze the hydrolysis of bonds in food molecules.



Defensive proteins

Function: Protection against disease

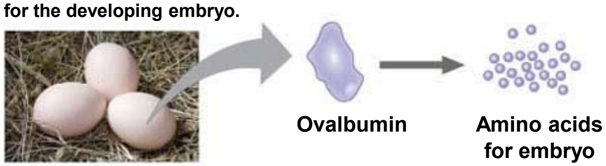
Example: Antibodies inactivate and help destroy viruses and bacteria.



Storage proteins

Function: Storage of amino acids

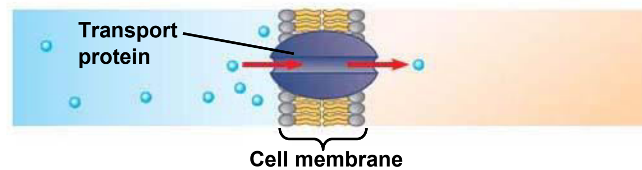
Examples: Casein, the protein of milk, is the major source of amino acids for baby mammals. Plants have storage proteins in their seeds. Ovalbumin is the protein of egg white, used as an amino acid source for the developing embryo.



Transport proteins

Function: Transport of substances

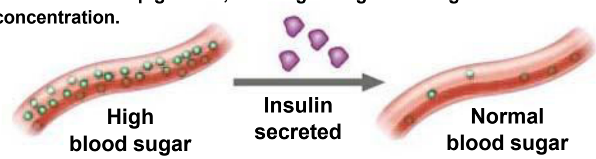
Examples: Hemoglobin, the iron-containing protein of vertebrate blood, transports oxygen from the lungs to other parts of the body. Other proteins transport molecules across membranes, as shown here.



Hormonal proteins

Function: Coordination of an organism's activities

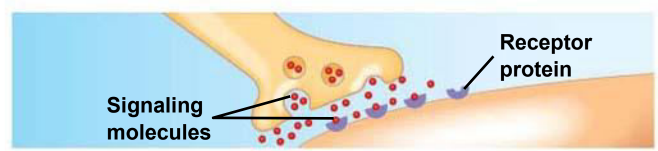
Example: Insulin, a hormone secreted by the pancreas, causes other tissues to take up glucose, thus regulating blood sugar concentration.



Receptor proteins

Function: Response of cell to chemical stimuli

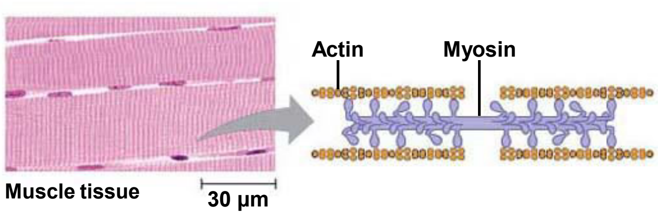
Example: Receptors built into the membrane of a nerve cell detect signaling molecules released by other nerve cells.



Contractile and motor proteins

Function: Movement

Examples: Motor proteins are responsible for the undulations of cilia and flagella. Actin and myosin proteins are responsible for the contraction of muscles.



Structural proteins

Function: Support

Examples: Keratin is the protein of hair, horns, feathers, and other skin appendages. Insects and spiders use silk fibers to make their cocoons and webs, respectively. Collagen and elastin proteins provide a fibrous framework in animal connective tissues.

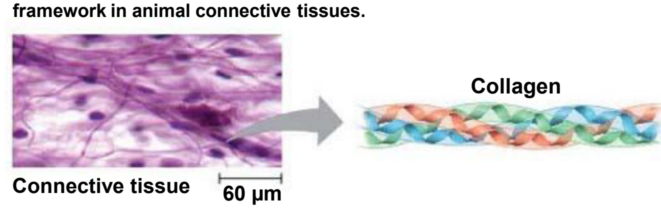


Figure 3.17-1

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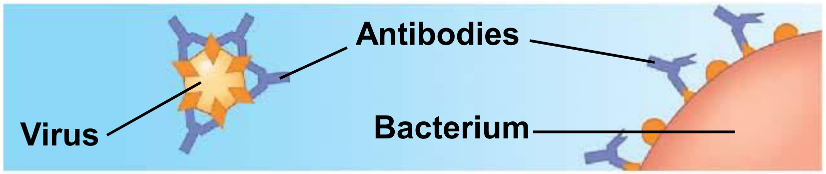

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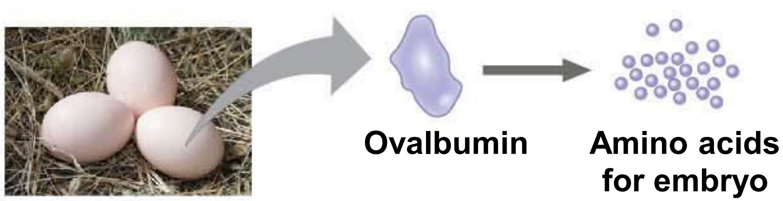

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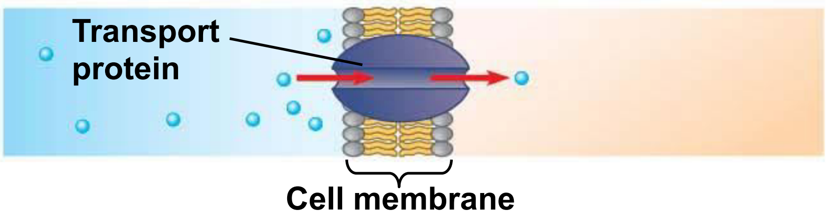

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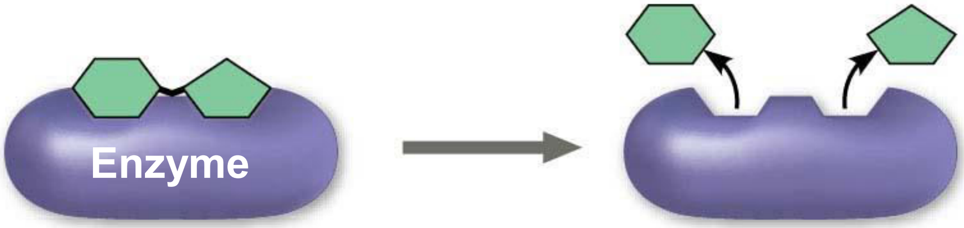

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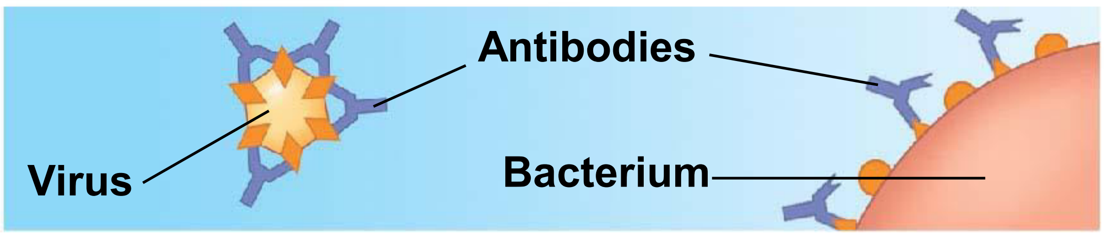

Figure 3.17-1c

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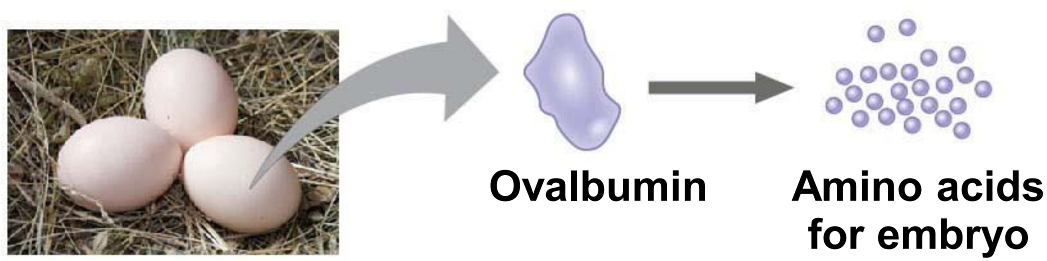

Figure 3.17-1ca

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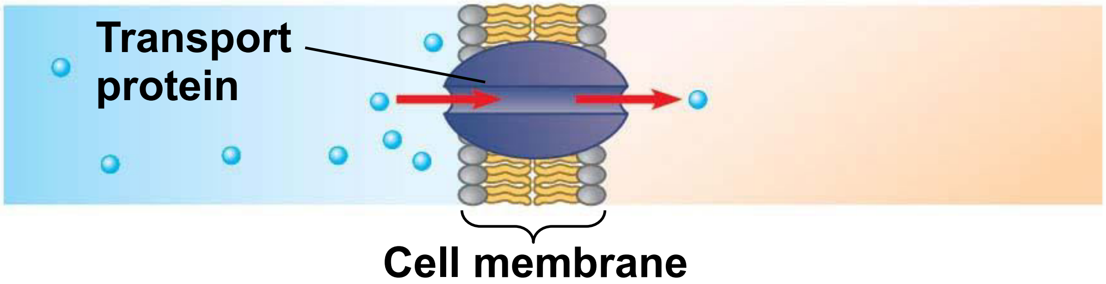
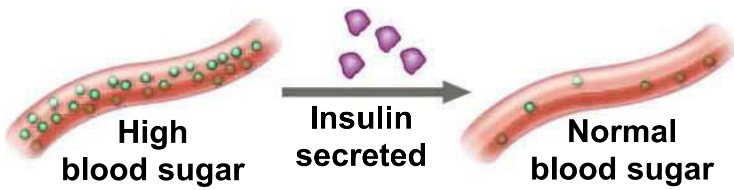


Figure 3.17-2

Hormonal proteins

Function: Coordination of an organism's activities

Example: Insulin, a hormone secreted by the pancreas, causes other tissues to take up glucose, thus regulating blood sugar concentration.



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Function: Response of cell to chemical stimuli

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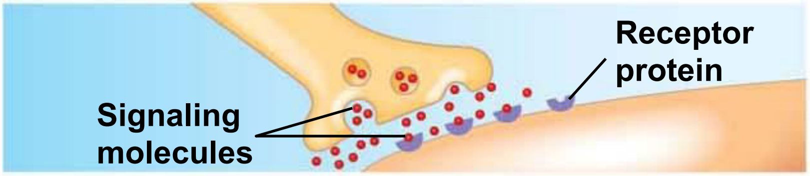

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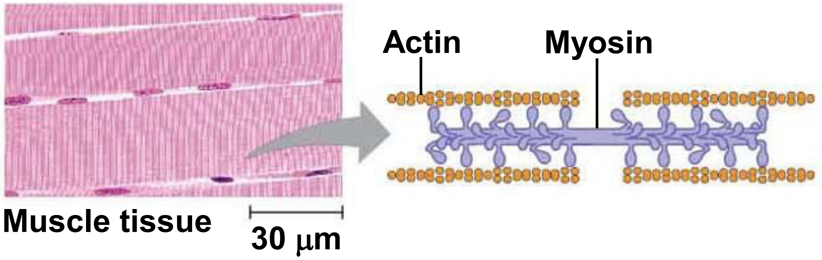

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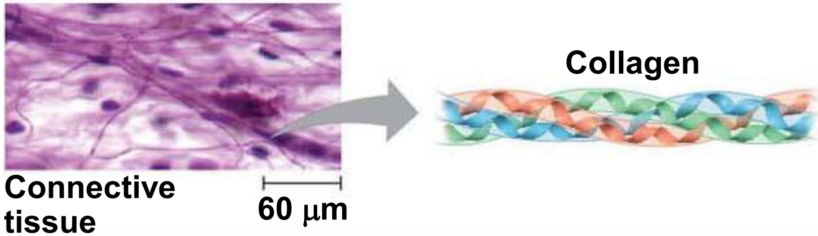

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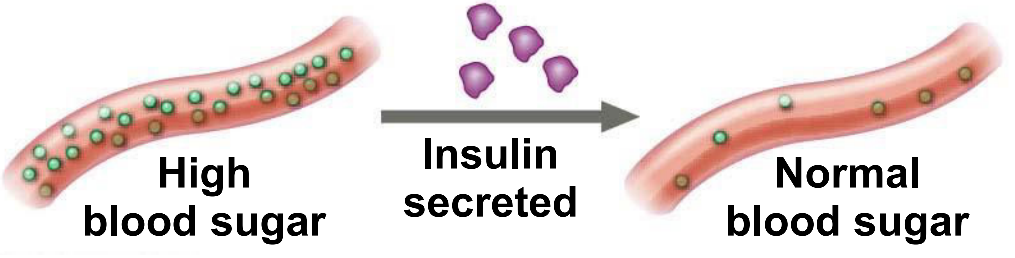

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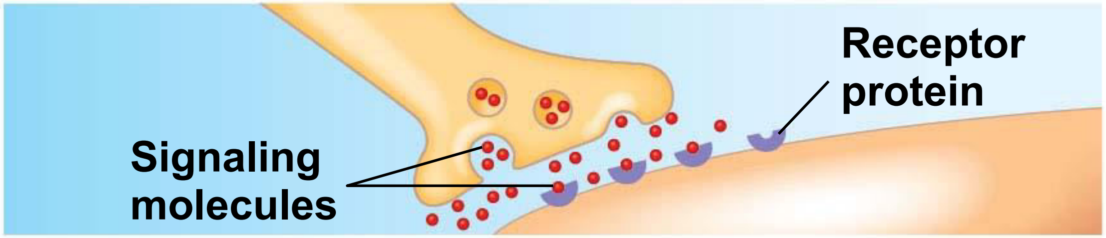

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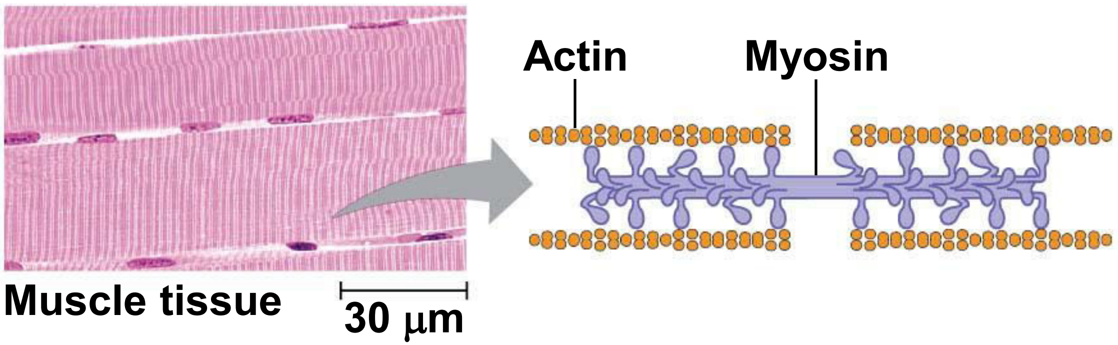
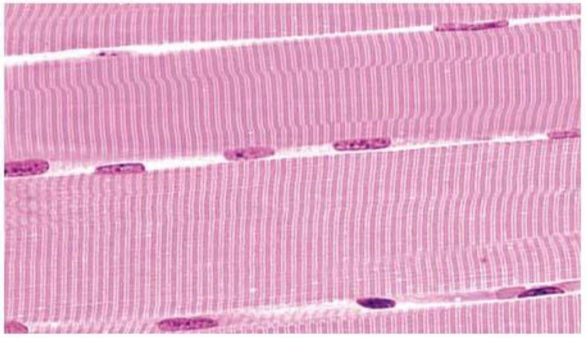


Figure 3.17-2ca



Muscle tissue

30 μm

Structural proteins

Function: Support

Examples: Keratin is the protein of hair, horns, feathers, and other skin appendages. Insects and spiders use silk fibers to make their cocoons and webs, respectively. Collagen and elastin proteins provide a fibrous framework in animal connective tissues.

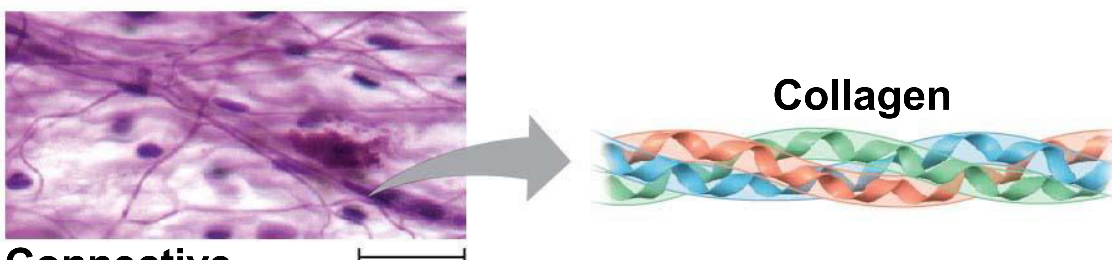
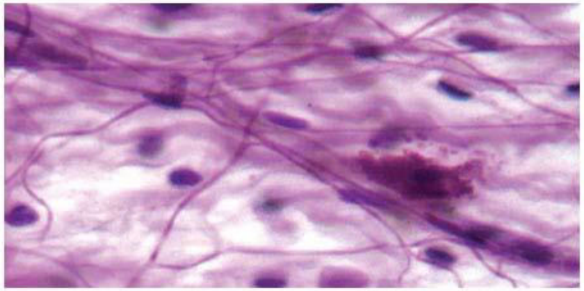


Figure 3.17-2da



Connective tissue

60 μm

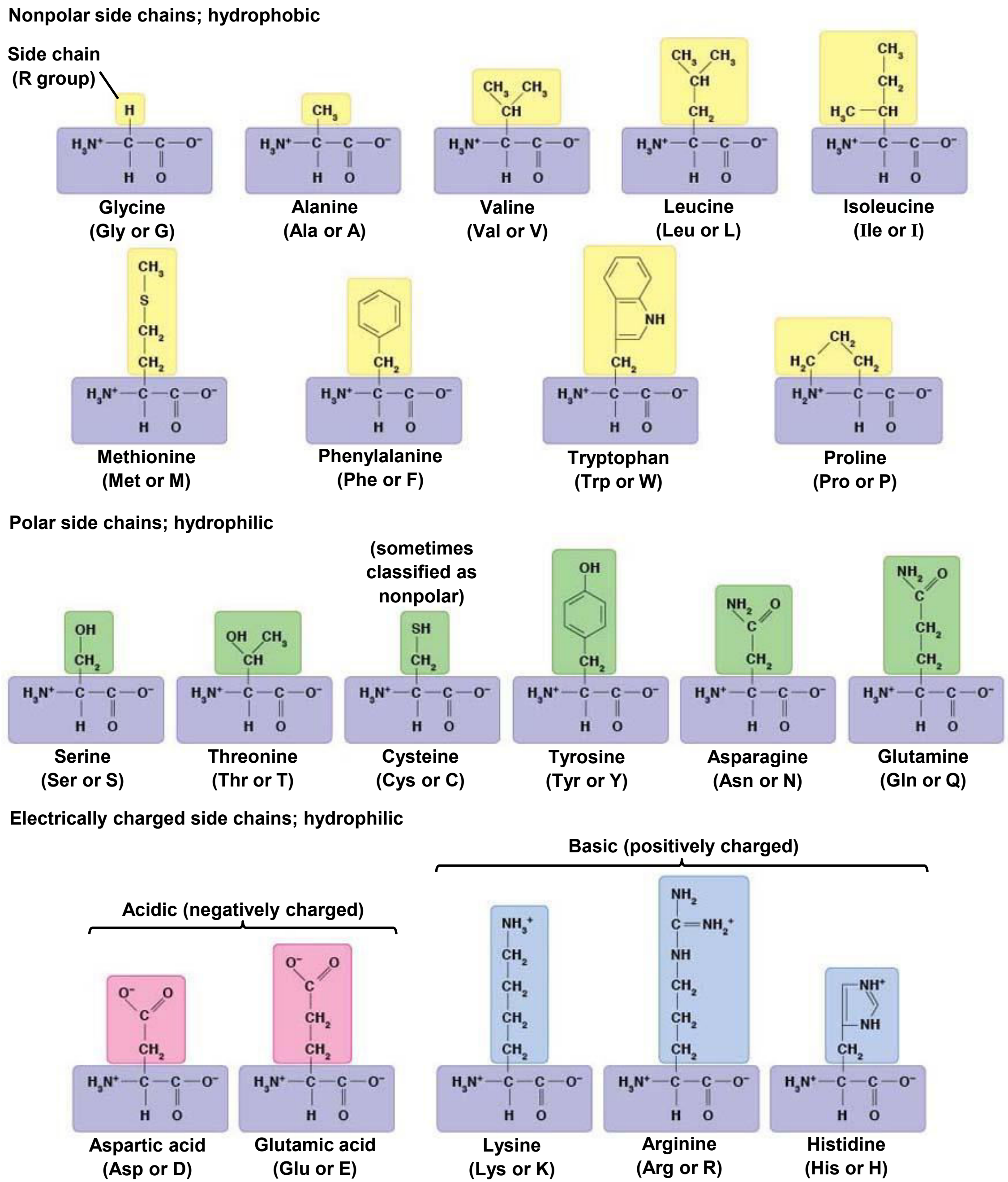
- Life would not be possible without enzymes
- Enzymatic proteins act as **catalysts**, to speed up chemical reactions without being consumed in the reaction

- **Polypeptides** are unbranched polymers built from the same set of 20 amino acids
- A **protein** is a biologically functional molecule that consists of one or more polypeptides

Amino Acid Monomers

- **Amino acids** are organic molecules with carboxyl and amino groups
- Amino acids differ in their properties due to differing side chains, called R groups

Figure 3.18



Nonpolar side chains; hydrophobic
Side chain (R group)
Glycine (Gly or G)
Alanine (Ala or A)
Valine (Val or V)
Leucine (Leu or L)
Isoleucine (Ile or I)
Methionine (Met or M)
Phenylalanine (Phe or F)
Tryptophan (Trp or W)
Proline (Pro or P)
Polar side chains; hydrophilic
(sometimes classified as nonpolar)
Serine (Ser or S)
Threonine (Thr or T)
Cysteine (Cys or C)
Tyrosine (Tyr or Y)
Asparagine (Asn or N)
Glutamine (Gln or Q)
Electrically charged side chains; hydrophilic
Acidic (negatively charged)
Basic (positively charged)
Aspartic acid (Asp or D)
Glutamic acid (Glu or E)
Lysine (Lys or K)
Arginine (Arg or R)
Histidine (His or H)

Figure 3.18-1

Nonpolar side chains; hydrophobic

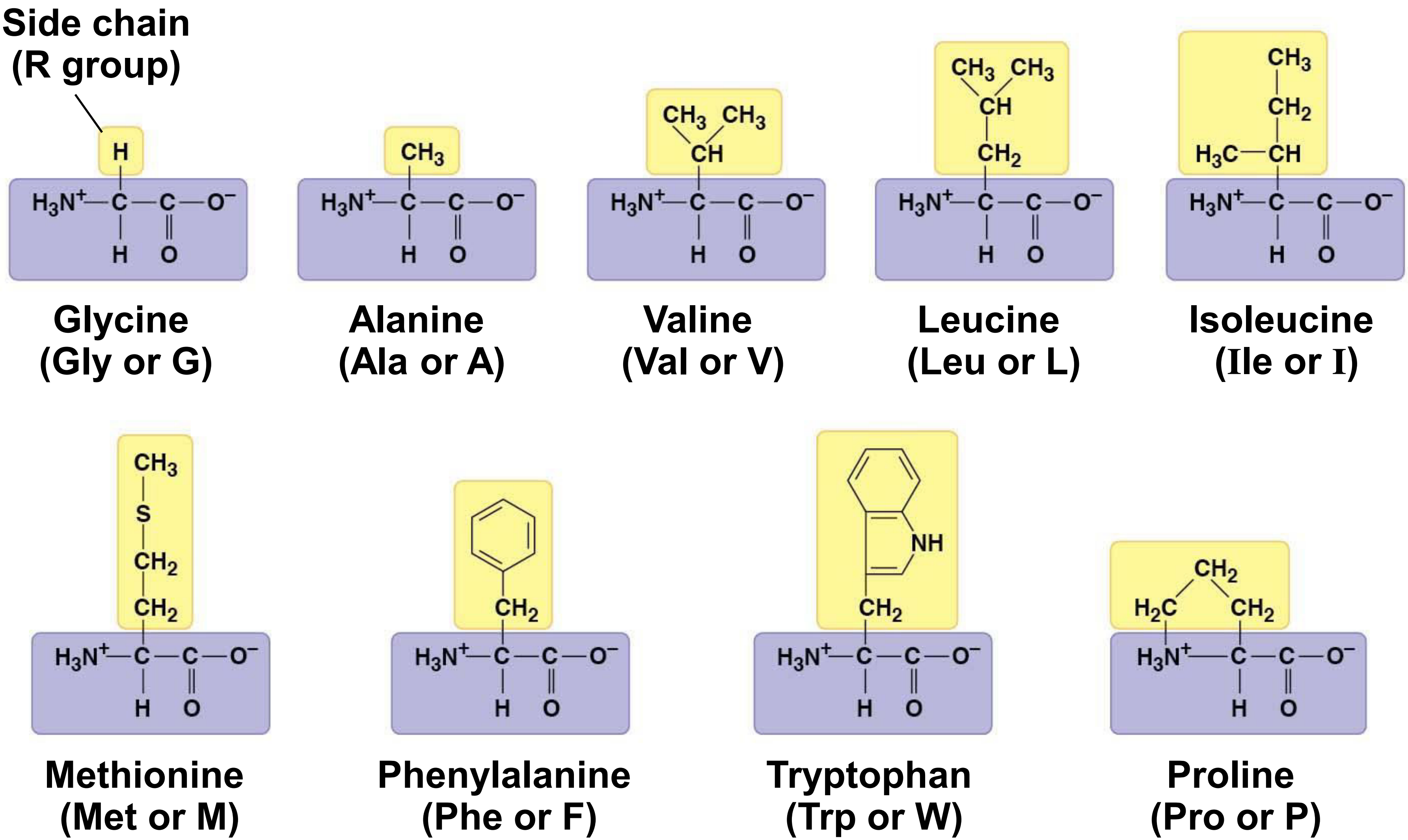
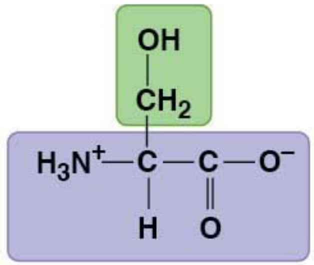
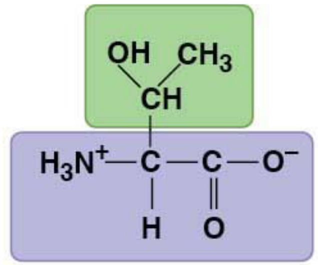


Figure 3.18-2

Polar side chains; hydrophilic

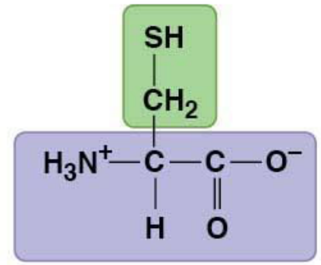


Serine
(Ser or S)

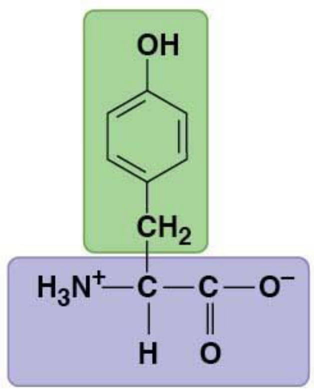


Threonine
(Thr or T)

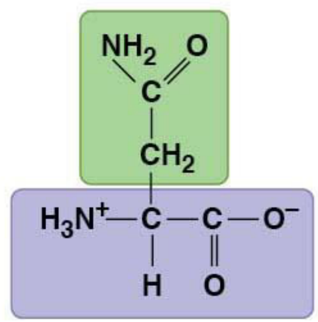
(sometimes classified as nonpolar)



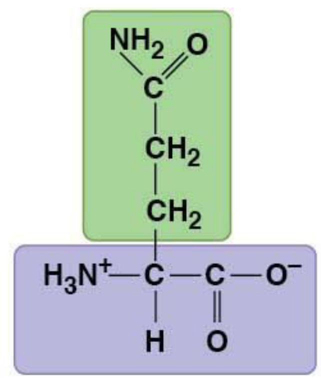
Cysteine
(Cys or C)



Tyrosine
(Tyr or Y)

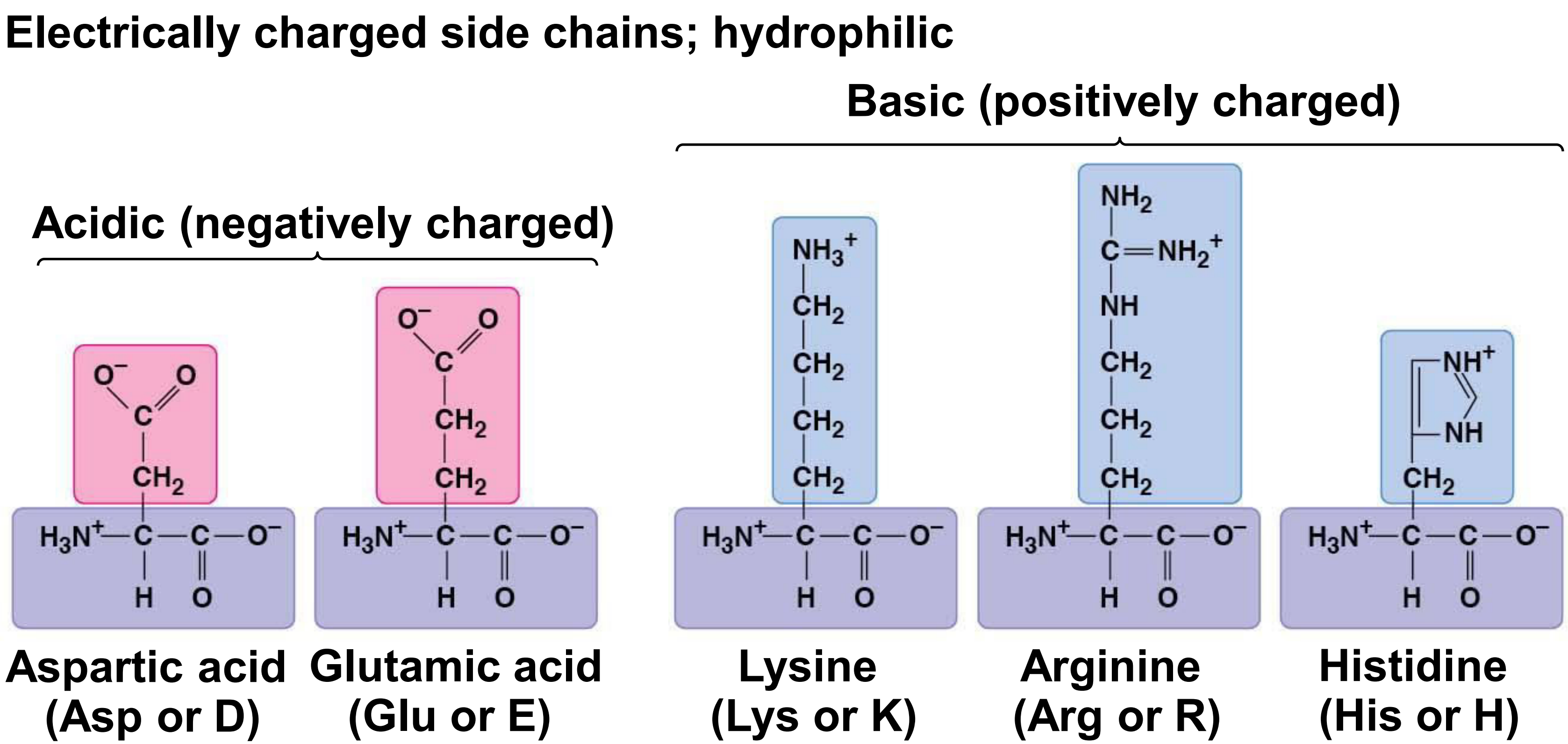


Asparagine
(Asn or N)



Glutamine
(Gln or Q)

Figure 3.18-3

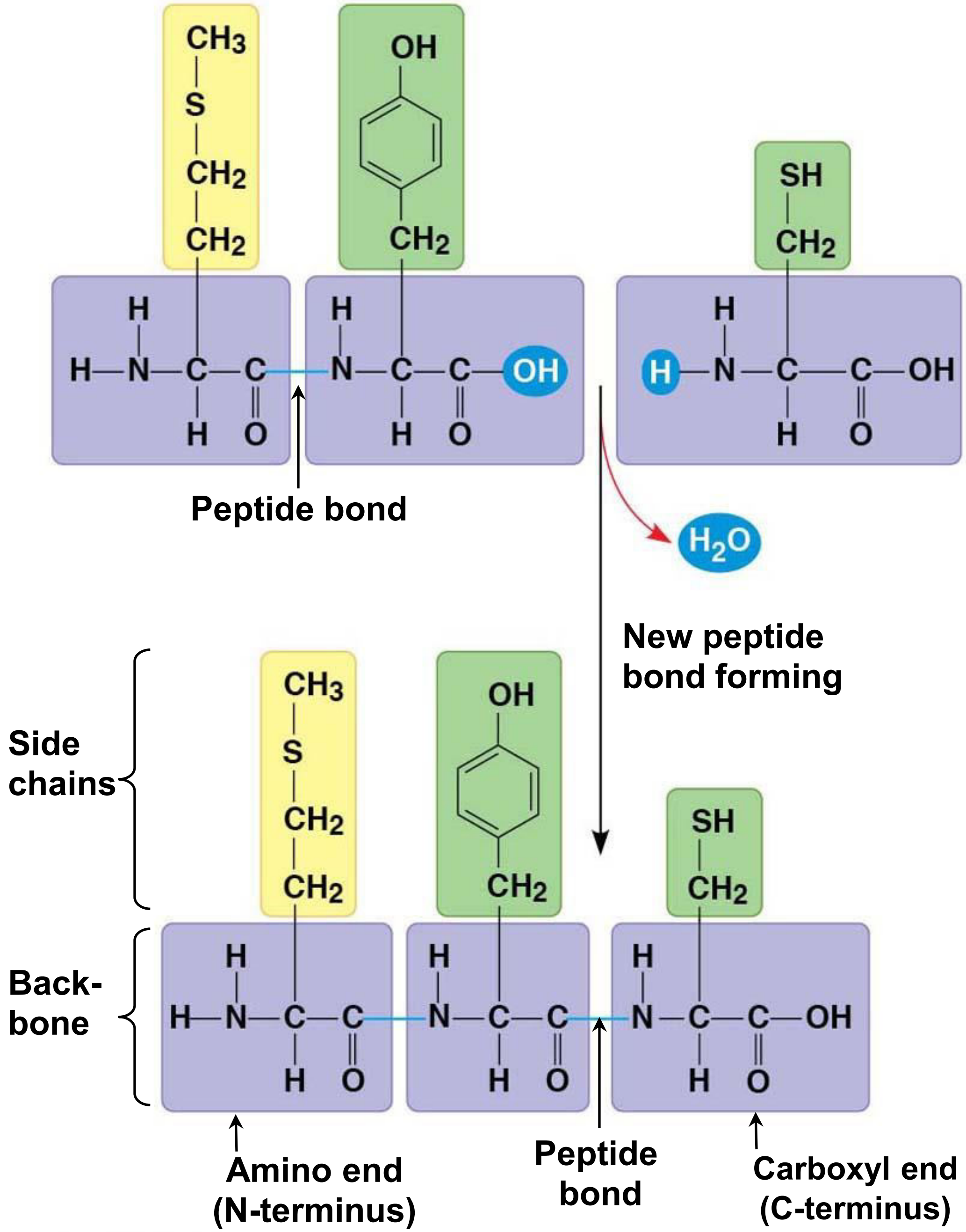


Electrically charged side chains; hydrophilic
Basic (positively charged)
Acidic (negatively charged)
O⁻ O C CH2 H3N+ C C O⁻ H O
Aspartic acid (Asp or D)
O⁻ O C CH2 CH2 H3N+ C C O⁻ H O
Glutamic acid (Glu or E)
NH3+ CH2 CH2 CH2 CH2 H3N+ C C O⁻ H O
Lysine (Lys or K)
NH2 C NH2+ NH CH2 CH2 CH2 H3N+ C C O⁻ H O
Arginine (Arg or R)
NH+ NH CH2 H3N+ C C O⁻ H O
Histidine (His or H)

Polypeptides (Amino Acid Polymers)

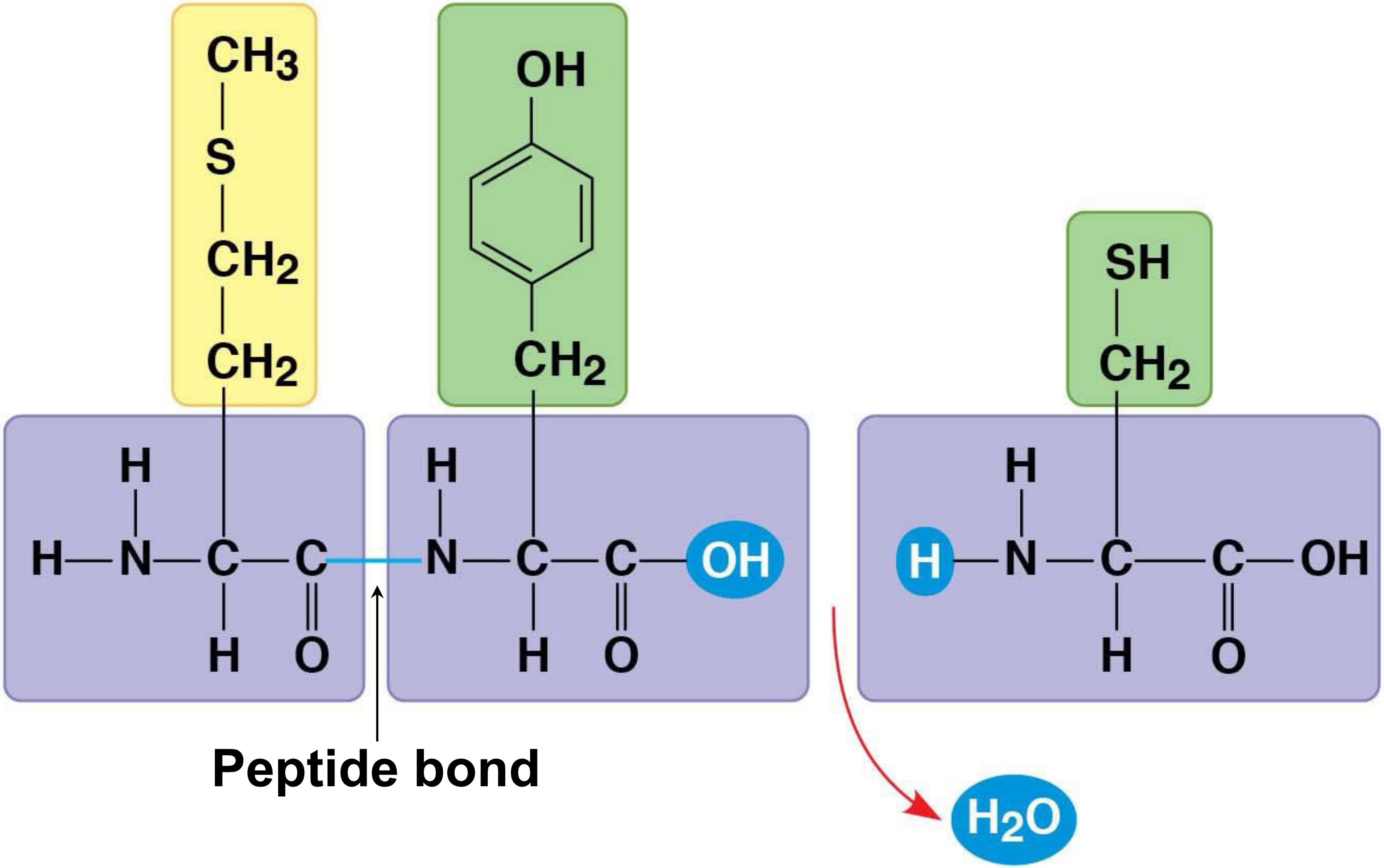
- Amino acids are linked by **peptide bonds**
- A polypeptide is a polymer of amino acids
- Polypeptides range in length from a few to more than a thousand monomers
- Each polypeptide has a unique linear sequence of amino acids, with a carboxyl end (C-terminus) and an amino end (N-terminus)

Figure 3.19



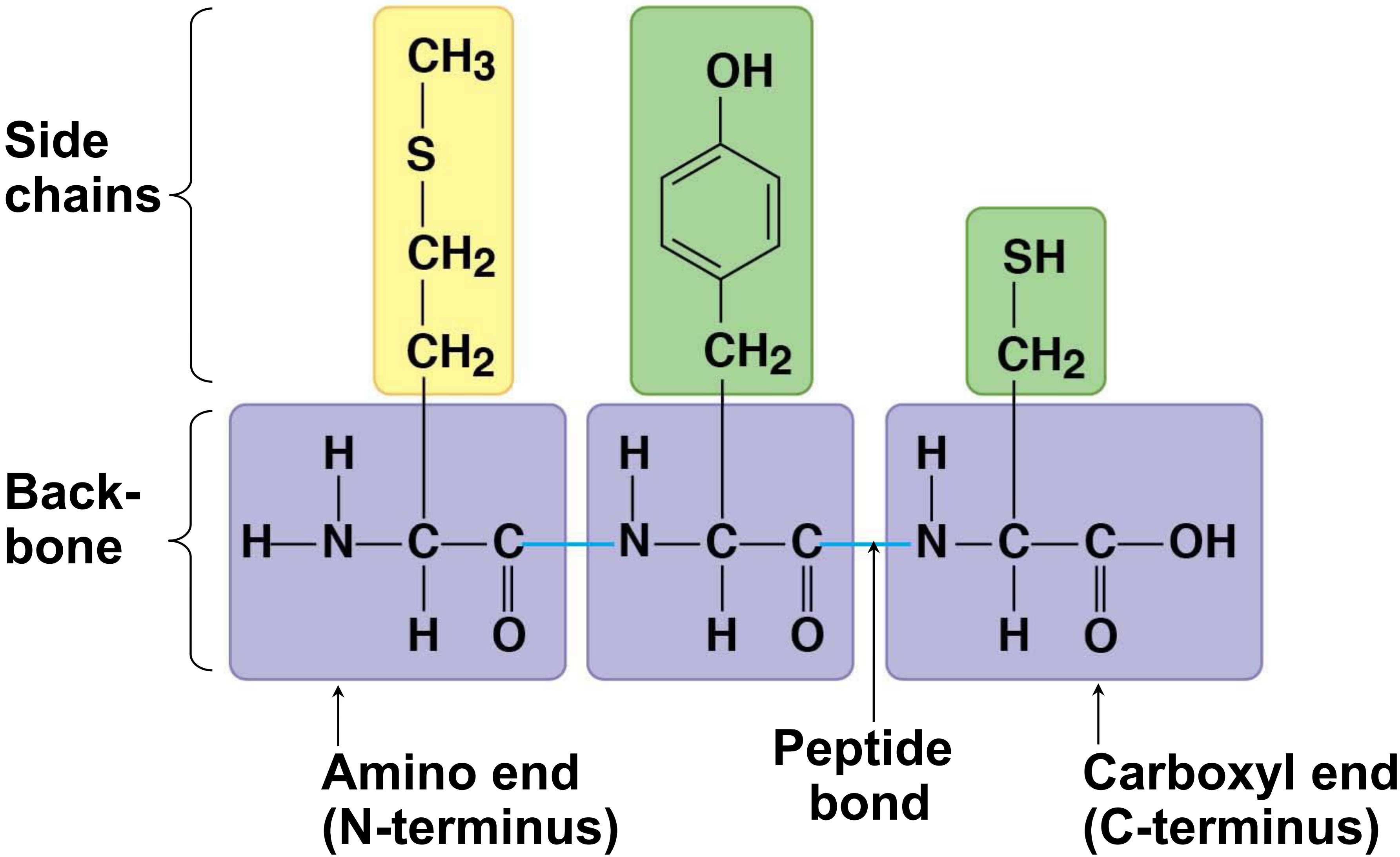
CH3
S
CH2
CH2
OH
CH2
SH
CH2
H
H—N—C—C
H O
H
N—C—C—OH
H O
H
H—N—C—C—OH
H O
Peptide bond
H2O
New peptide
bond forming
Side
chains
Back-
bone
Amino end
(N-terminus)
Peptide
bond
Carboxyl end
(C-terminus)

Figure 3.19-1



CH3
S
CH2
CH2
OH
CH2
SH
CH2
H
H—N—C—C
H O
H
N—C—C—OH
H O
H
H—N—C—C—OH
H O
Peptide bond
H2O

Figure 3.19-2

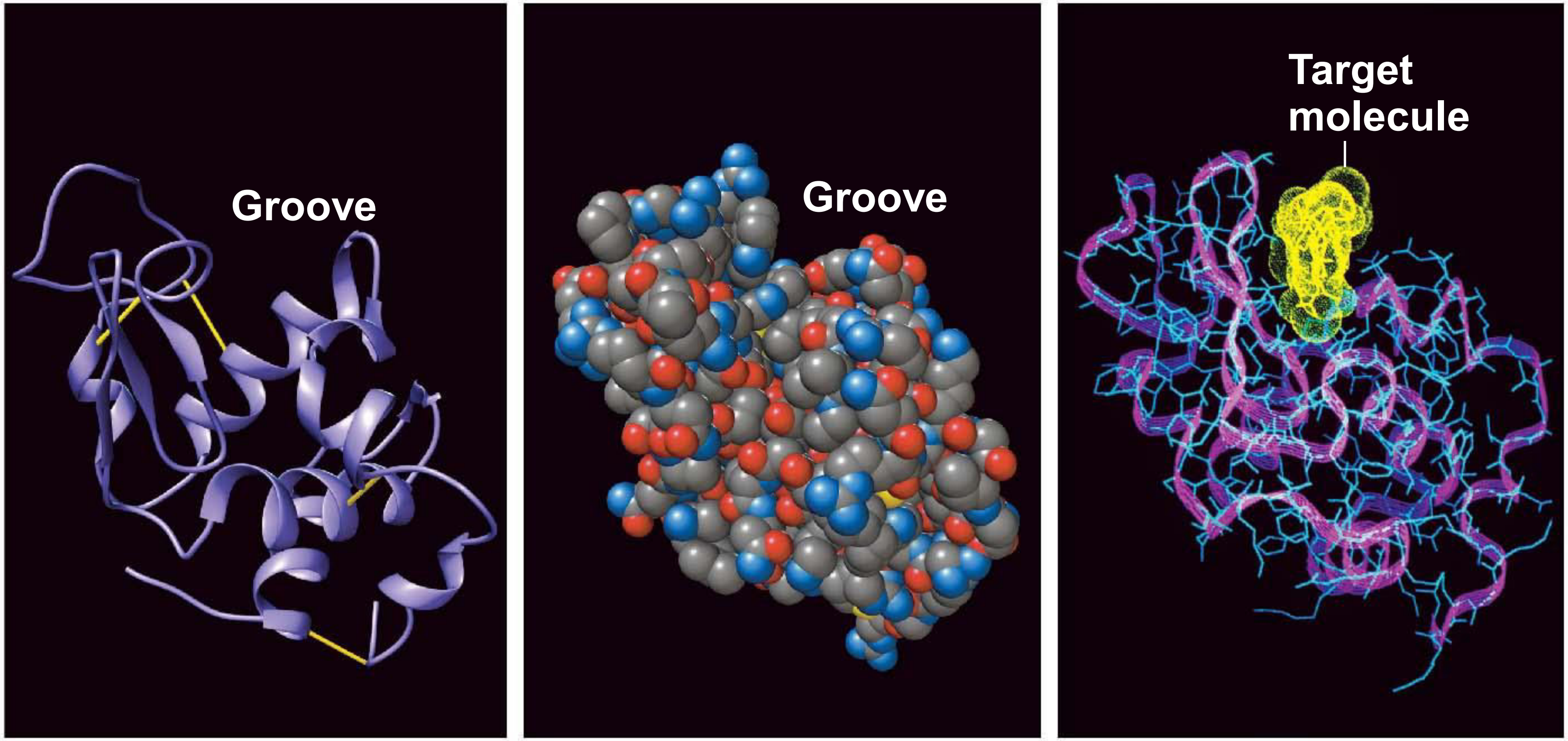


Side chains
Back-bone
CH3
S
CH2
CH2
OH
CH2
SH
CH2
H
H—N—C—C
H O
H
N—C—C
H O
H
N—C—C—OH
H O
Amino end (N-terminus)
Peptide bond
Carboxyl end (C-terminus)

Protein Structure and Function

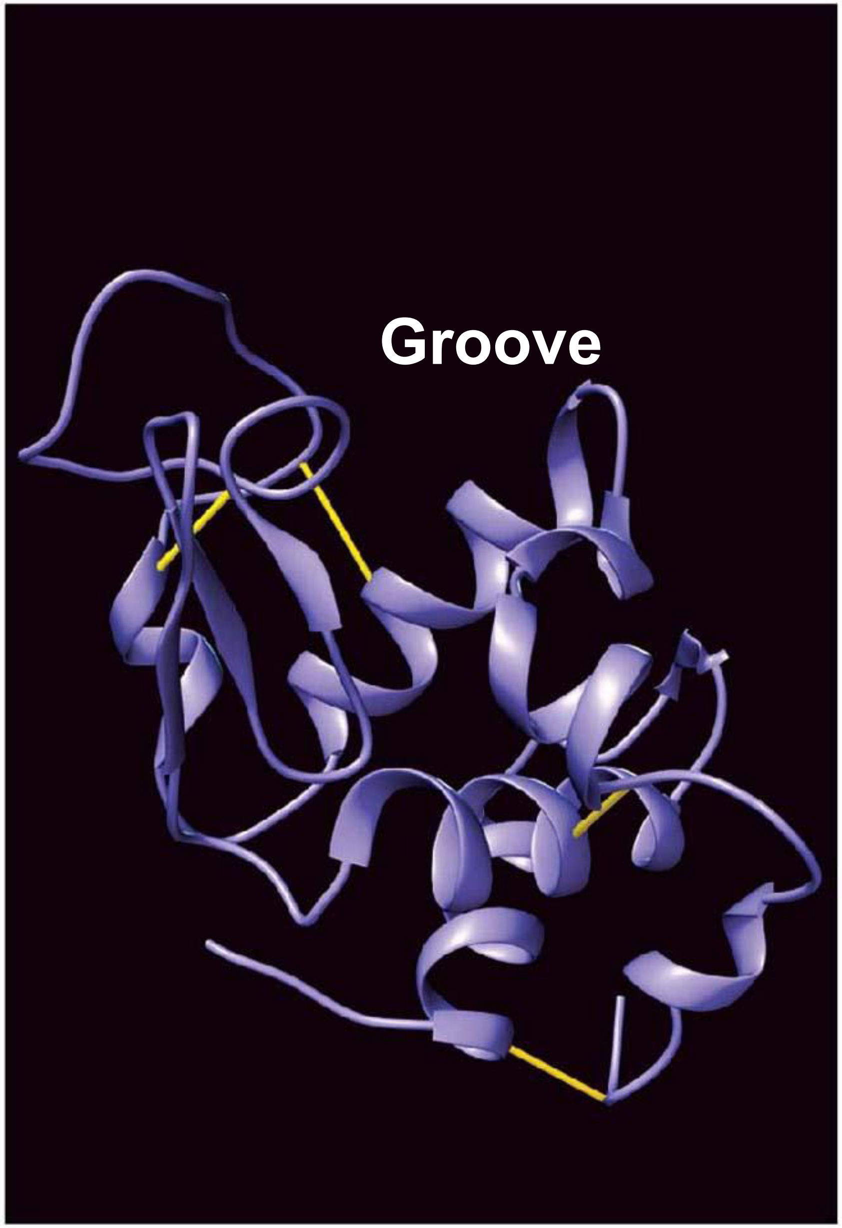
- A functional protein consists of one or more polypeptides precisely twisted, folded, and coiled into a unique shape

Figure 3.20



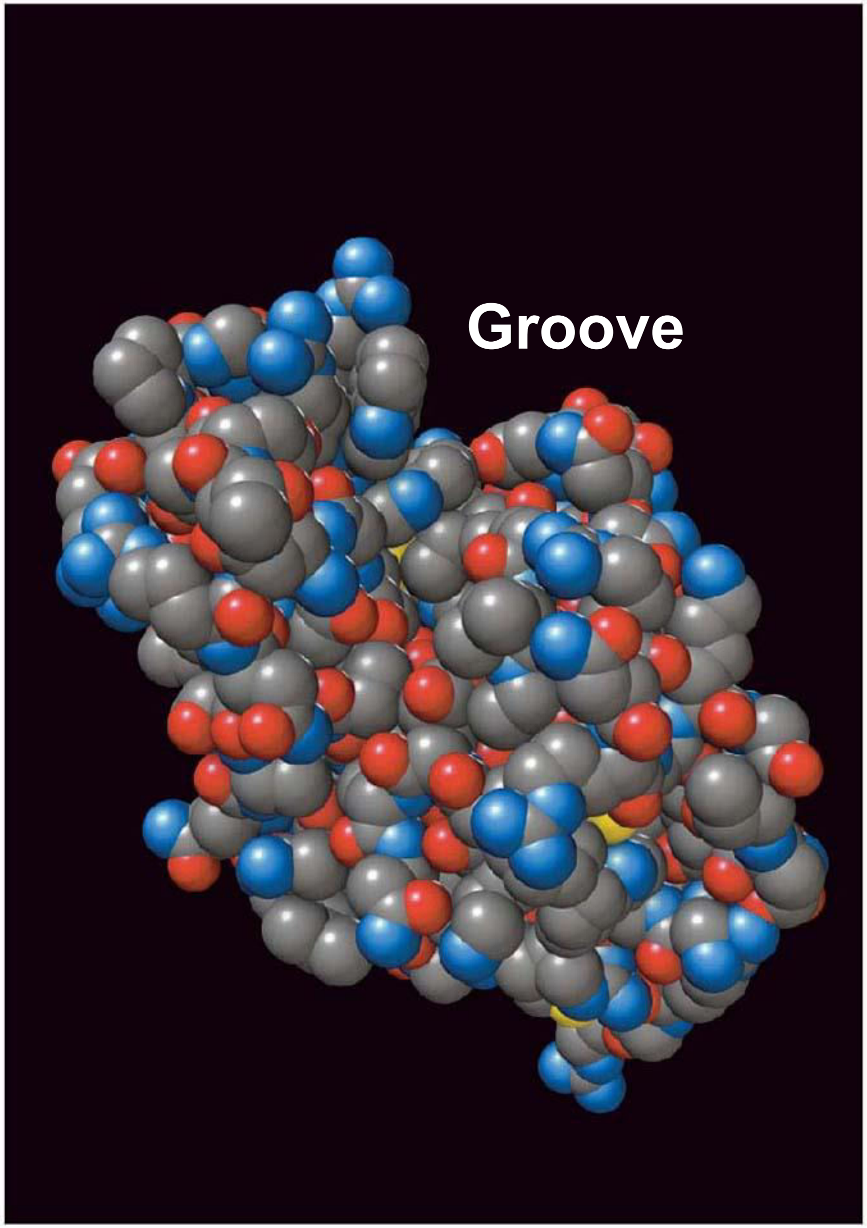
(a) A ribbon model (b) A space-filling model (c) A wireframe model

Figure 3.20-1



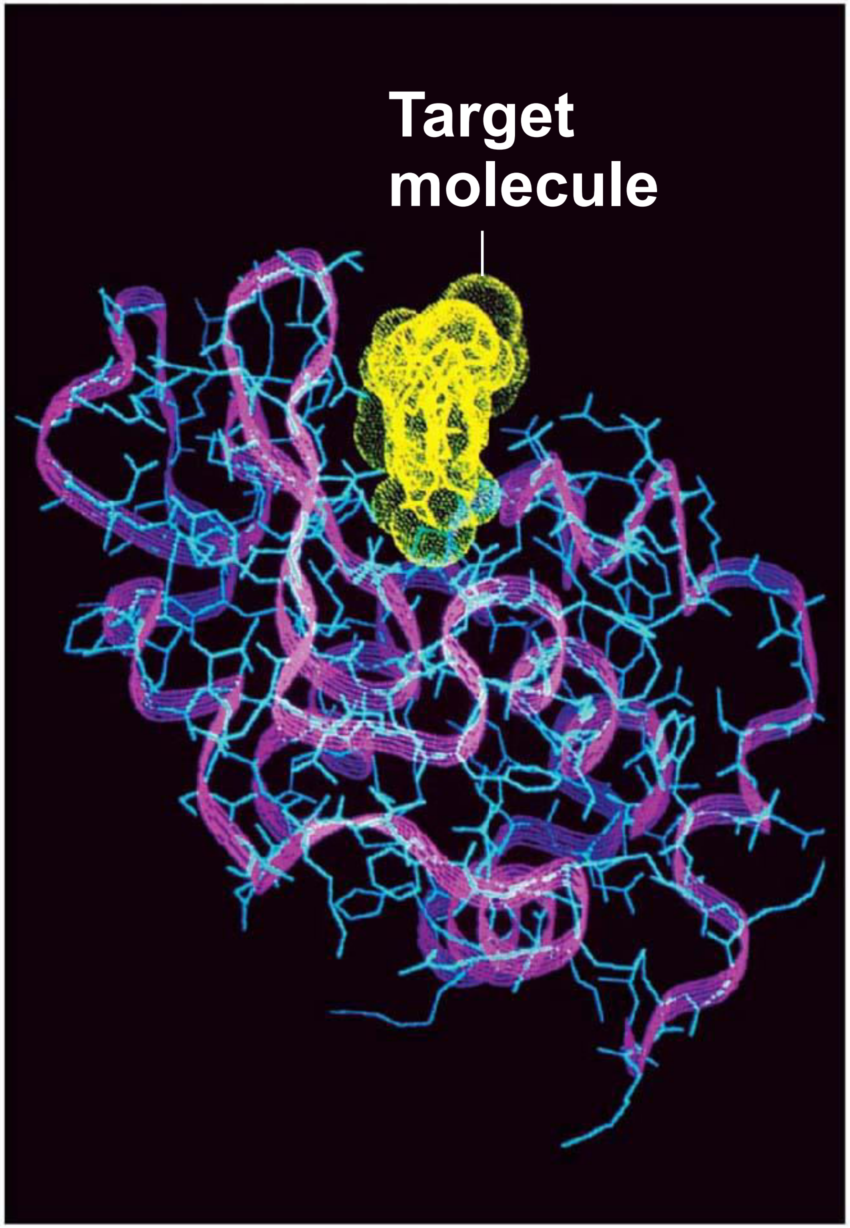
(a) A ribbon model

Figure 3.20-2



(b) A space-filling model

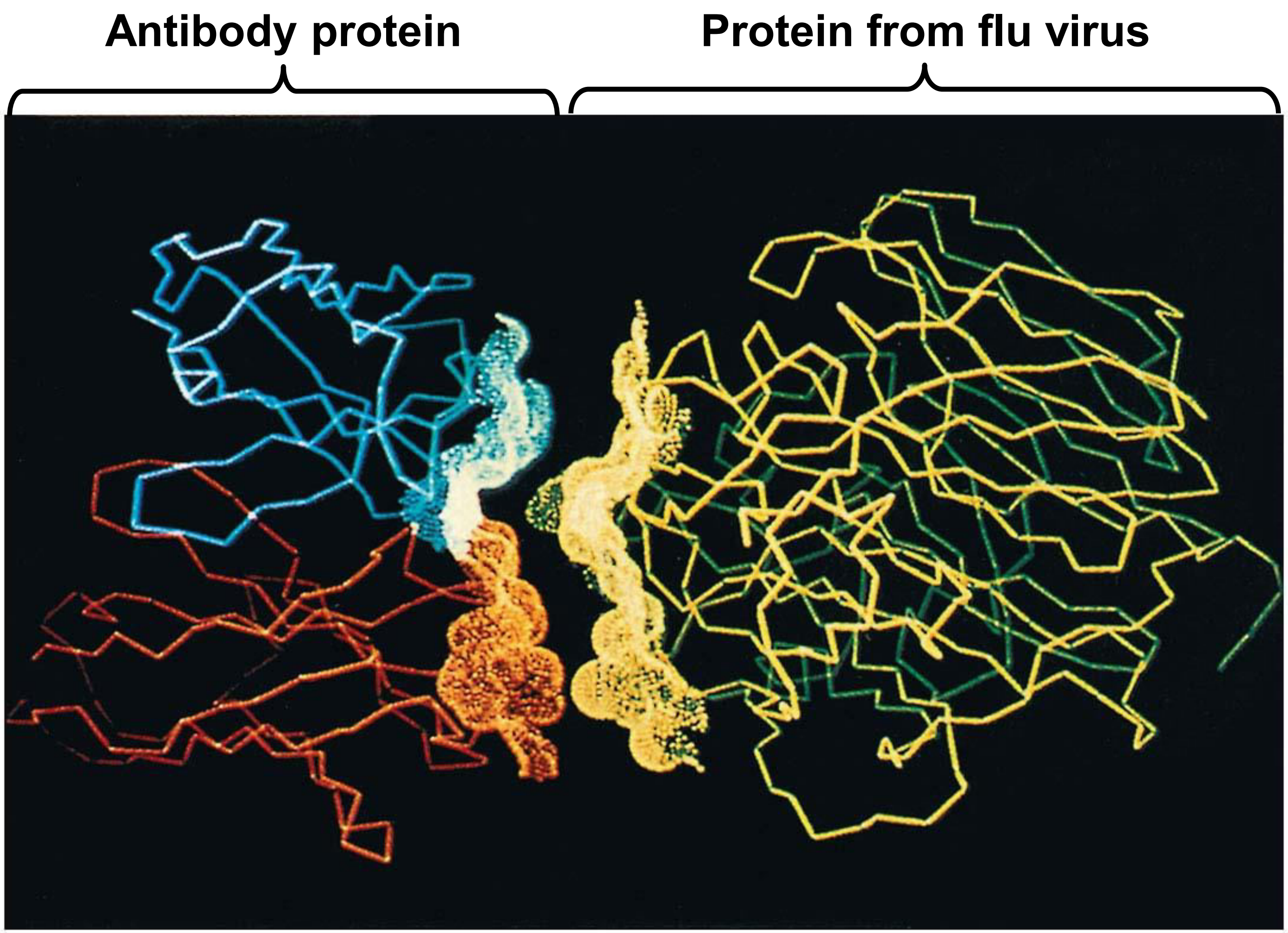
Figure 3.20-3



(c) A wireframe model

- The amino acid sequence of each polypeptide leads to a protein’s three-dimensional structure
- A protein’s structure determines its function

Figure 3.21



Four Levels of Protein Structure

- Proteins are very diverse, but share three superimposed levels of structure called primary, secondary, and tertiary structure
- A fourth level, quaternary structure, arises when a protein consists of two or more polypeptide chains

- The primary structure of a protein is its unique sequence of amino acids
- Secondary structure, found in most proteins, consists of coils and folds in the polypeptide chain
- Tertiary structure is determined by interactions among various side chains (R groups)
- Quaternary structure results from interactions between multiple polypeptide chains

Figure 3.22-1

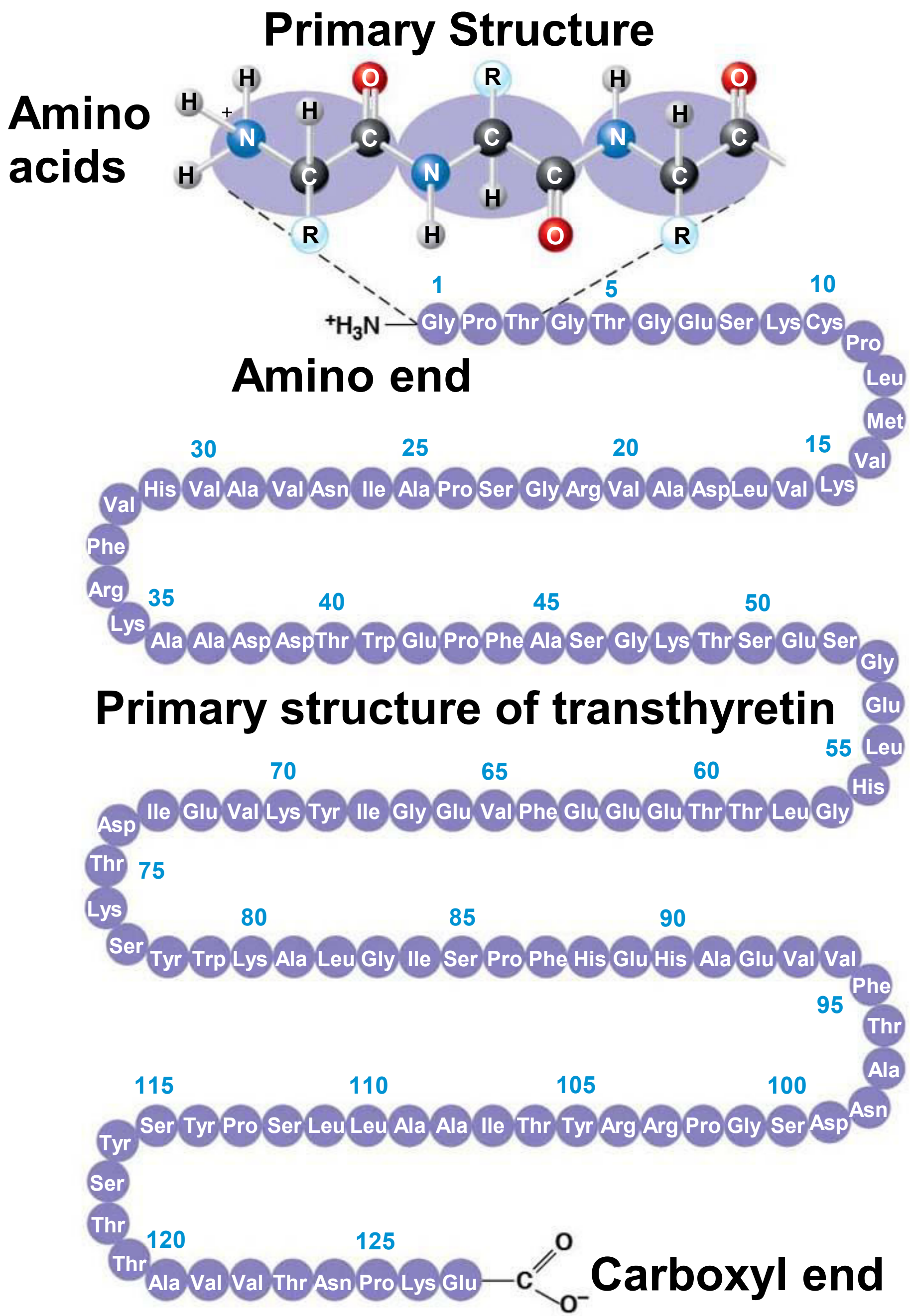

Primary Structure
Amino acids
H H H O R H H O
N C C N C C N C
H R H H O R
+
Amino end
^+H_3N
1 5 10
Gly Pro Thr Gly Thr Gly Glu Ser Lys Cys
Pro Leu Met Val
15 20 25 30
Lys Val Leu Asp Ala Val Arg Gly Ser Pro Ala Ile Asn Val Ala Val His
Val Phe Arg Lys
35 40 45 50
Ala Ala Asp Asp Thr Trp Glu Pro Phe Ala Ser Gly Lys Thr Ser Glu Ser
Gly Glu Leu
Primary structure of transthyretin
55 60 65 70
His Gly Leu Thr Thr Glu Glu Glu Phe Val Glu Gly Ile Tyr Lys Val Glu Ile
Asp Thr Lys
75 80 85 90
Ser Tyr Trp Lys Ala Leu Gly Ile Ser Pro Phe His Glu His Ala Glu Val Val
Phe Thr Ala
95 100 105 110 115
Asn Asp Ser Gly Pro Arg Arg Tyr Thr Ile Ala Ala Leu Leu Ser Pro Tyr Ser
Tyr Ser Thr
120 125
Thr Ala Val Val Thr Asn Pro Lys Glu
C O O⁻
Carboxyl end

Figure 3.22-1a

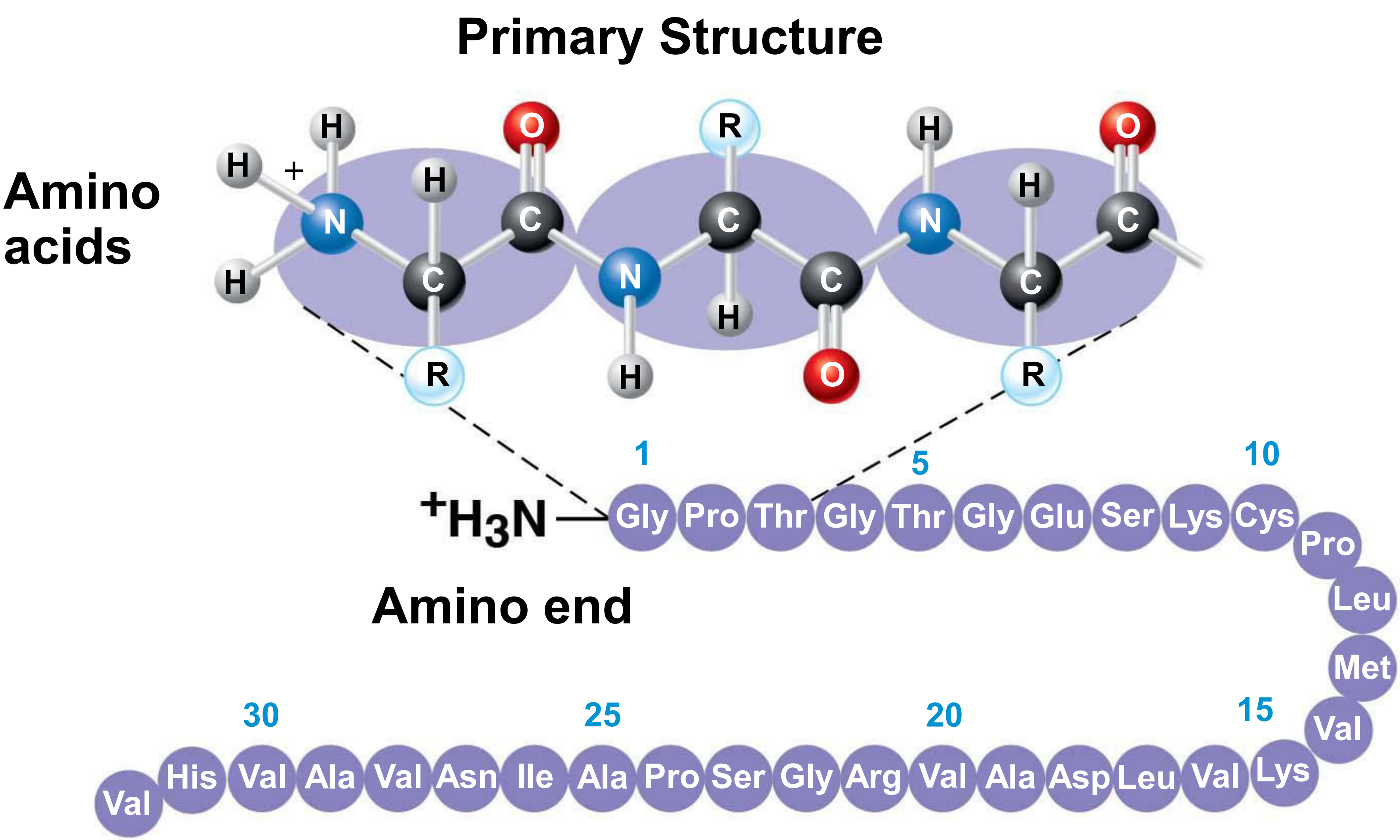


Figure 3.22-2

Secondary Structure

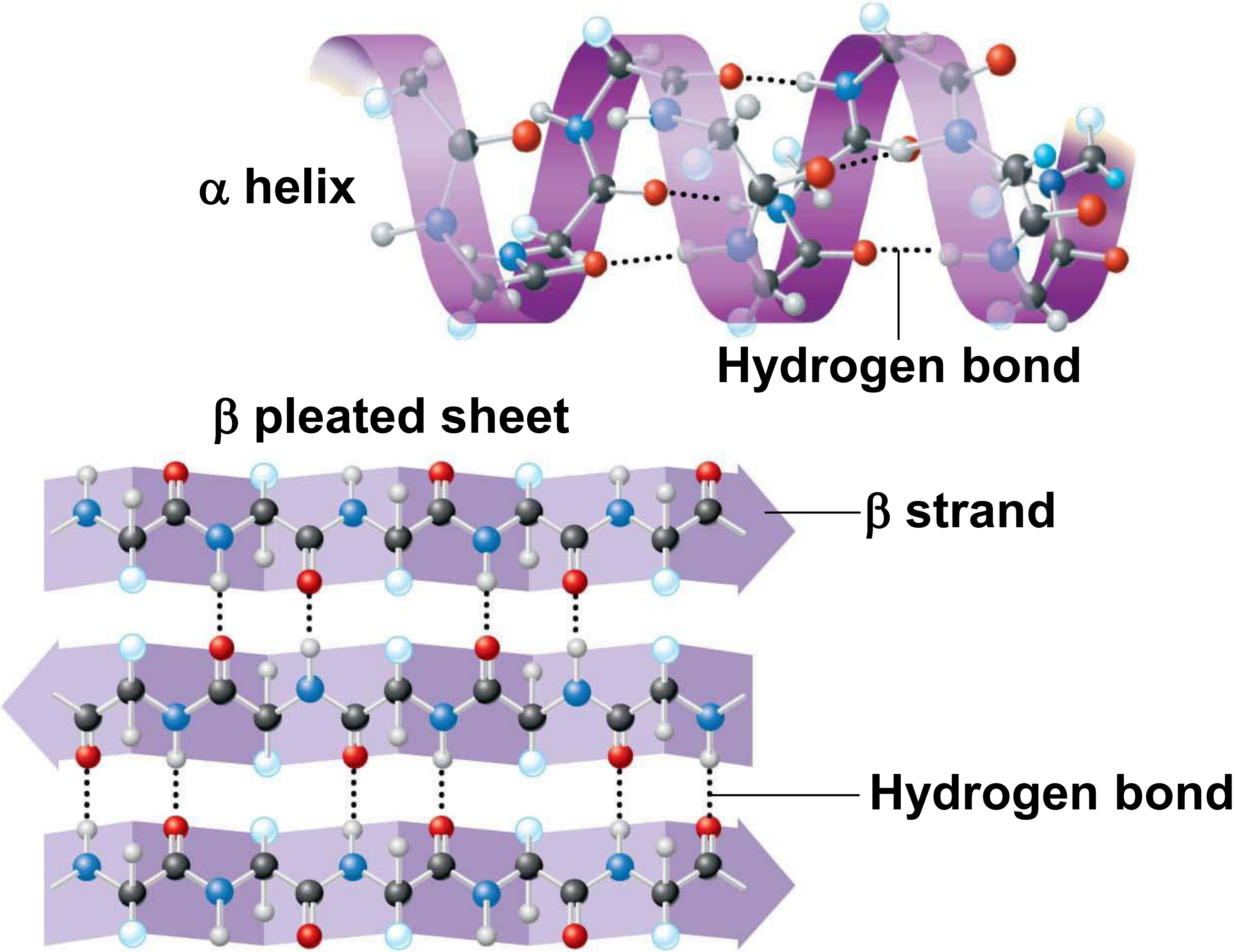


Figure 3.22-2a

Tertiary Structure

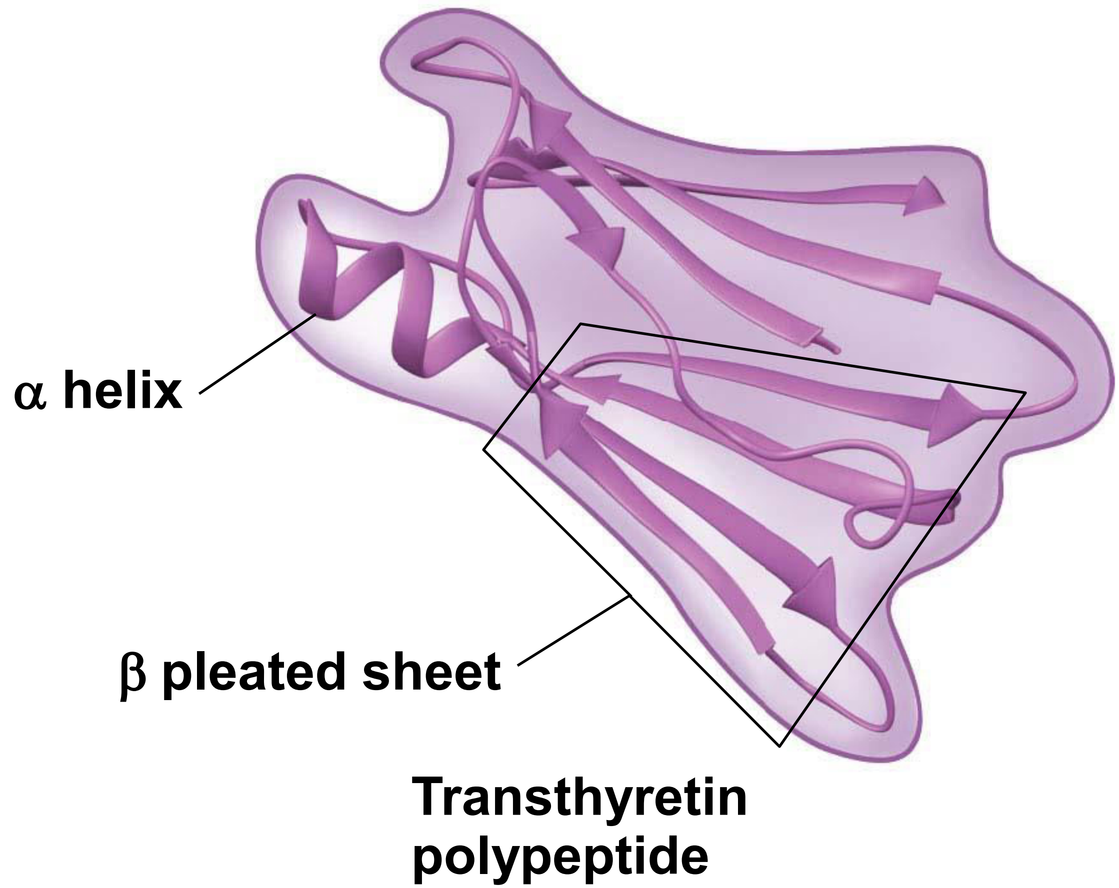
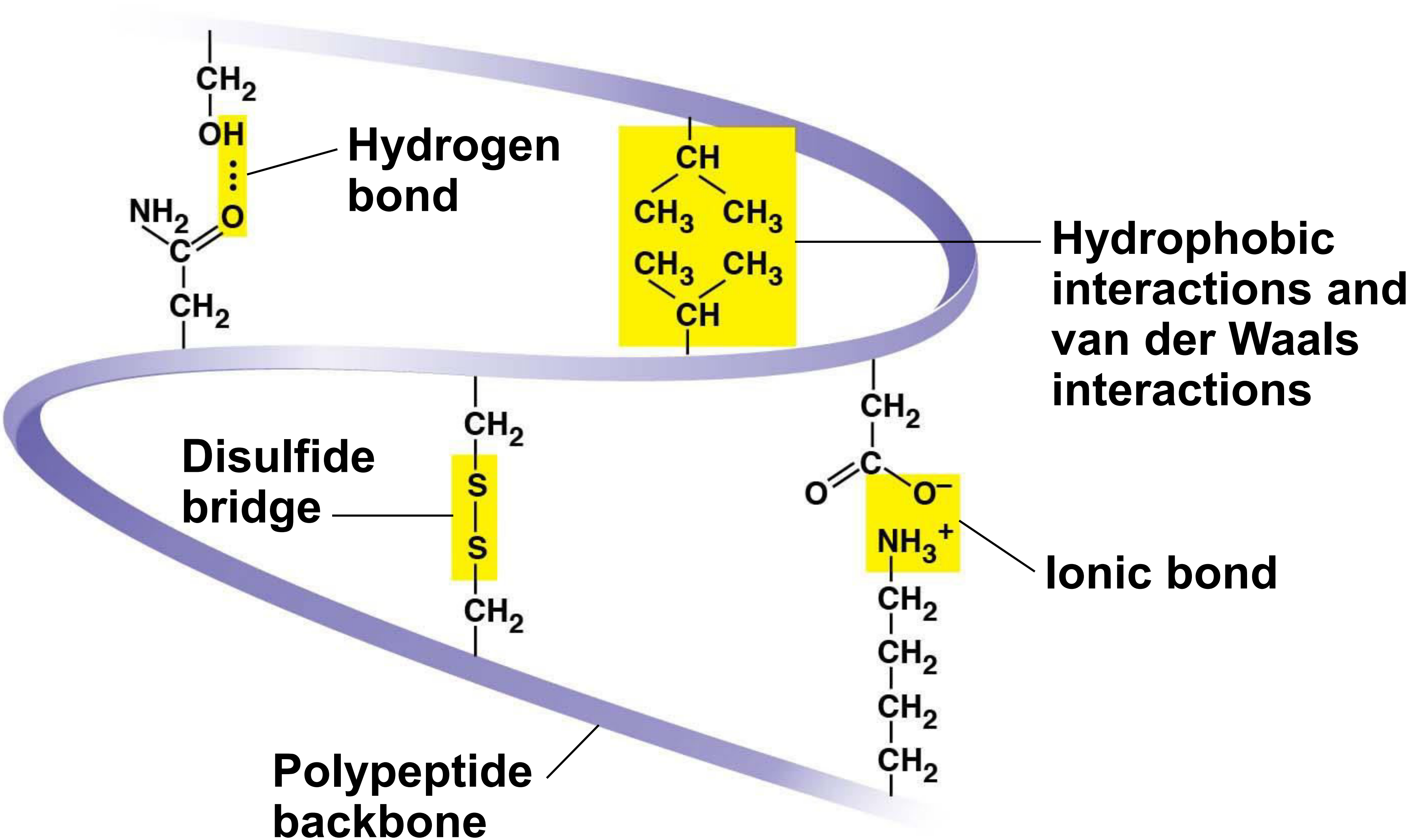
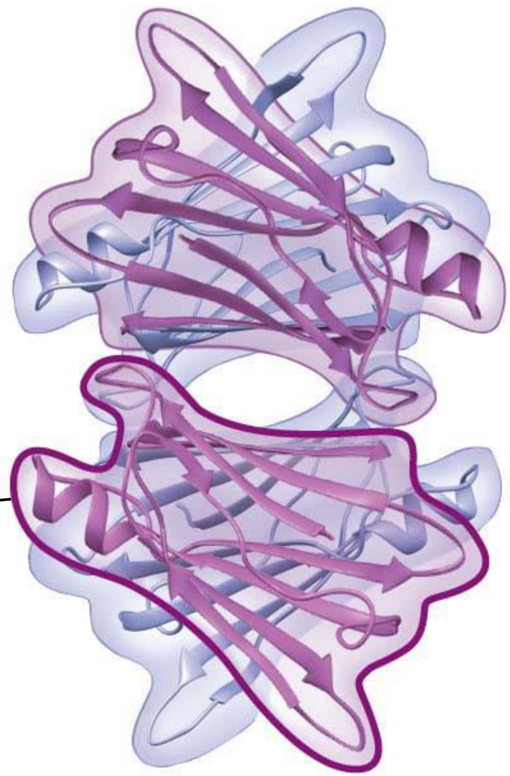


Figure 3.22-3a



Quaternary structure



Collagen

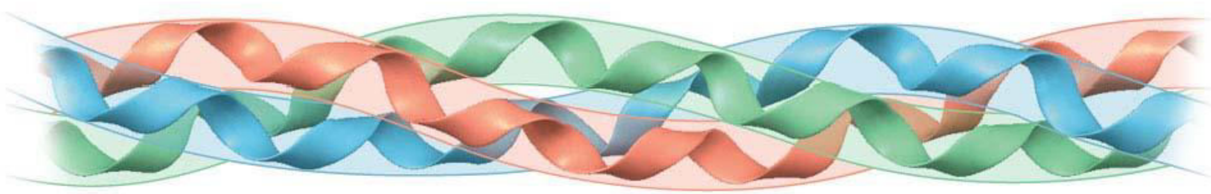
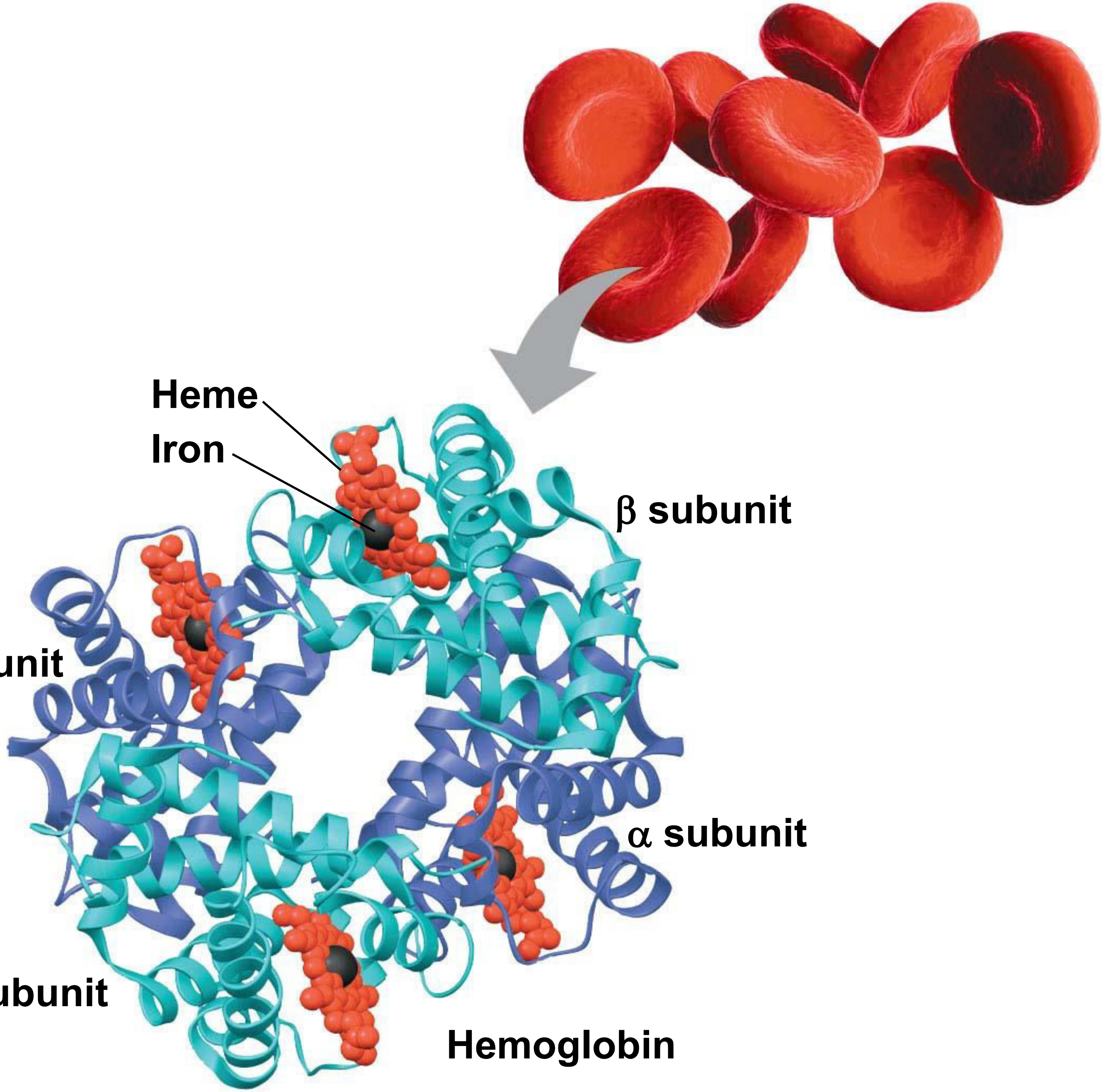
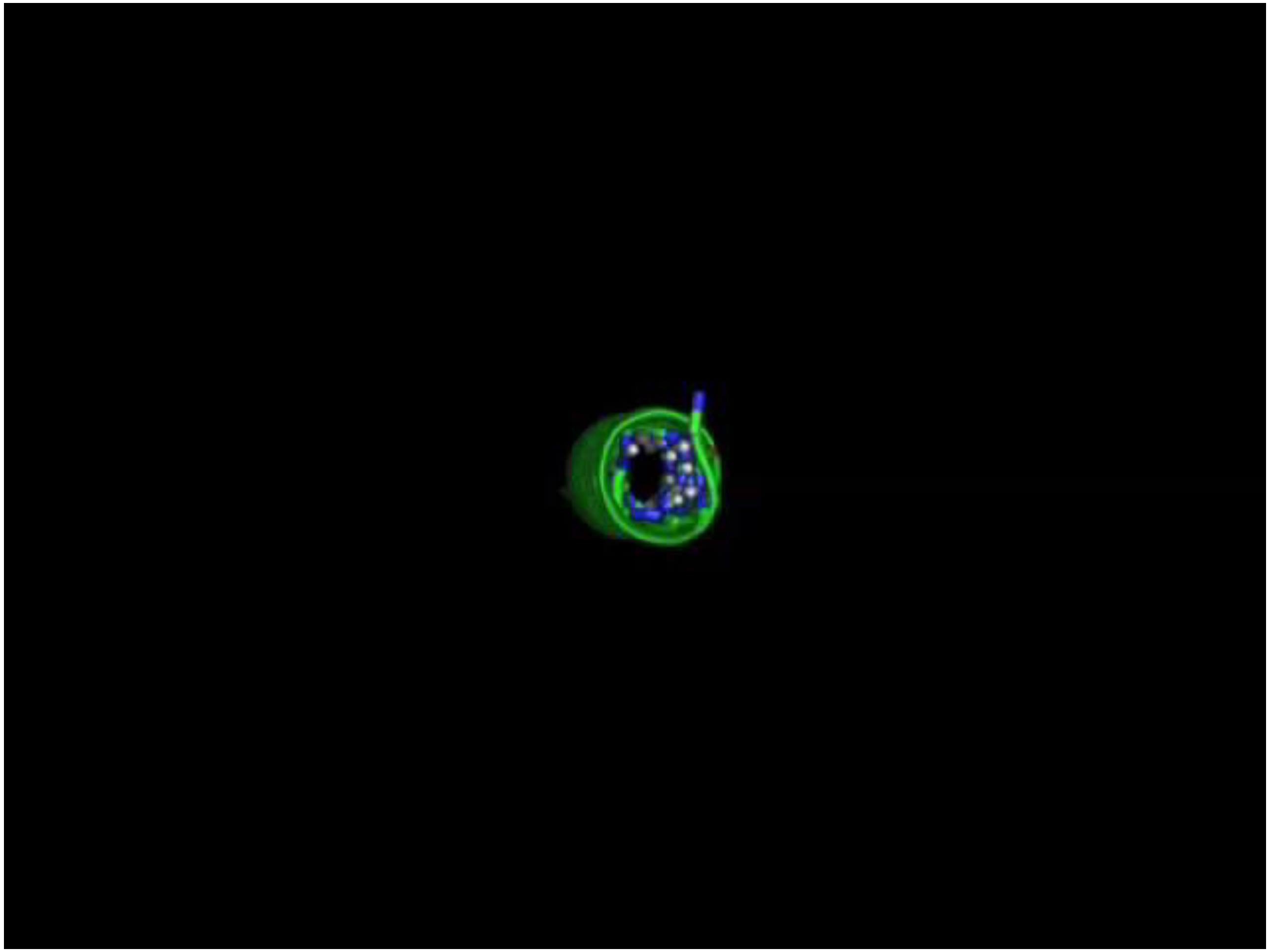


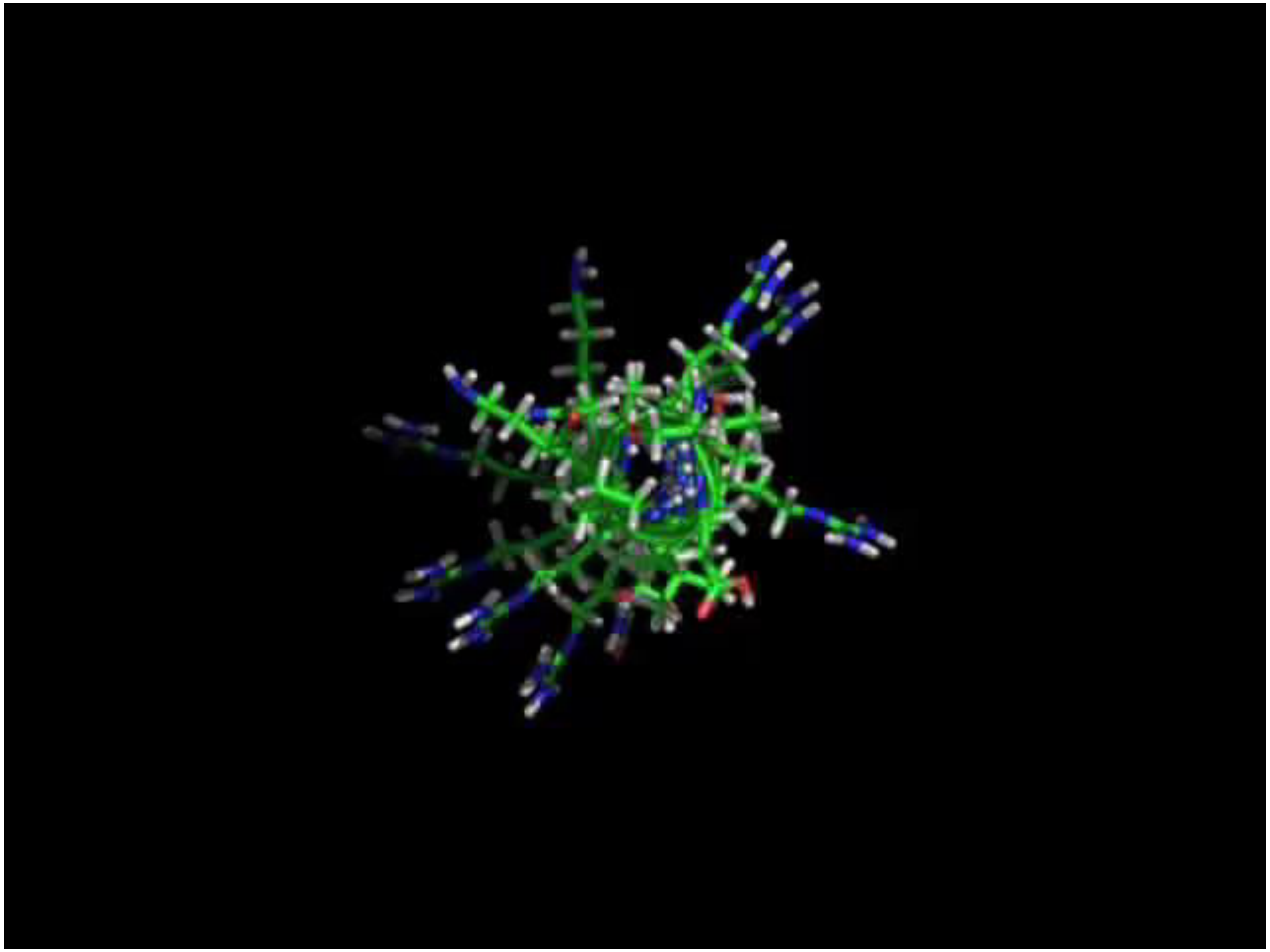
Figure 3.22-4b



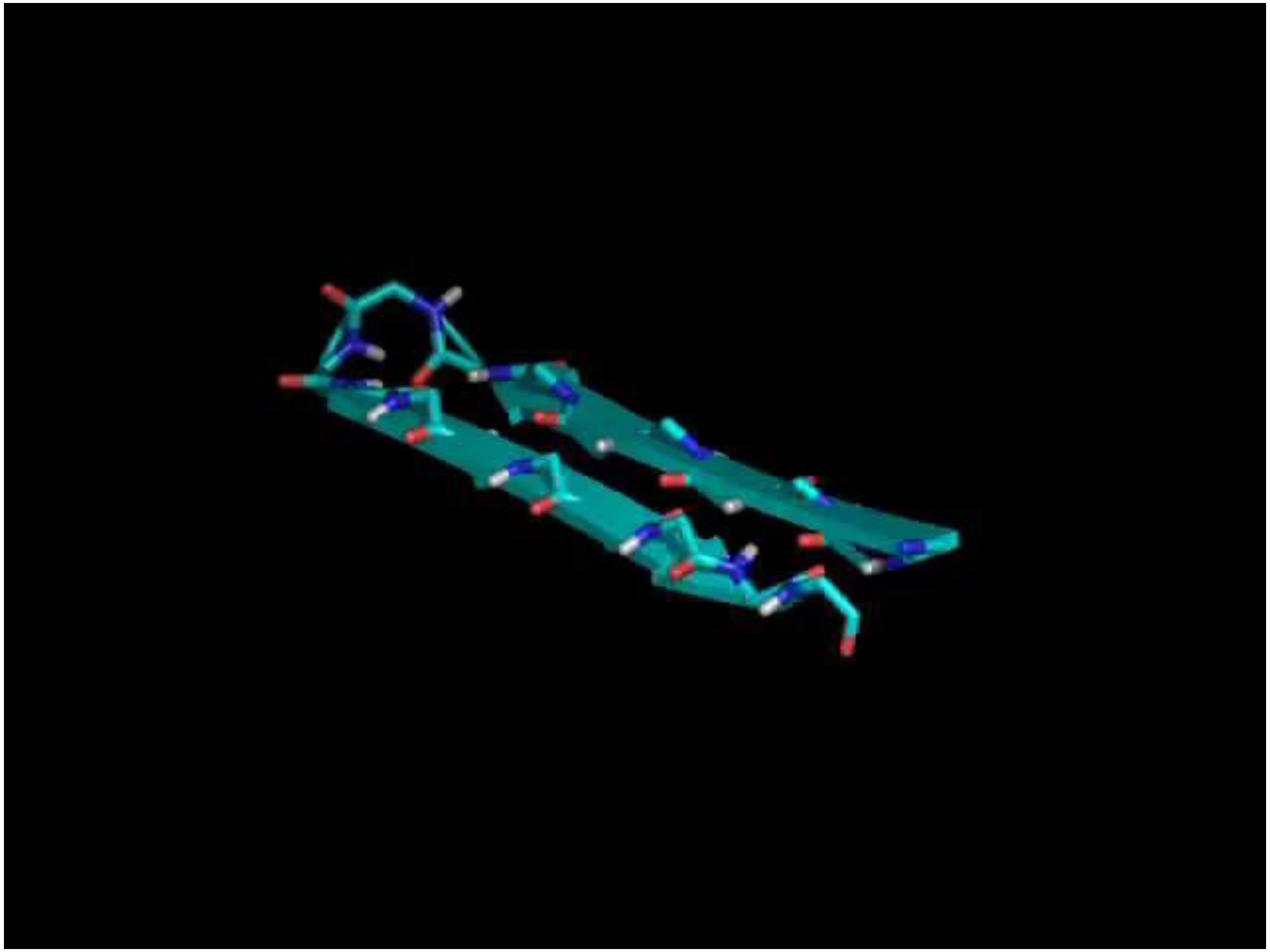
Video: Alpha Helix with No Side Chain



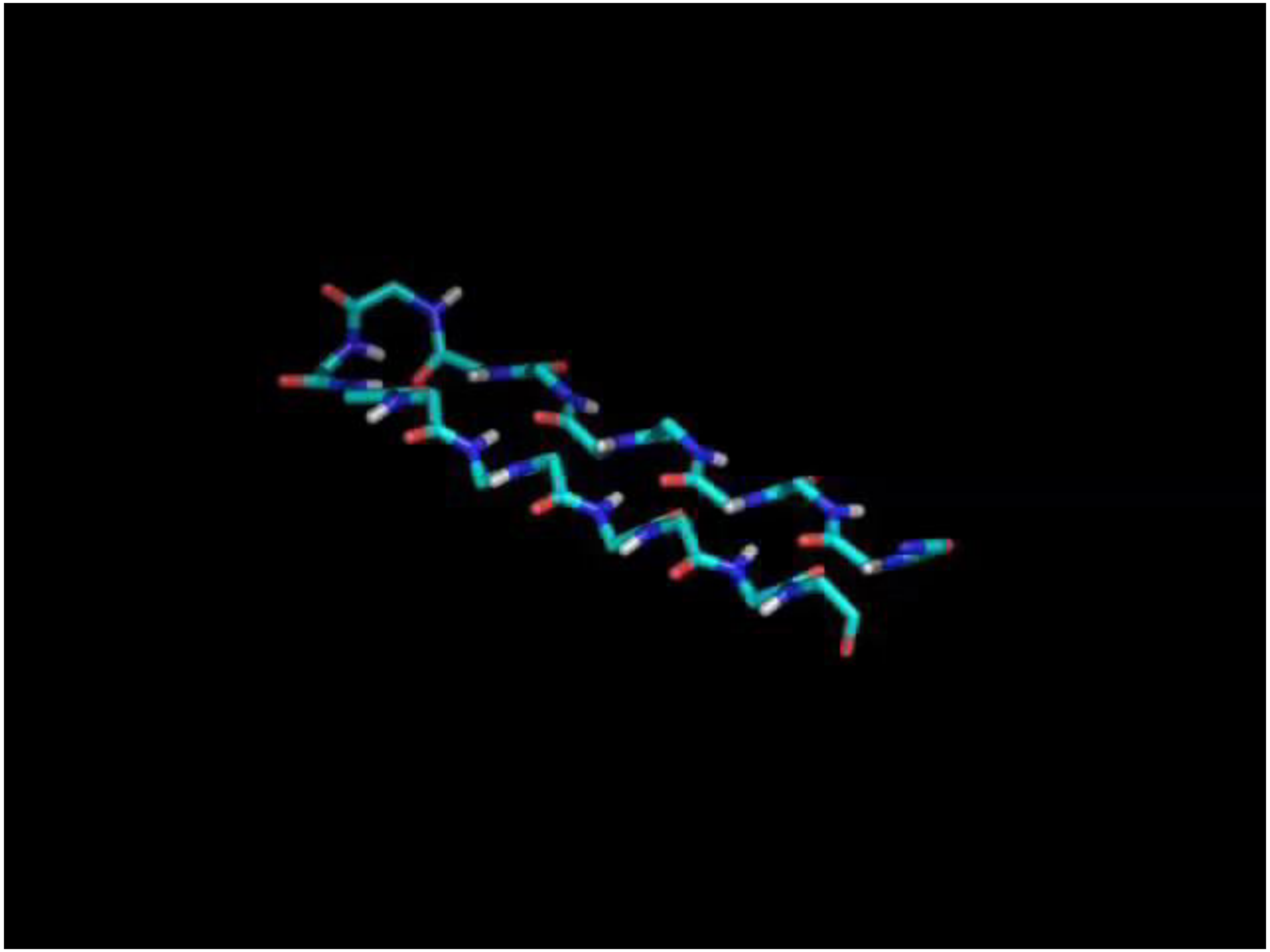
Video: Alpha Helix with Side Chain



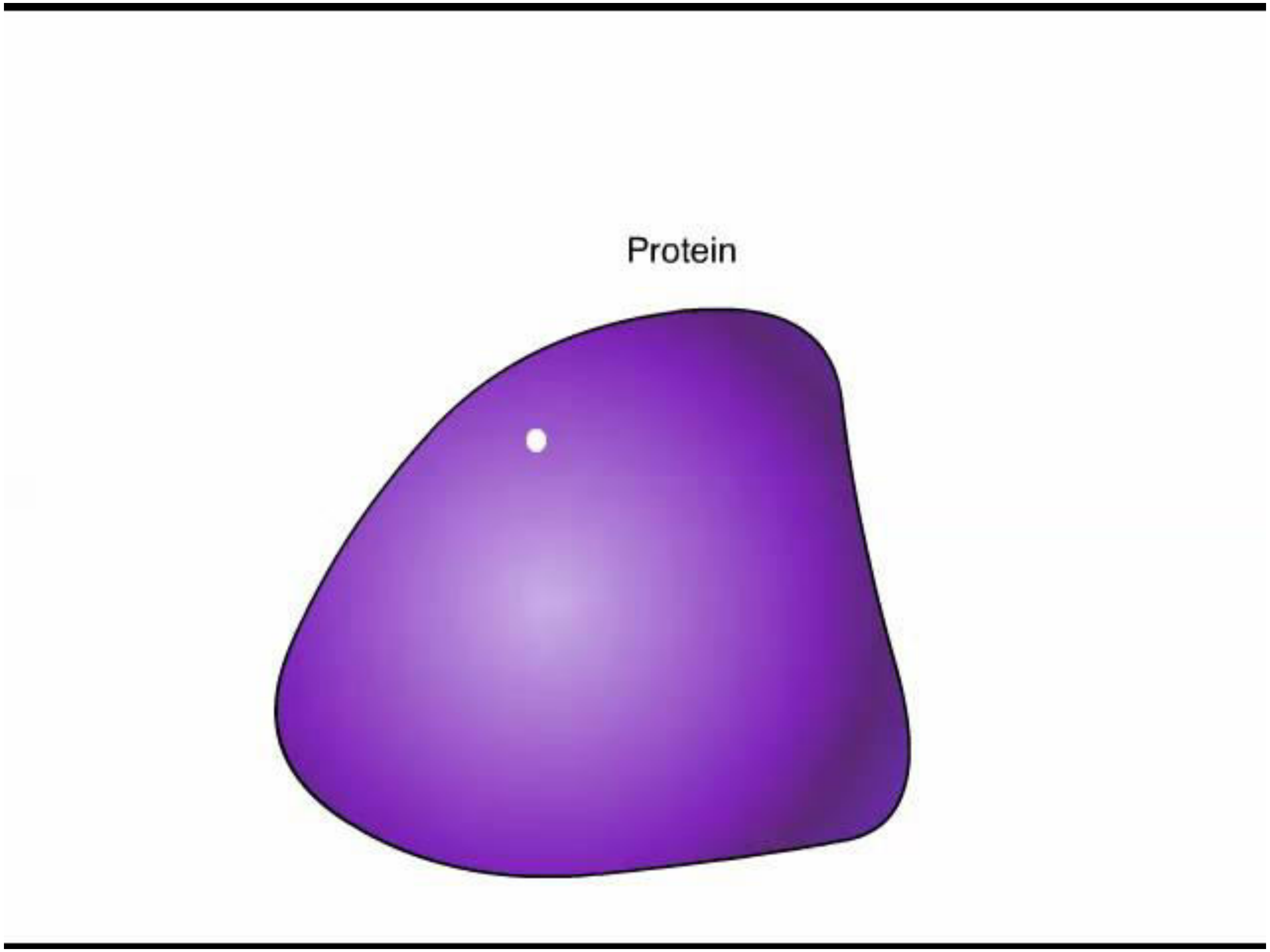
Video: Beta Pleated Sheet



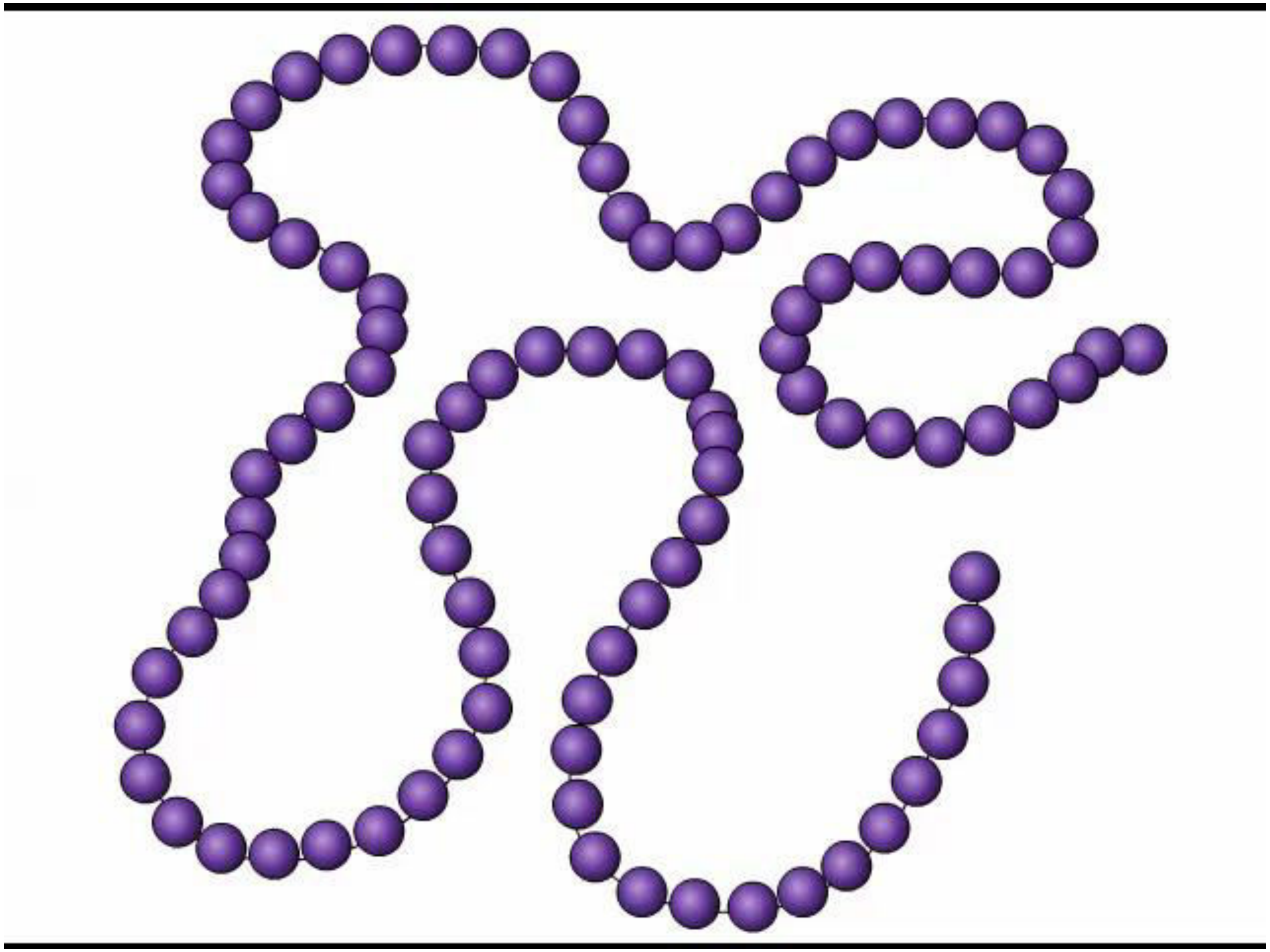
Video: Beta Pleated Stick



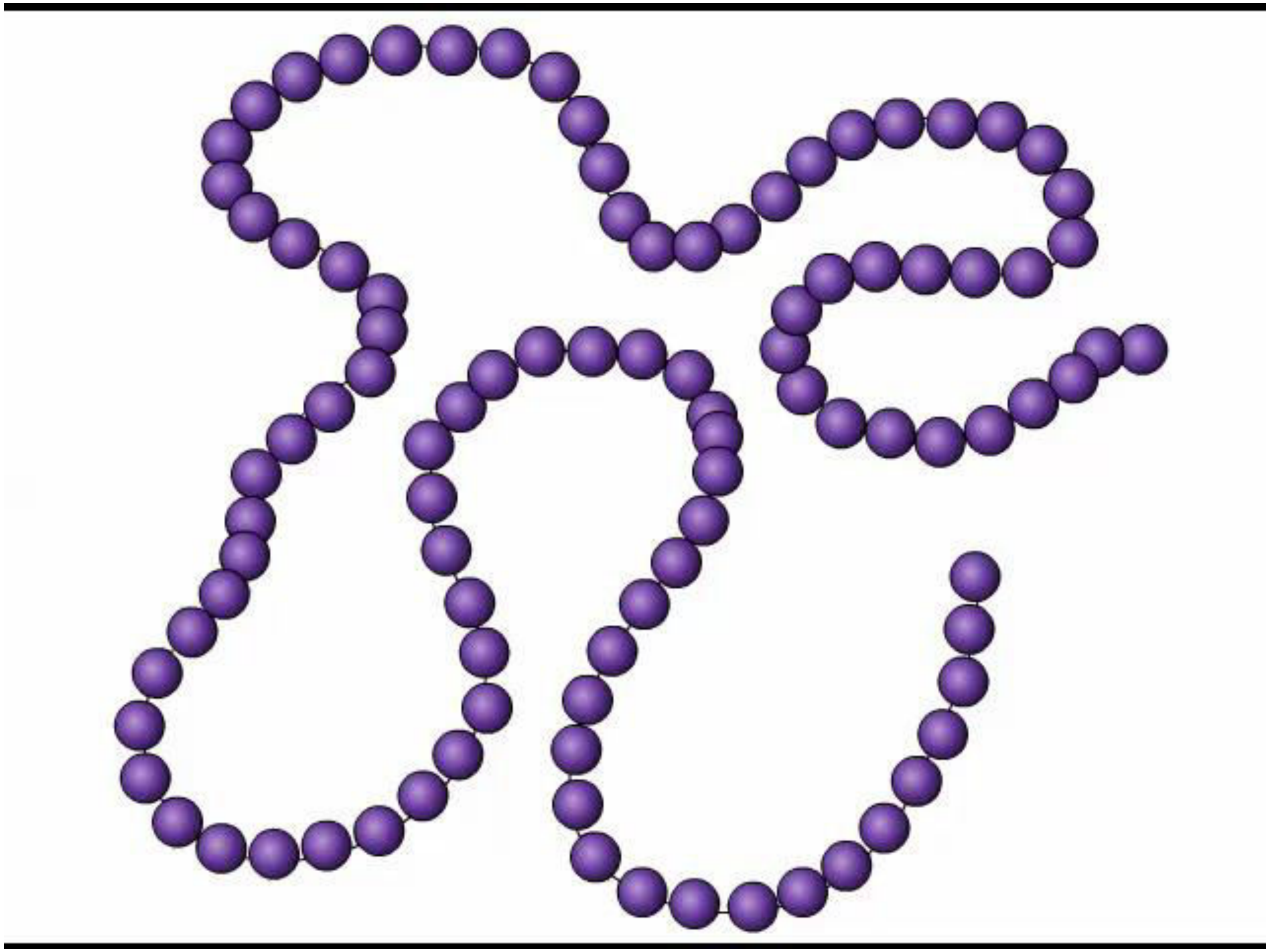
Animation: Introduction to Protein Structure



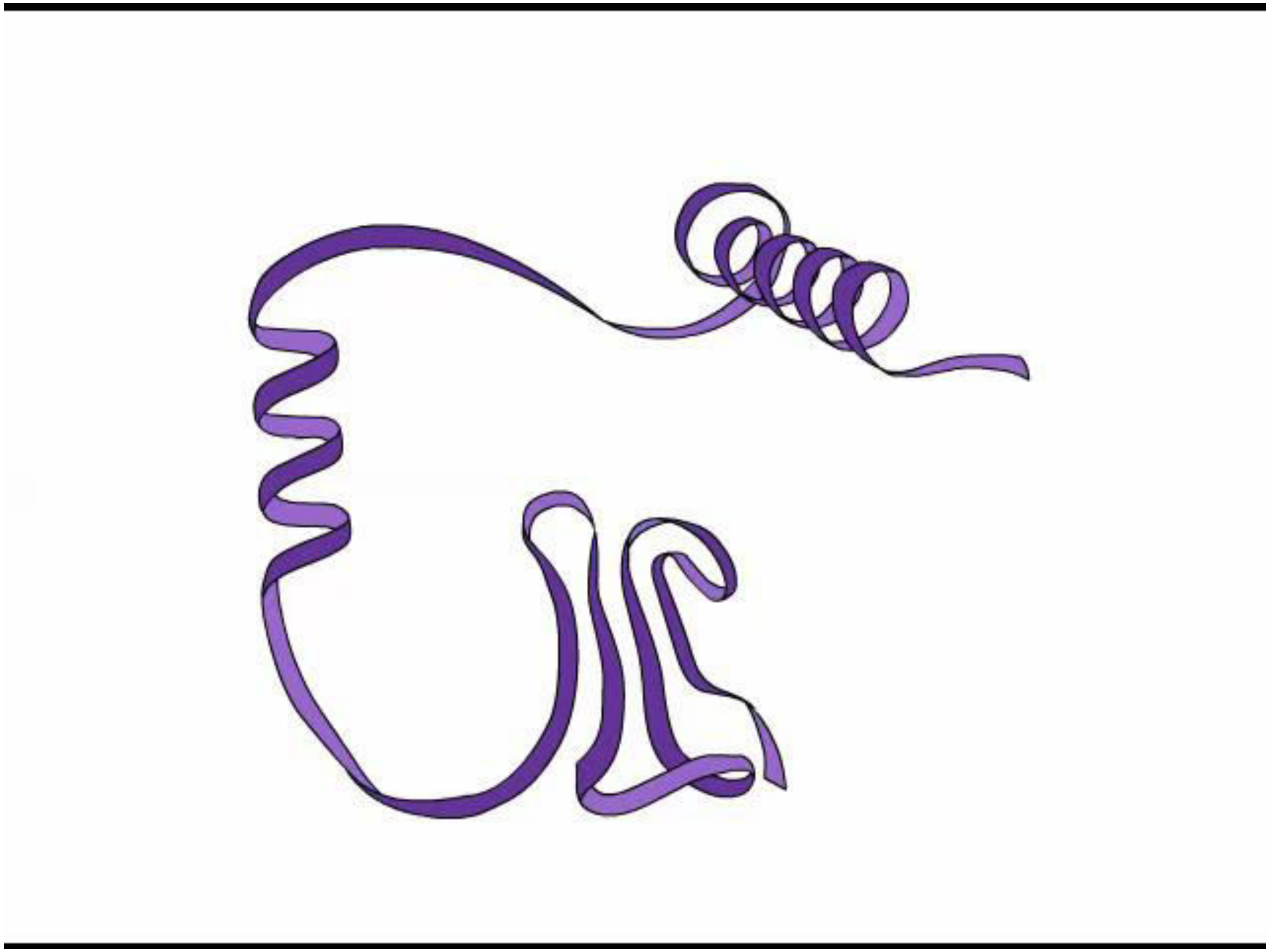
Animation: Primary Structure



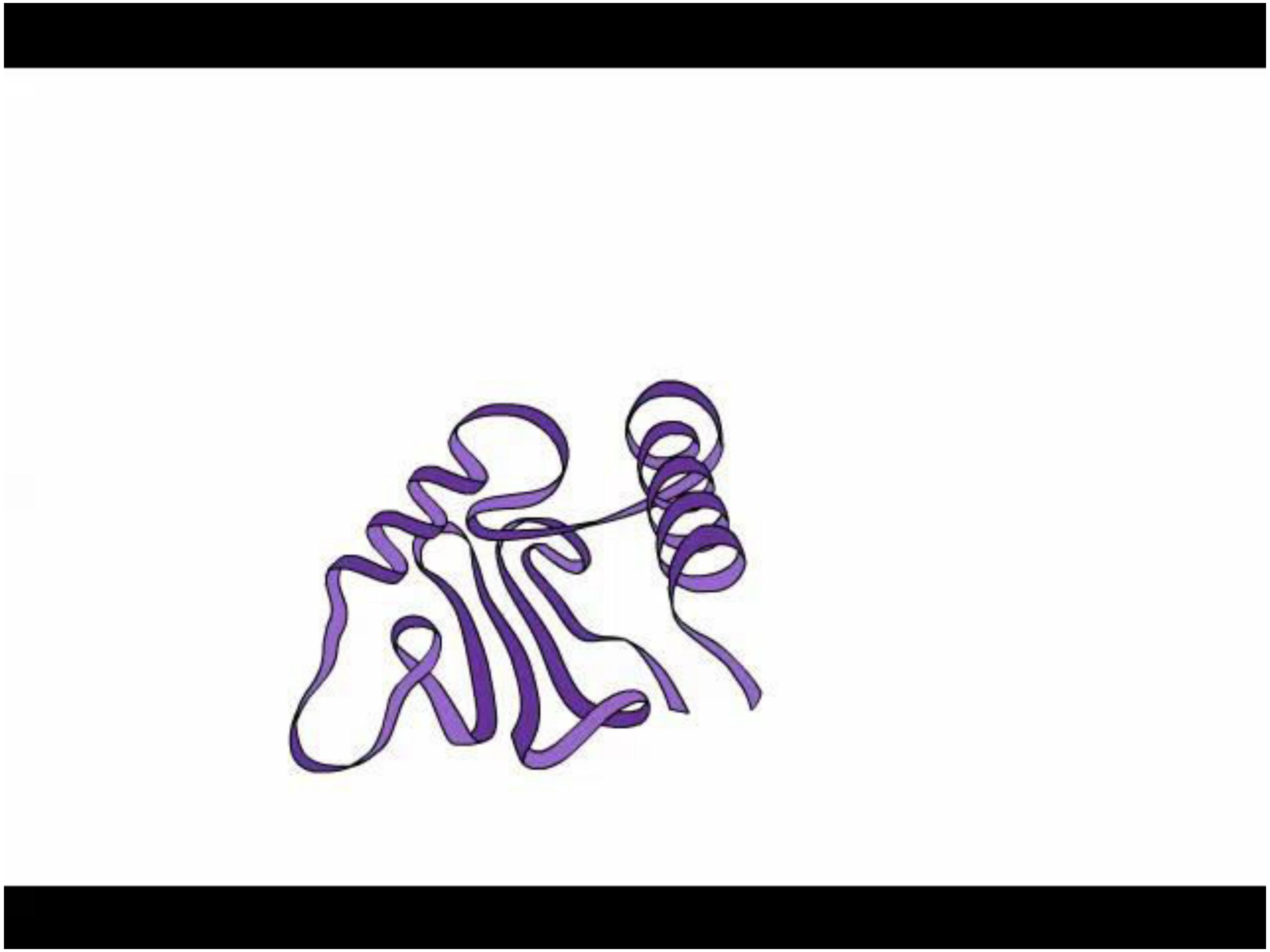
Animation: Secondary Structure



Animation: Tertiary Structure



Animation: Quaternary Structure



Sickle-Cell Disease: A Change in Primary Structure

- A slight change in primary structure can affect a protein's structure and ability to function
- **Sickle-cell disease**, an inherited blood disorder, results from a single amino acid substitution in the protein hemoglobin

Figure 3.23

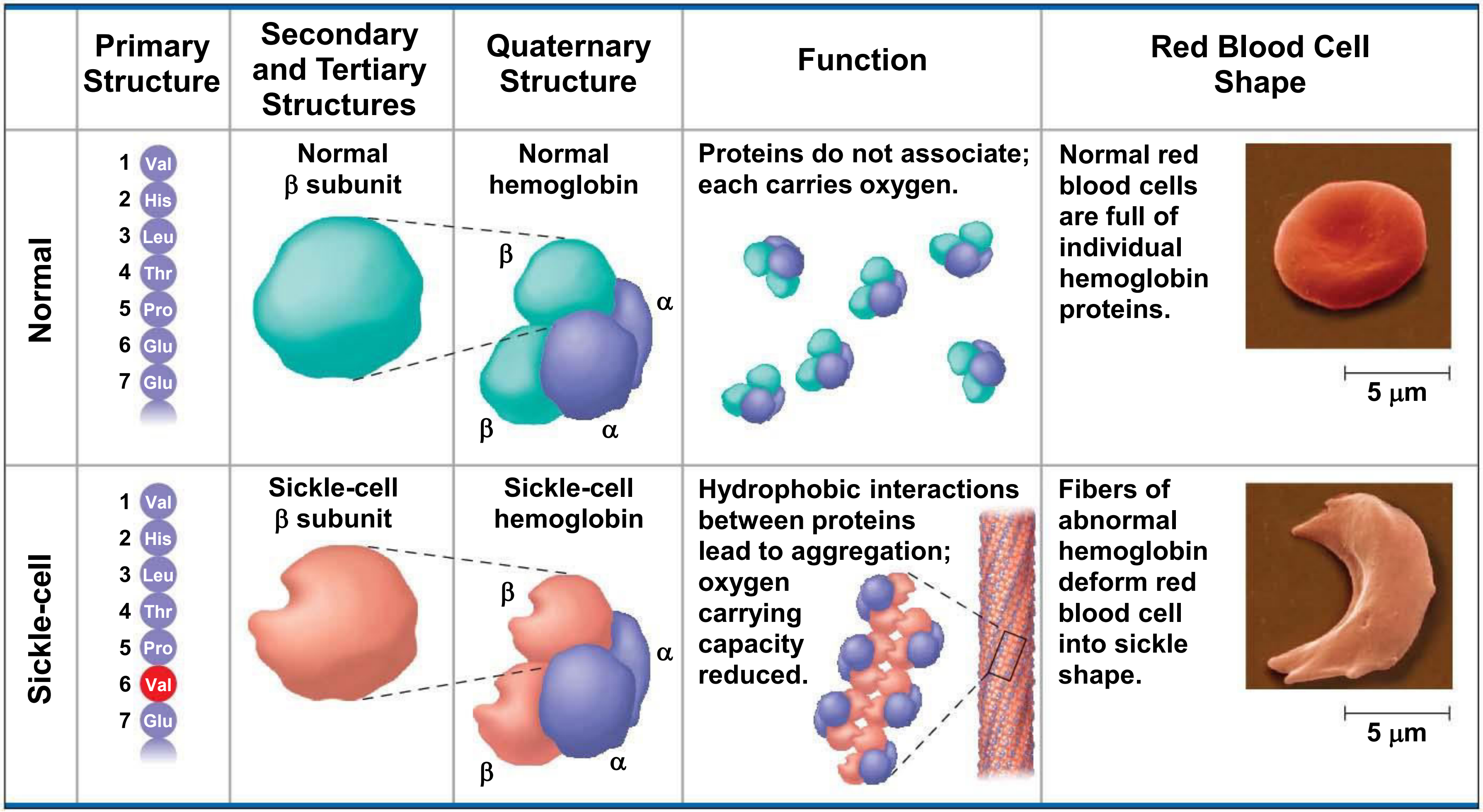

Primary Structure
Secondary and Tertiary Structures
Quaternary Structure
Function
Red Blood Cell Shape
Normal
1 Val
2 His
3 Leu
4 Thr
5 Pro
6 Glu
7 Glu
Normal β subunit
Normal hemoglobin
β
α
β
α
Proteins do not associate; each carries oxygen.
Normal red blood cells are full of individual hemoglobin proteins.
5 μm
Sickle-cell
1 Val
2 His
3 Leu
4 Thr
5 Pro
6 Val
7 Glu
Sickle-cell β subunit
Sickle-cell hemoglobin
β
α
β
α
Hydrophobic interactions between proteins lead to aggregation; oxygen carrying capacity reduced.
Fibers of abnormal hemoglobin deform red blood cell into sickle shape.
5 μm

Figure 3.23-1

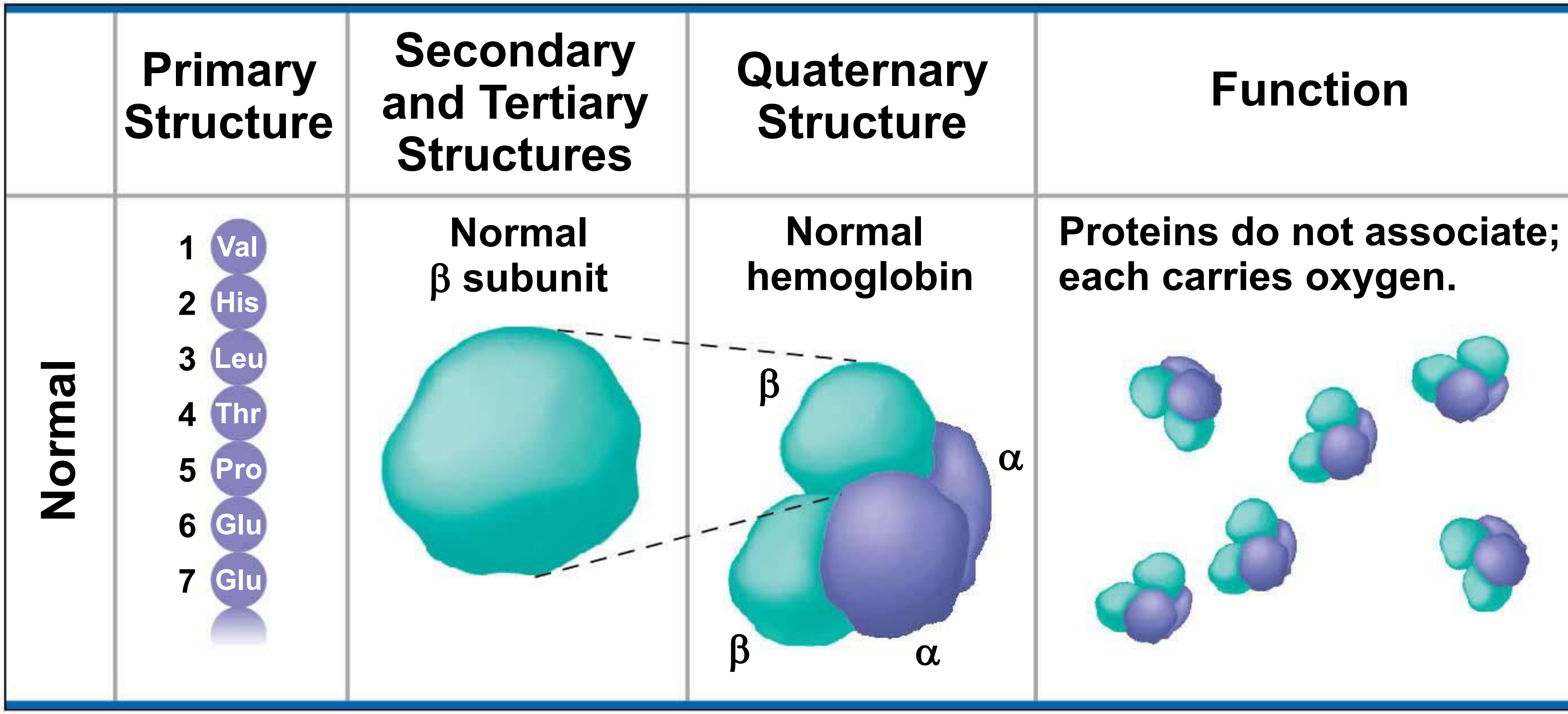

Primary Structure
Secondary and Tertiary Structures
Quaternary Structure
Function
Normal
1 Val
2 His
3 Leu
4 Thr
5 Pro
6 Glu
7 Glu
Normal β subunit
Normal hemoglobin
β
α
β
α
Proteins do not associate; each carries oxygen.

Figure 3.23-1a

Normal red blood cells are full of individual hemoglobin proteins.

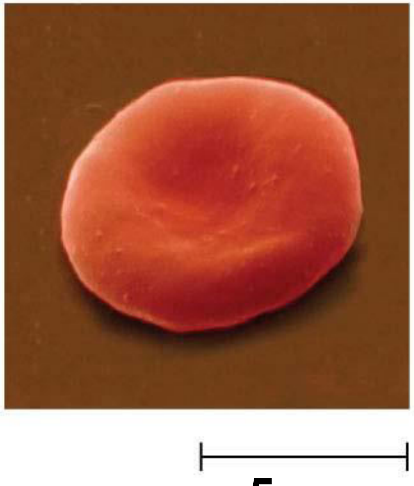


Figure 3.23-2

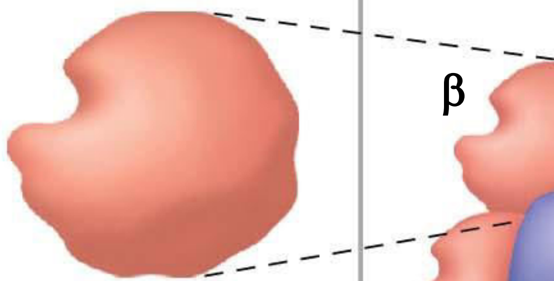
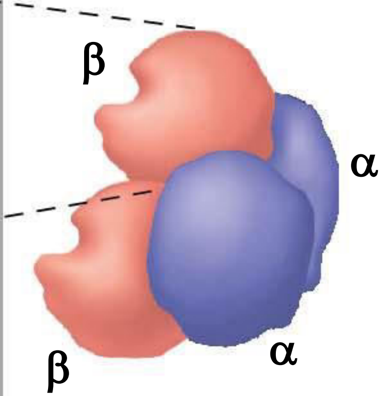
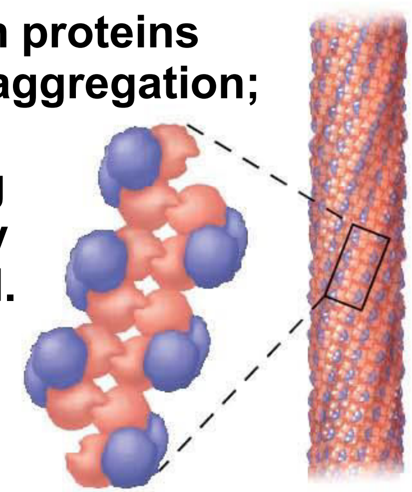
	Primary Structure	Secondary and Tertiary Structures	Quaternary Structure	Function
Sickle-cell		Sickle-cell β subunit 	Sickle-cell hemoglobin 	Hydrophobic interactions between proteins lead to aggregation; oxygen carrying capacity reduced. 

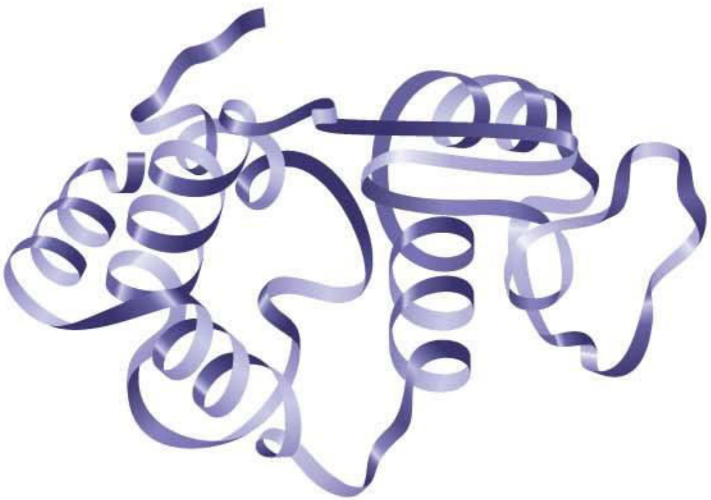
Figure 3.23-2a

Fibers of abnormal hemoglobin deform red blood cell into sickle shape.

5 μm

What Determines Protein Structure?

- In addition to amino acid sequence, physical and chemical conditions can affect protein structure
- Alterations in pH, salt concentration, temperature, or other environmental factors can cause a protein to unravel
- This loss of a protein's native structure is called **denaturation**
- A denatured protein is biologically inactive



Normal protein

Figure 3.24-s2

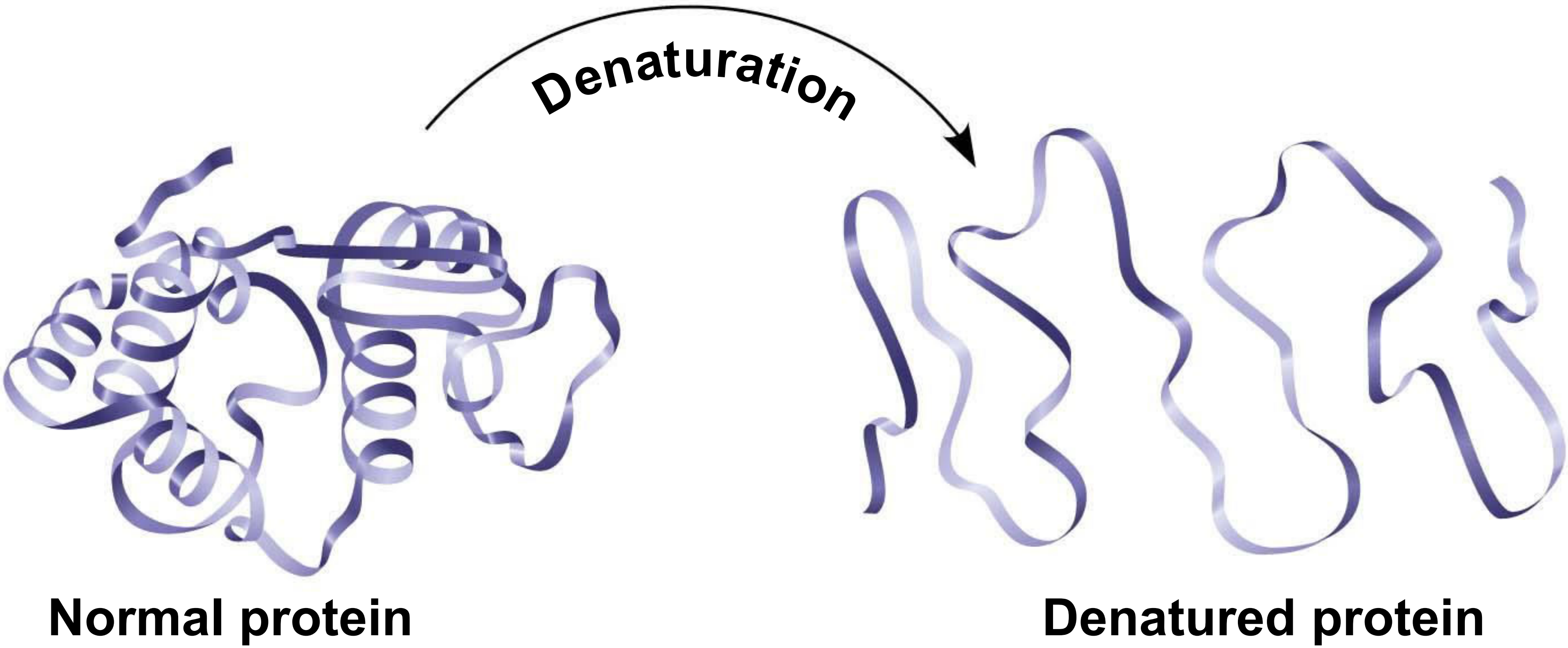
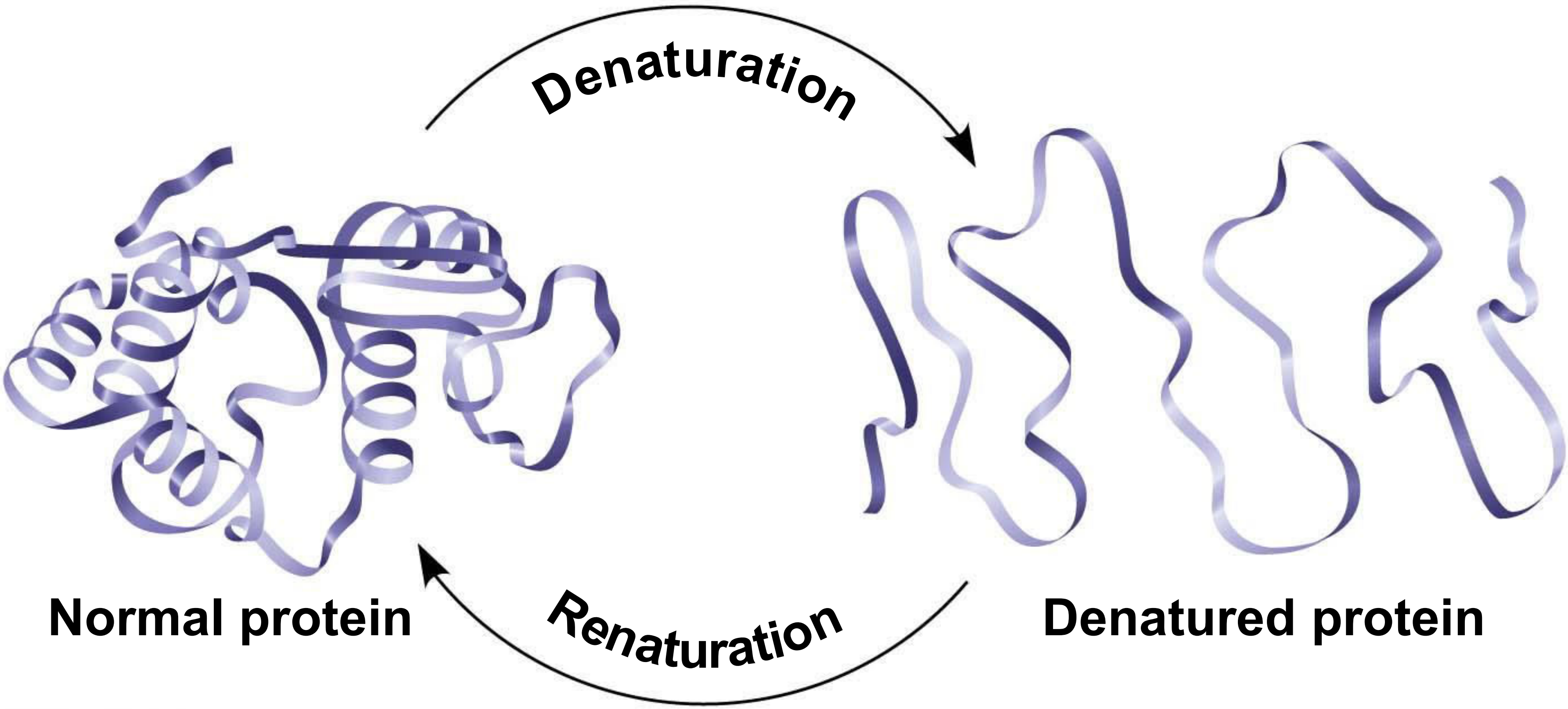


Figure 3.24-s3

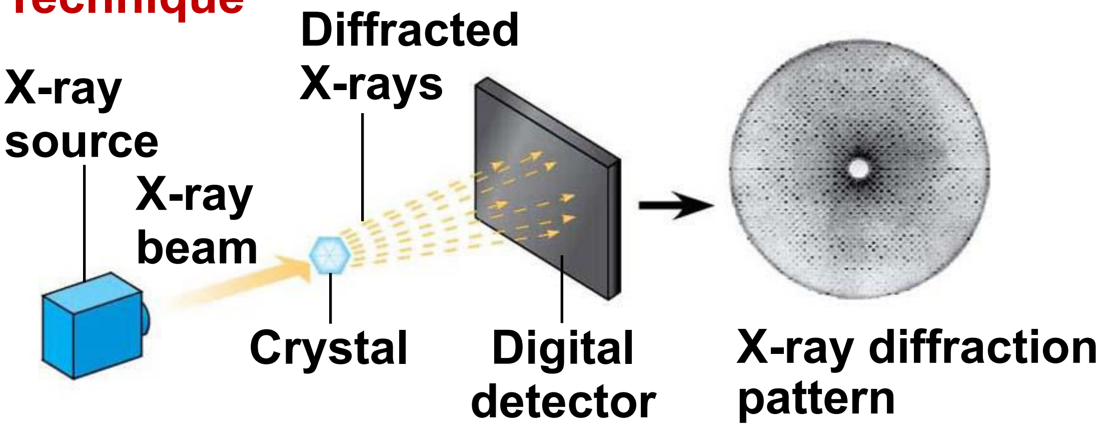


Protein Folding in the Cell

- It is difficult to predict a protein's structure from its primary structure
- Most proteins probably go through several intermediate structures on their way to their final, stable shape
- Scientists use **X-ray crystallography** to determine 3-D protein structure based on diffractions of an X-ray beam by atoms of the crystalized molecule

Figure 3.25

Technique



Results

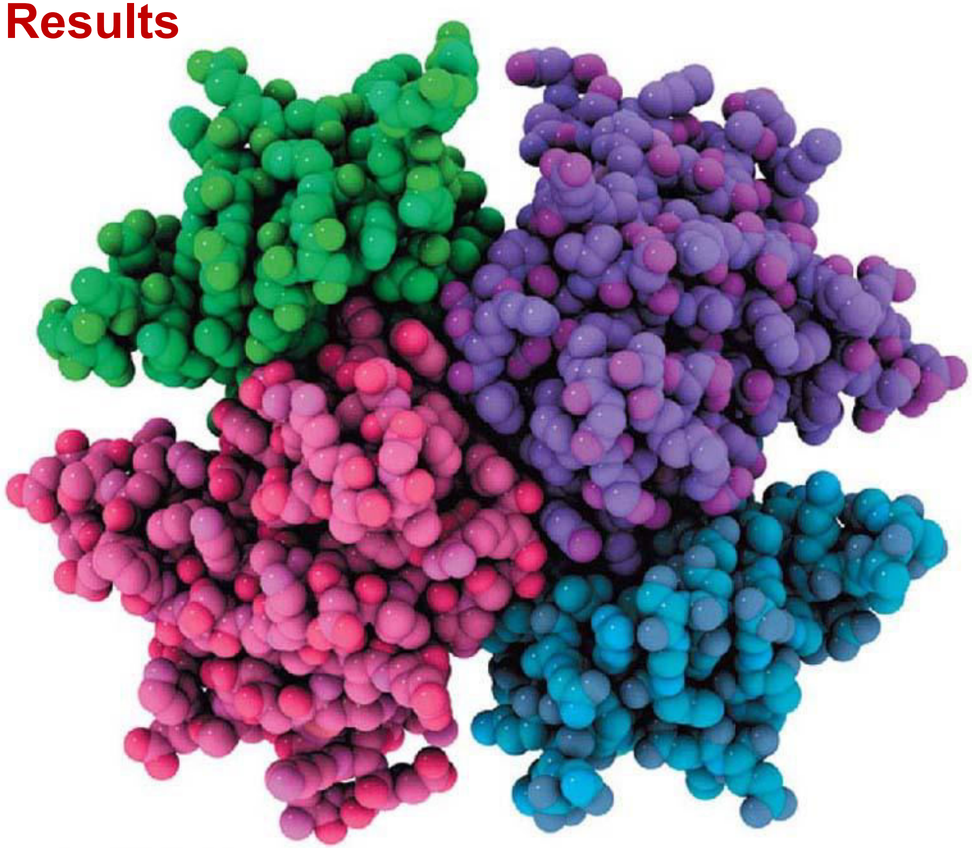


Figure 3.25-1

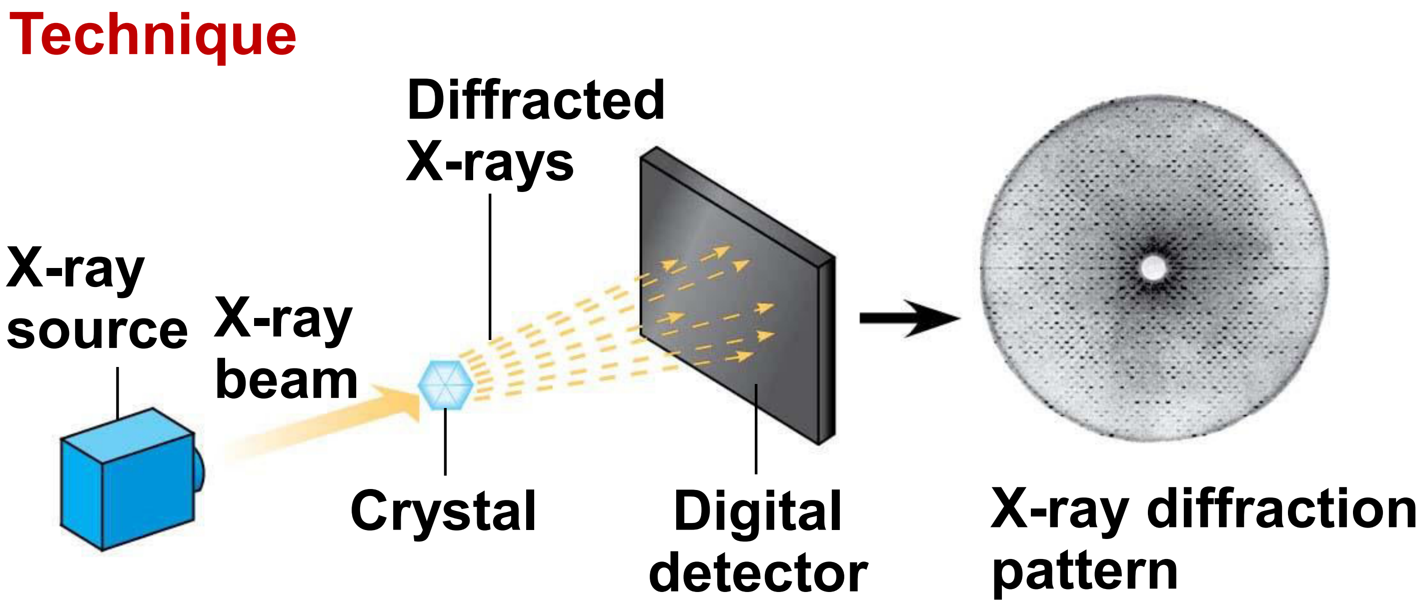
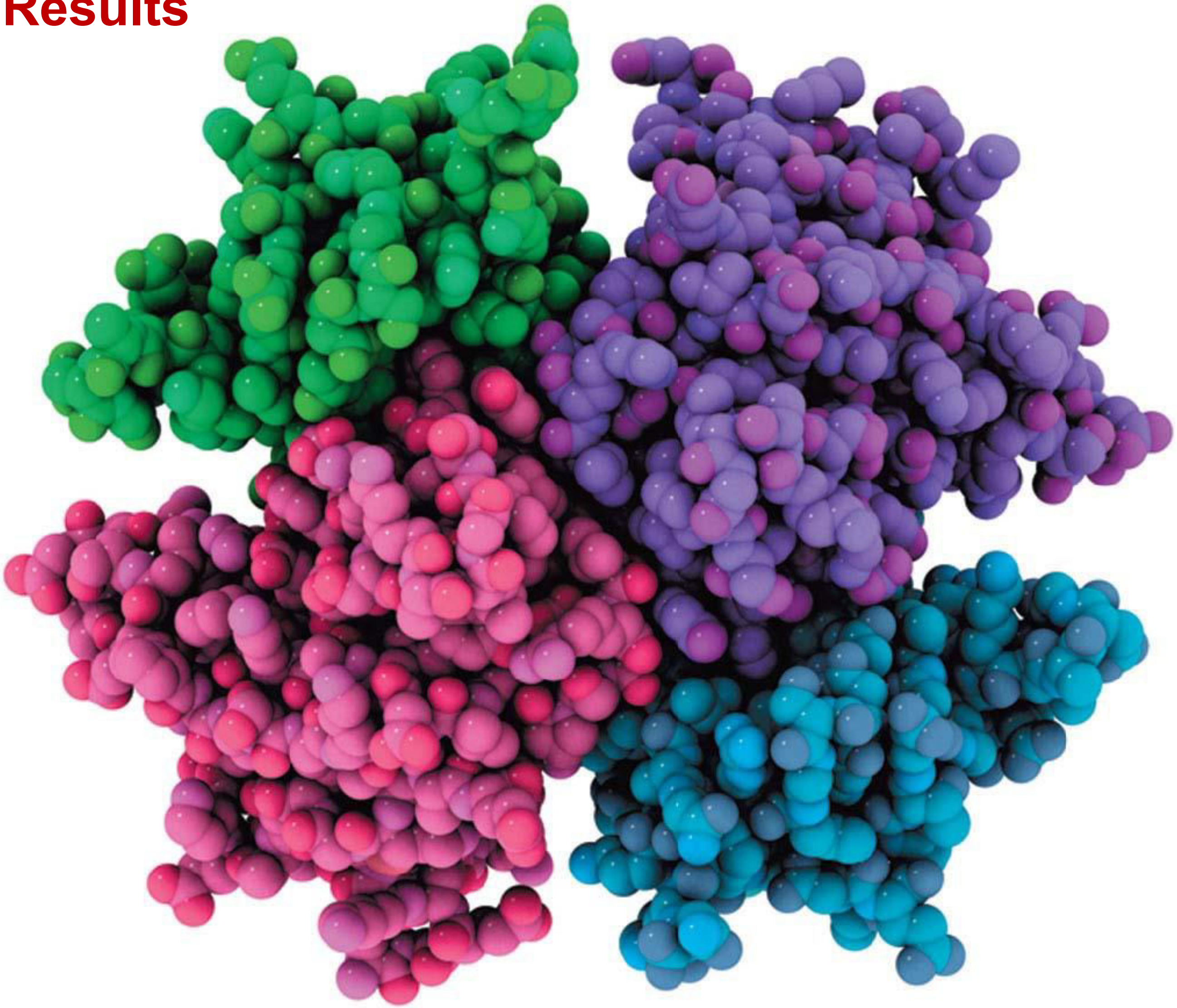

Technique
Diffracted
X-rays
X-ray
source
X-ray
beam
Crystal
Digital
detector
X-ray diffraction
pattern

Figure 3.25-2

Results



Concept 3.6: Nucleic acids store, transmit, and help express hereditary information

- The amino acid sequence of a polypeptide is programmed by a unit of inheritance called a **gene**
- Genes are made of DNA, a **nucleic acid** made of monomers called nucleotides

The Roles of Nucleic Acids

- There are two types of nucleic acids
  - **Deoxyribonucleic acid** (**DNA**)
  - **Ribonucleic acid** (**RNA**)
- DNA provides directions for its own replication
- DNA also directs synthesis of messenger RNA (mRNA) and, through mRNA, controls protein synthesis

Figure 3.26-s1

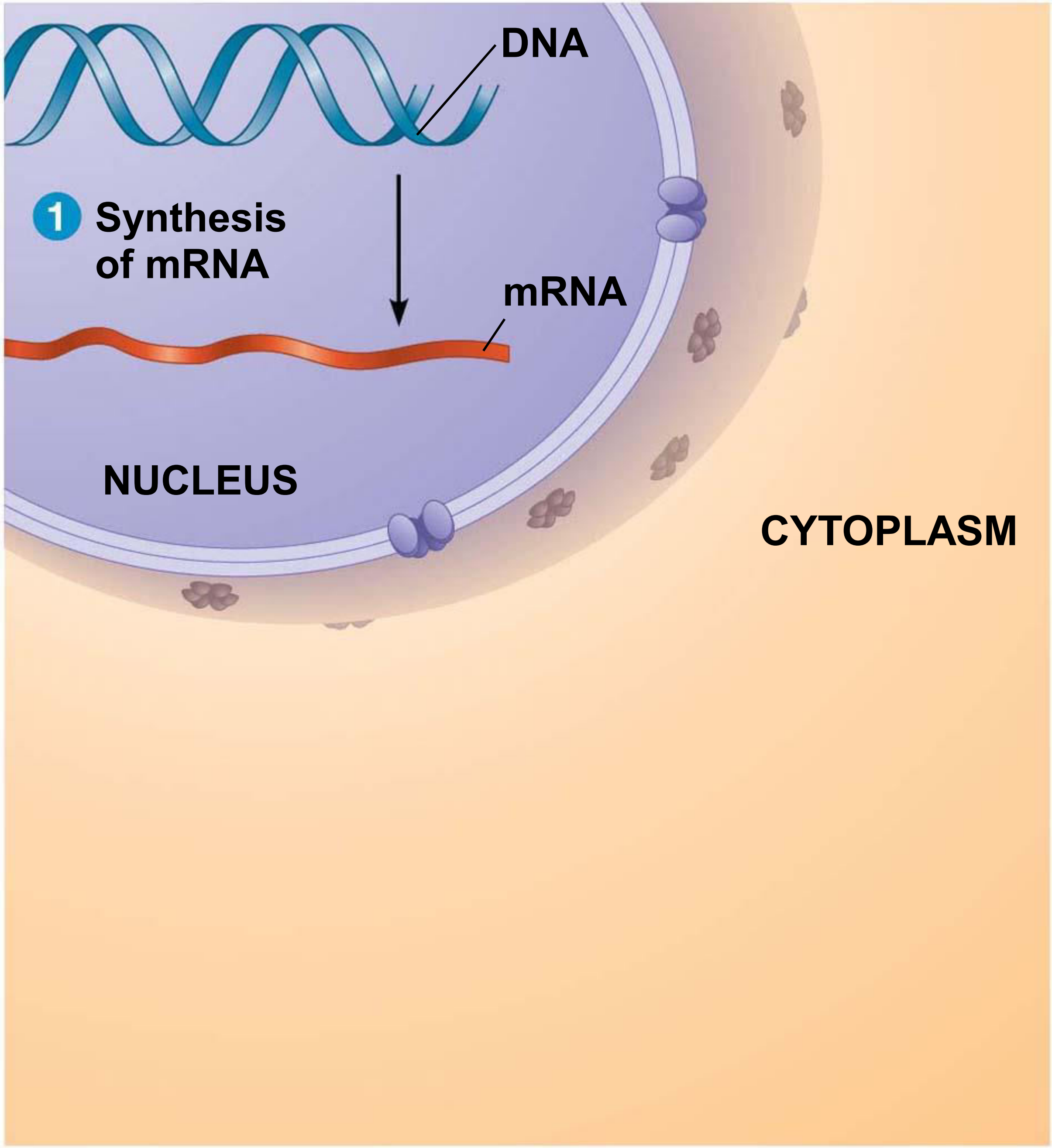


Figure 3.26-s2

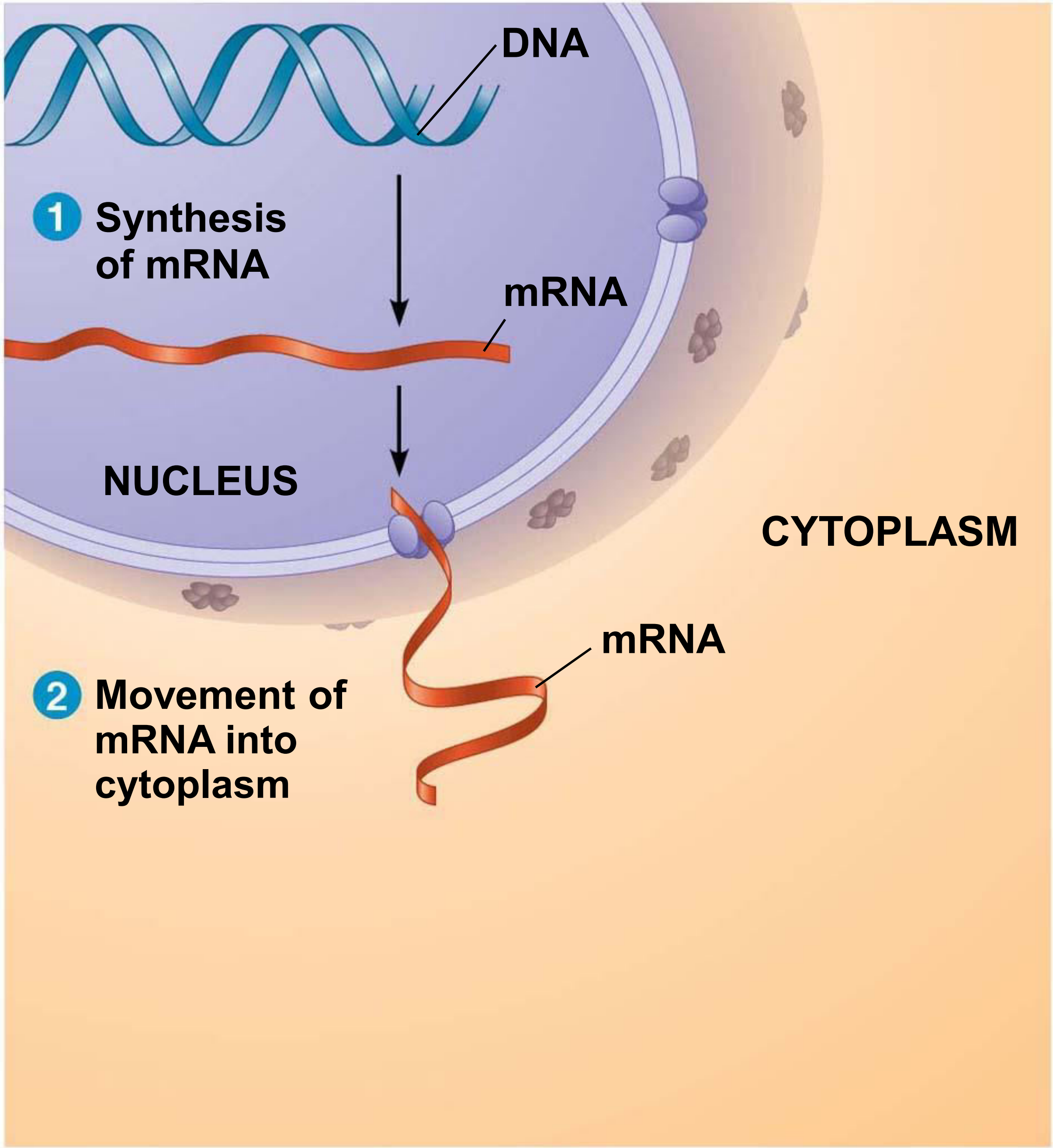
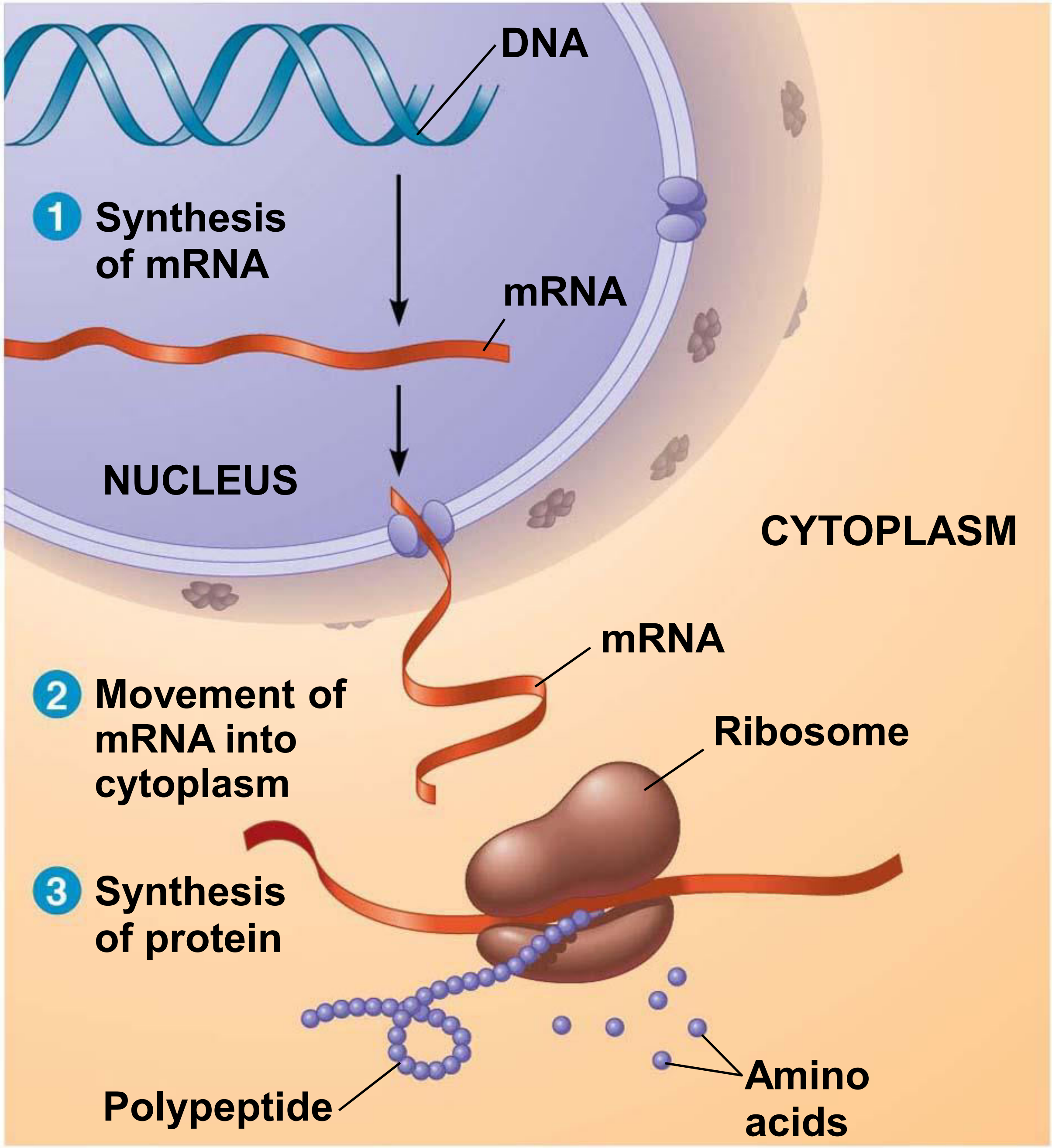


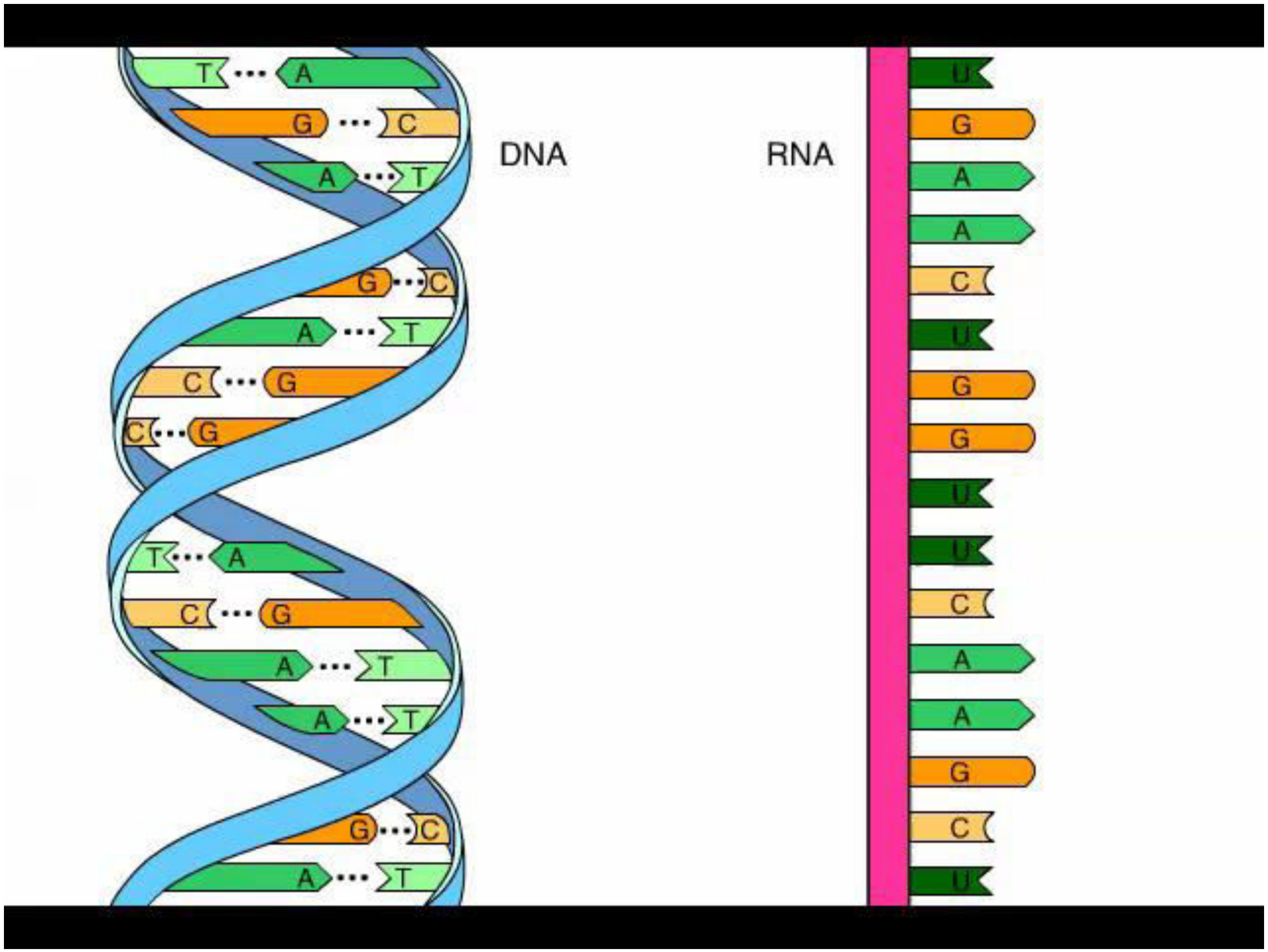
Figure 3.26-s3



The Components of Nucleic Acids

- Nucleic acids are polymers called **polynucleotides**
- Each polynucleotide is made of monomers called **nucleotides**
- Each nucleotide consists of a nitrogenous base, a pentose sugar, and one or more phosphate groups
- The portion of a nucleotide without the phosphate group is called a nucleoside

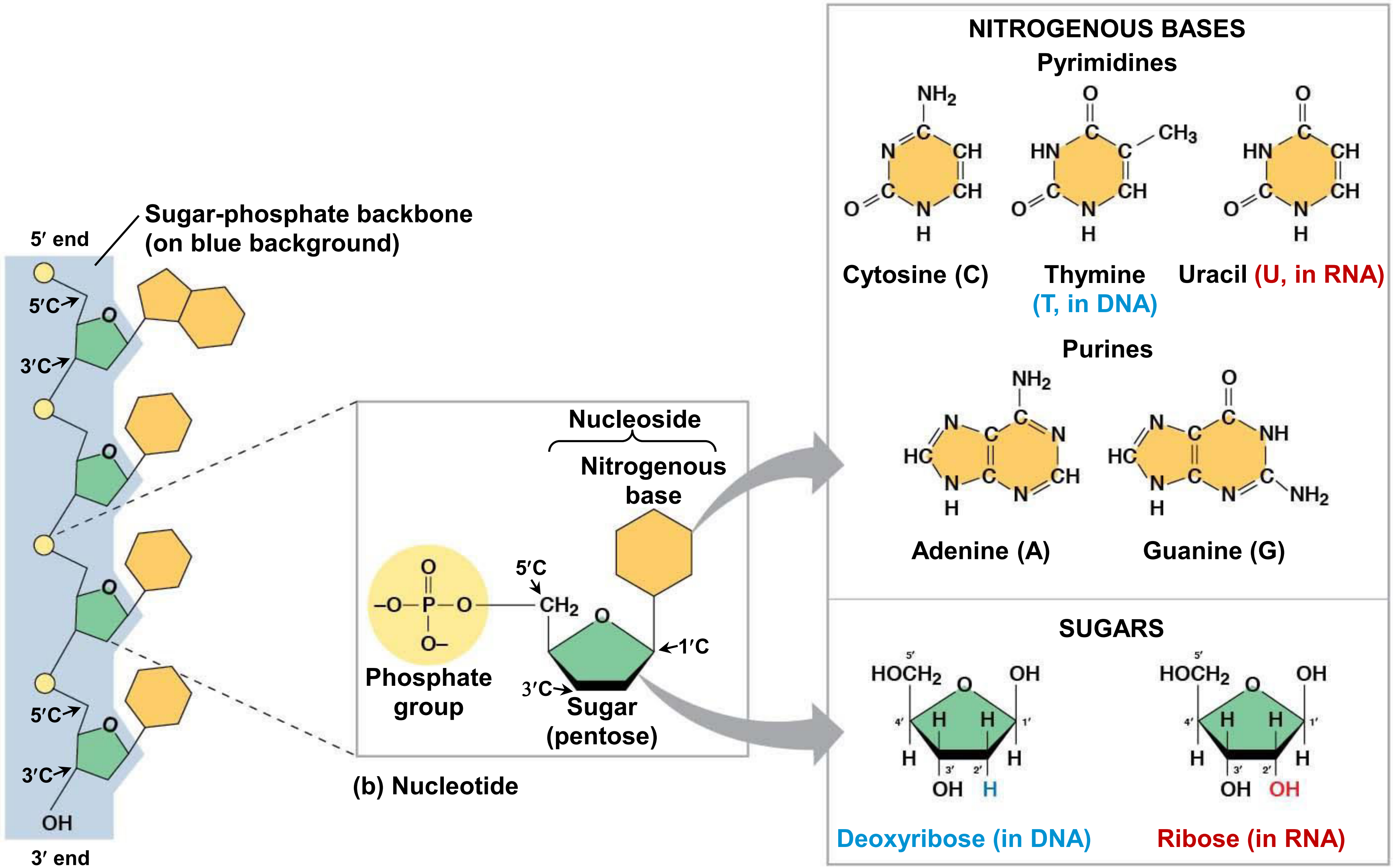
Animation: DNA and RNA Structure



- Each nitrogenous base has one or two rings that include nitrogen atoms
- There are two families of nitrogenous bases
  - **Pyrimidines** include cytosine (C), thymine (T), and uracil (U)
  - **Purines** include adenine (A) and guanine (G)
- Thymine is found only in DNA, and uracil only in RNA; the rest are found in both DNA and RNA

- The sugar in DNA is **deoxyribose**; in RNA it is **ribose**
- A prime (′) is used to identify the carbon atoms in the ribose, such as the 2′ carbon or 5′ carbon
- A nucleoside with at least one phosphate attached is a nucleotide

Figure 3.27

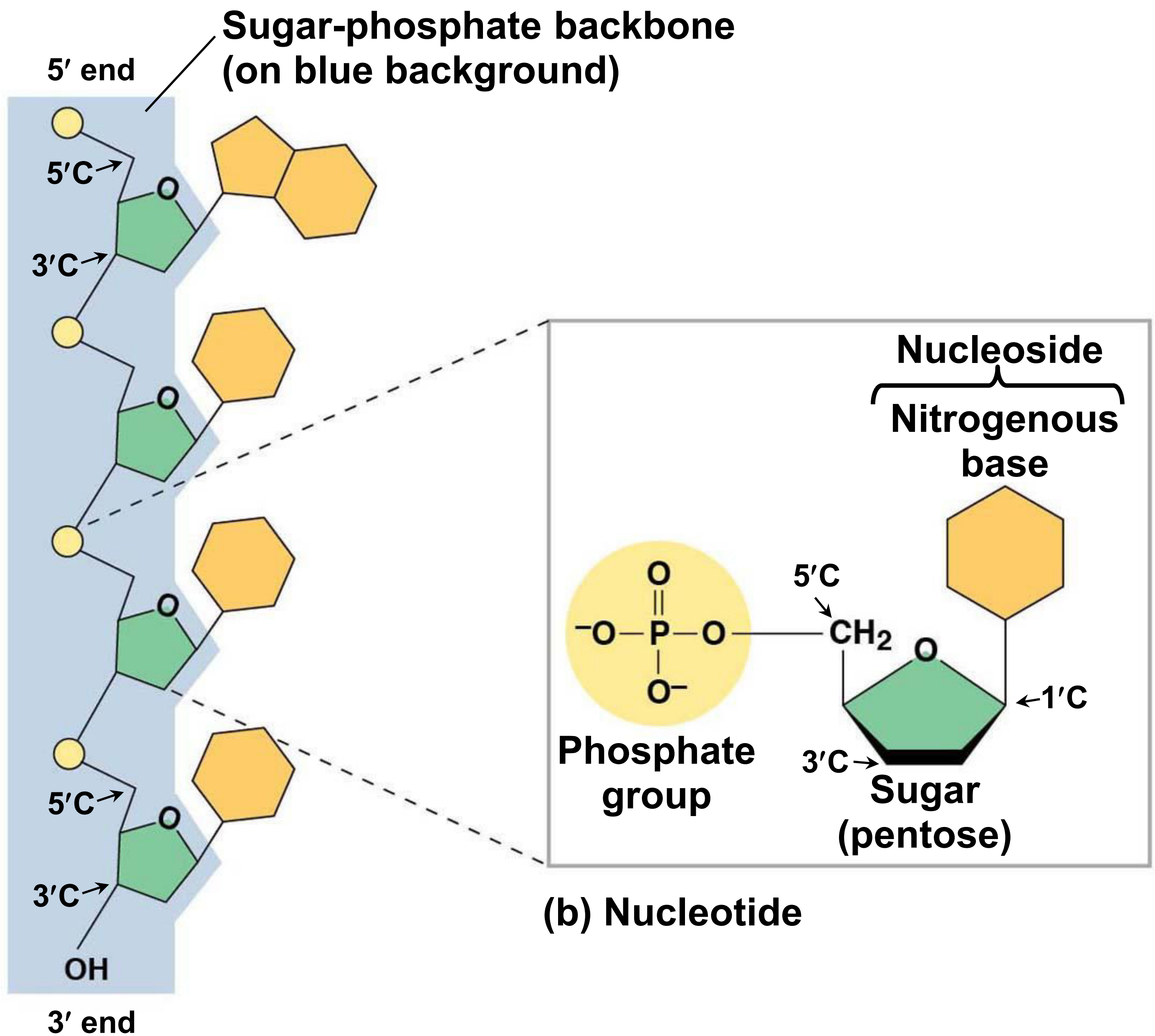


(a) Polynucleotide, or nucleic acid

(b) Nucleotide

(c) Nucleoside components

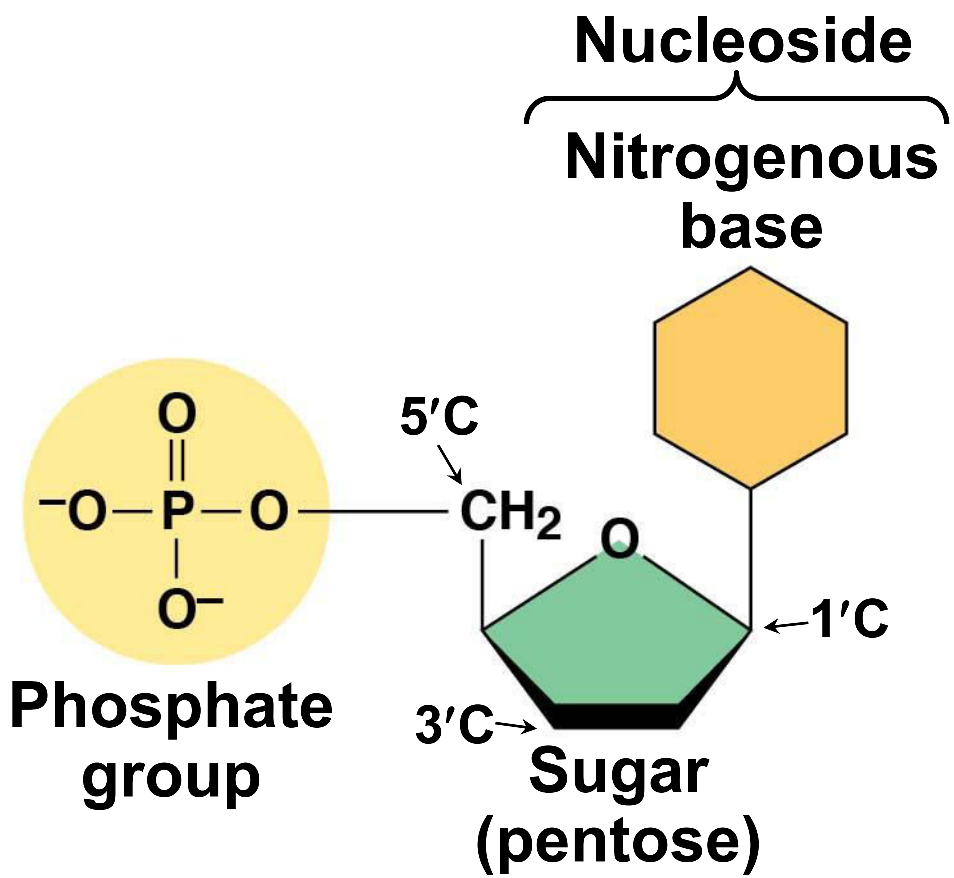
Figure 3.27-1



(b) Nucleotide

(a) Polynucleotide, or nucleic acid

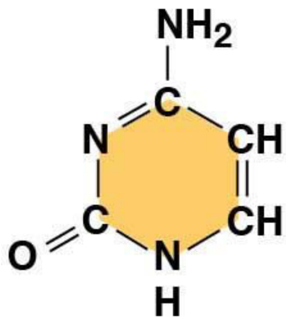
Figure 3.27-2



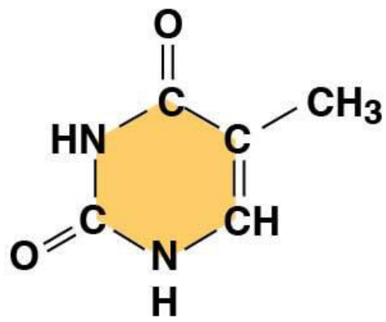
(b) Nucleotide

NITROGENOUS BASES

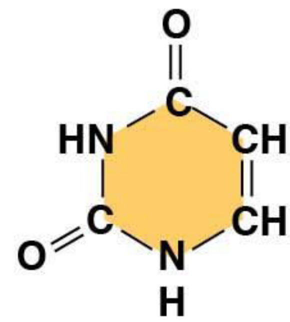
Pyrimidines



Cytosine (C)

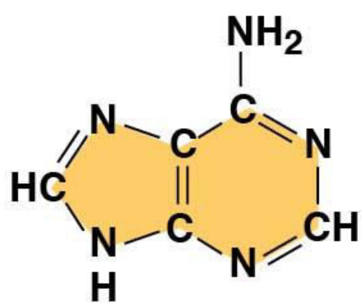


Thymine
(T, in DNA)

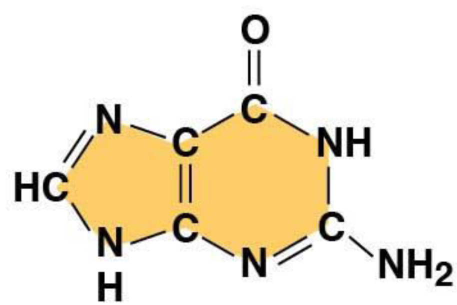


Uracil (U, in RNA)

Purines

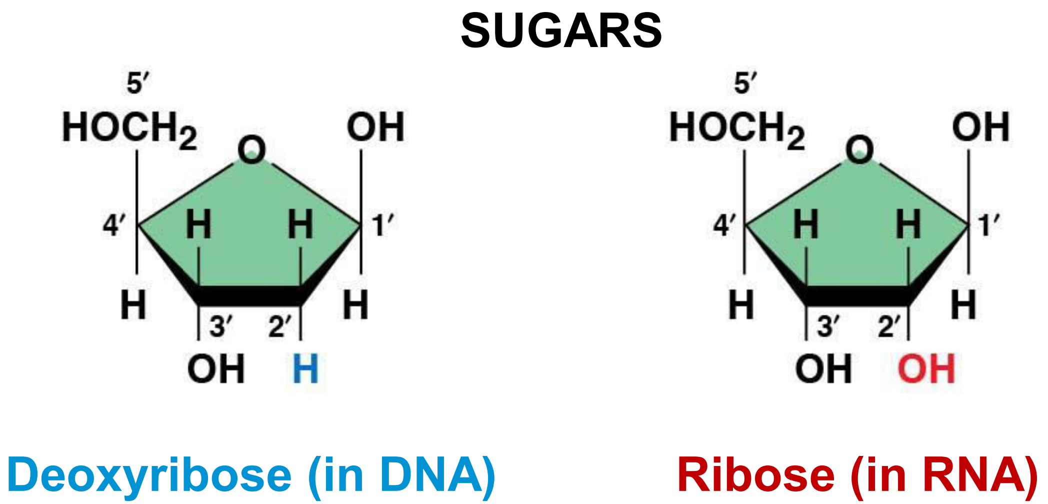


Adenine (A)



Guanine (G)

(c) Nucleoside components



(c) Nucleoside components

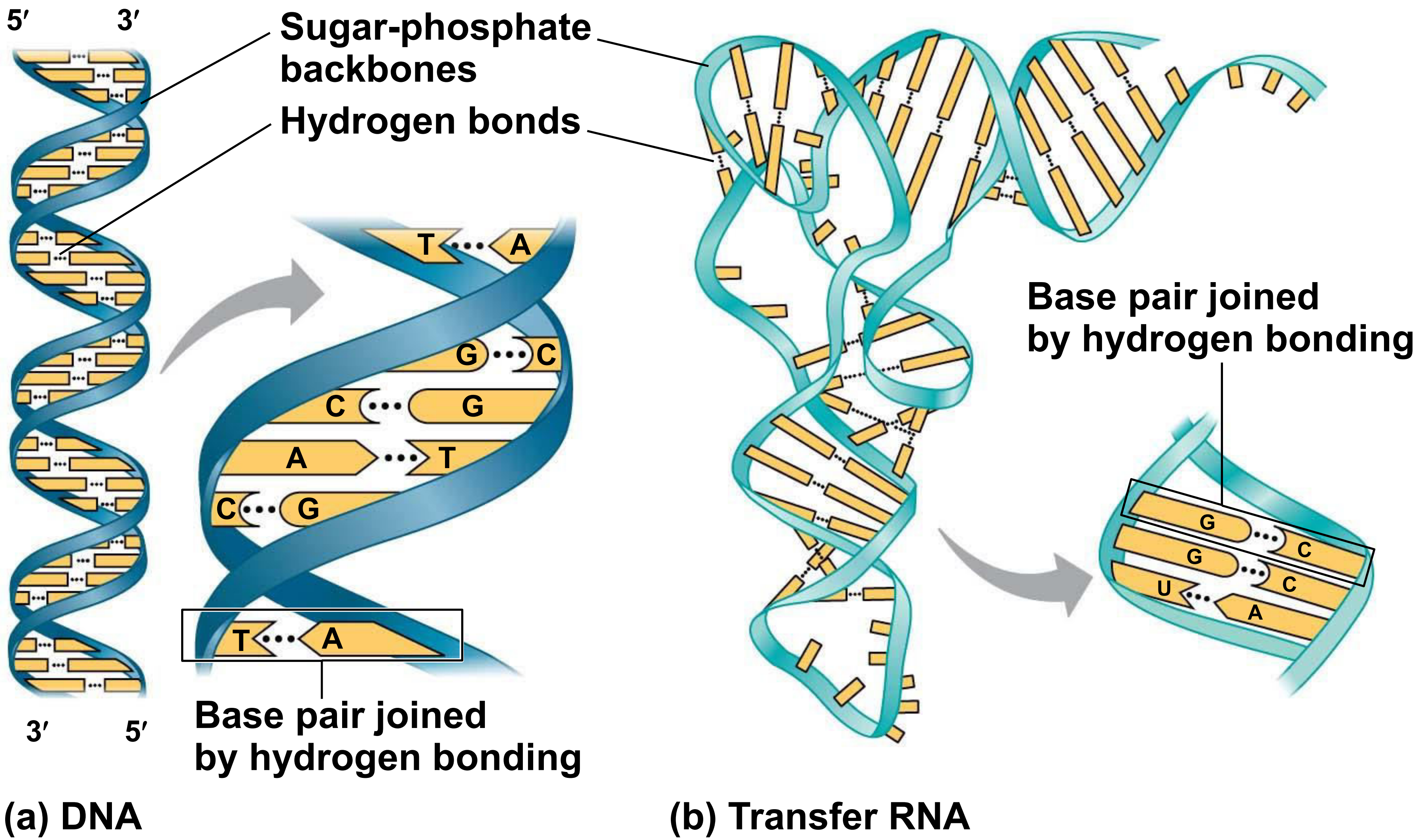
Nucleotide Polymers

- Adjacent nucleotides are joined by covalent bonds between the —OH group on the 3′ carbon of one nucleotide and the phosphate on the 5′ carbon of the next
- These links create a backbone of sugar-phosphate units with nitrogenous bases as appendages
- The sequence of bases along a DNA or mRNA polymer is unique for each gene

The Structures of DNA and RNA Molecules

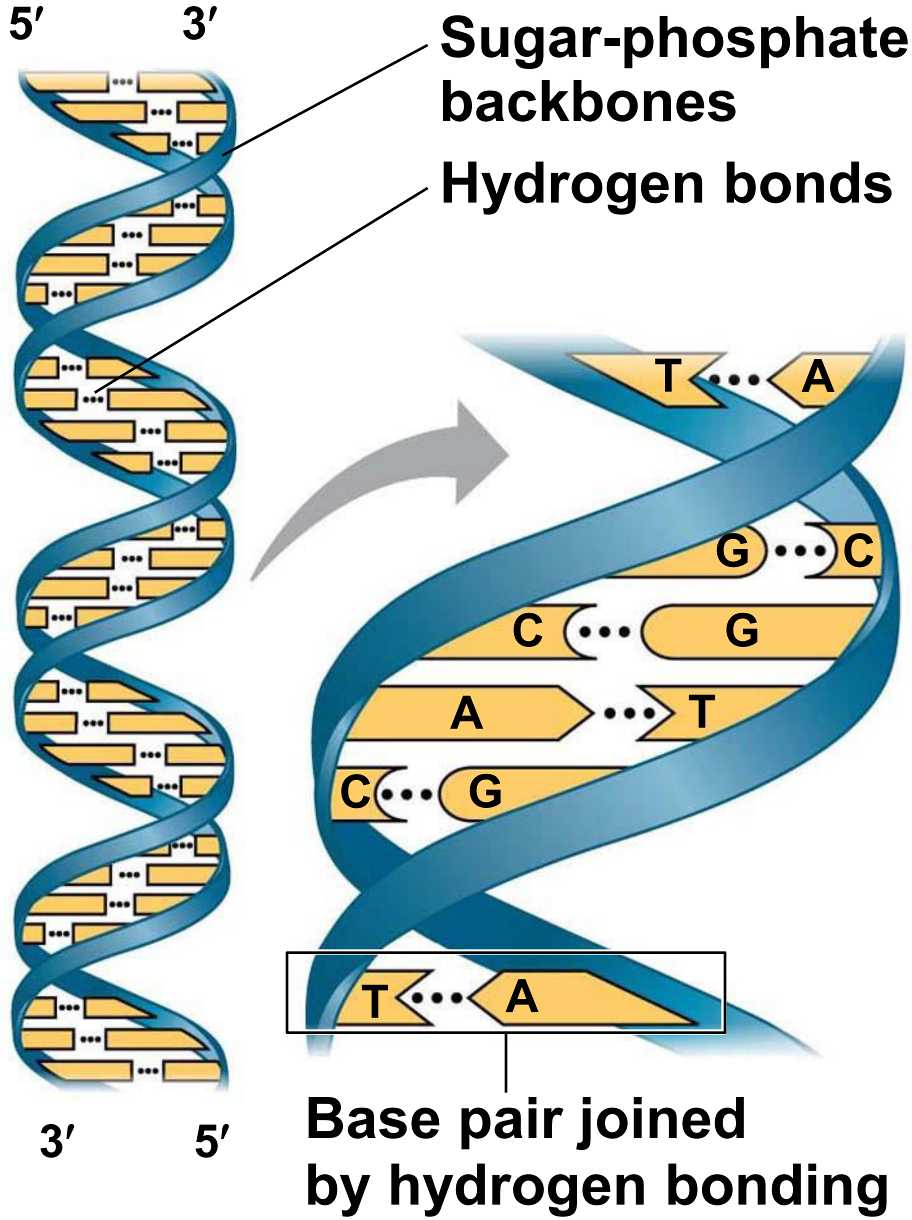
- RNA molecules usually exist as single polypeptide chains
- DNA molecules have two polynucleotides spiraling around an imaginary axis, forming a **double helix**
- In the DNA double helix, the two backbones run in opposite $5' \rightarrow 3'$ directions from each other, an arrangement referred to as **antiparallel**
- One DNA molecule includes many genes

Figure 3.28



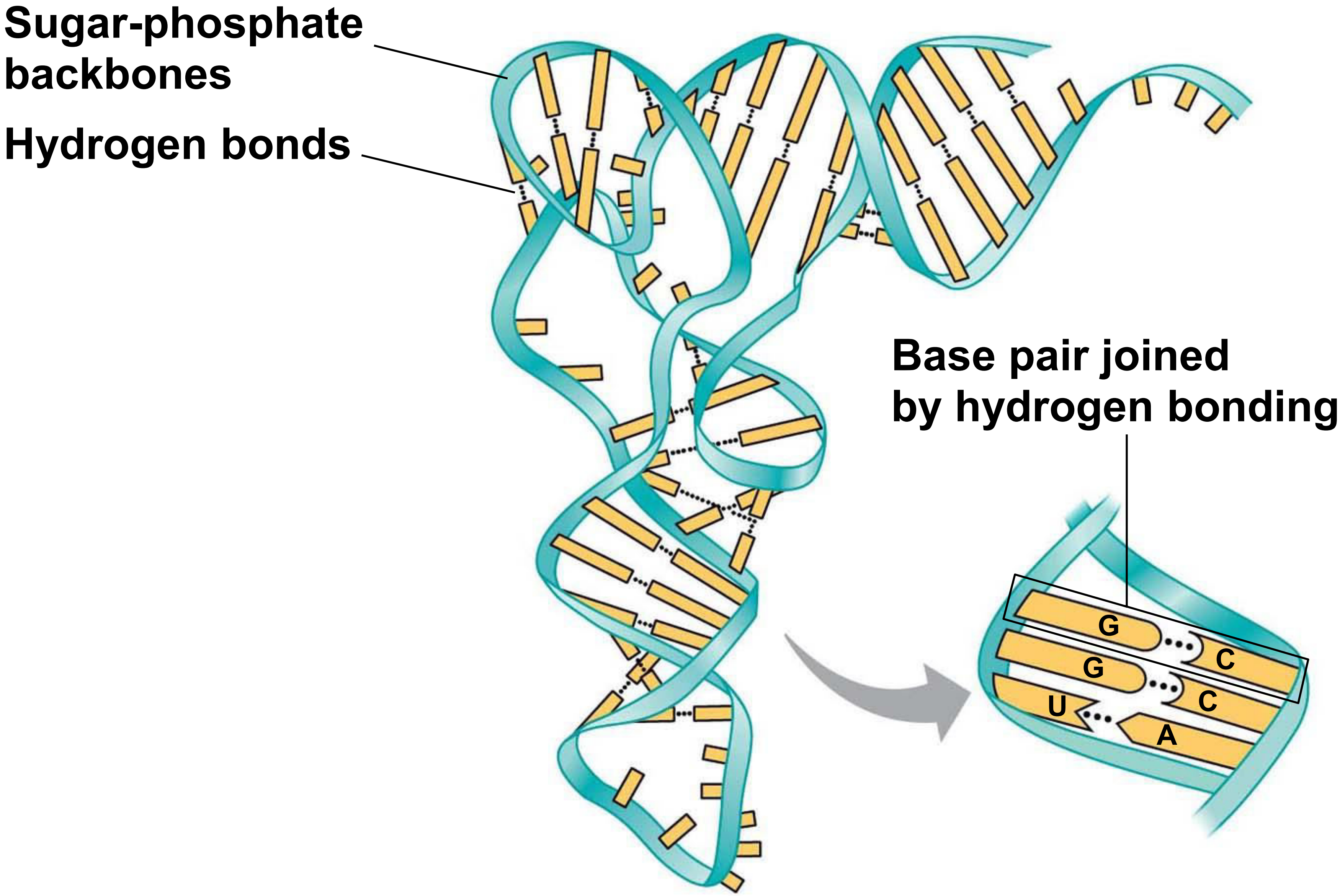
5′
3′
Sugar-phosphate backbones
Hydrogen bonds
T A
G C
C G
A T
C G
T A
Base pair joined by hydrogen bonding
3′
5′
(a) DNA
Base pair joined by hydrogen bonding
G C
G C
U A
(b) Transfer RNA

Figure 3.28-1



(a) DNA

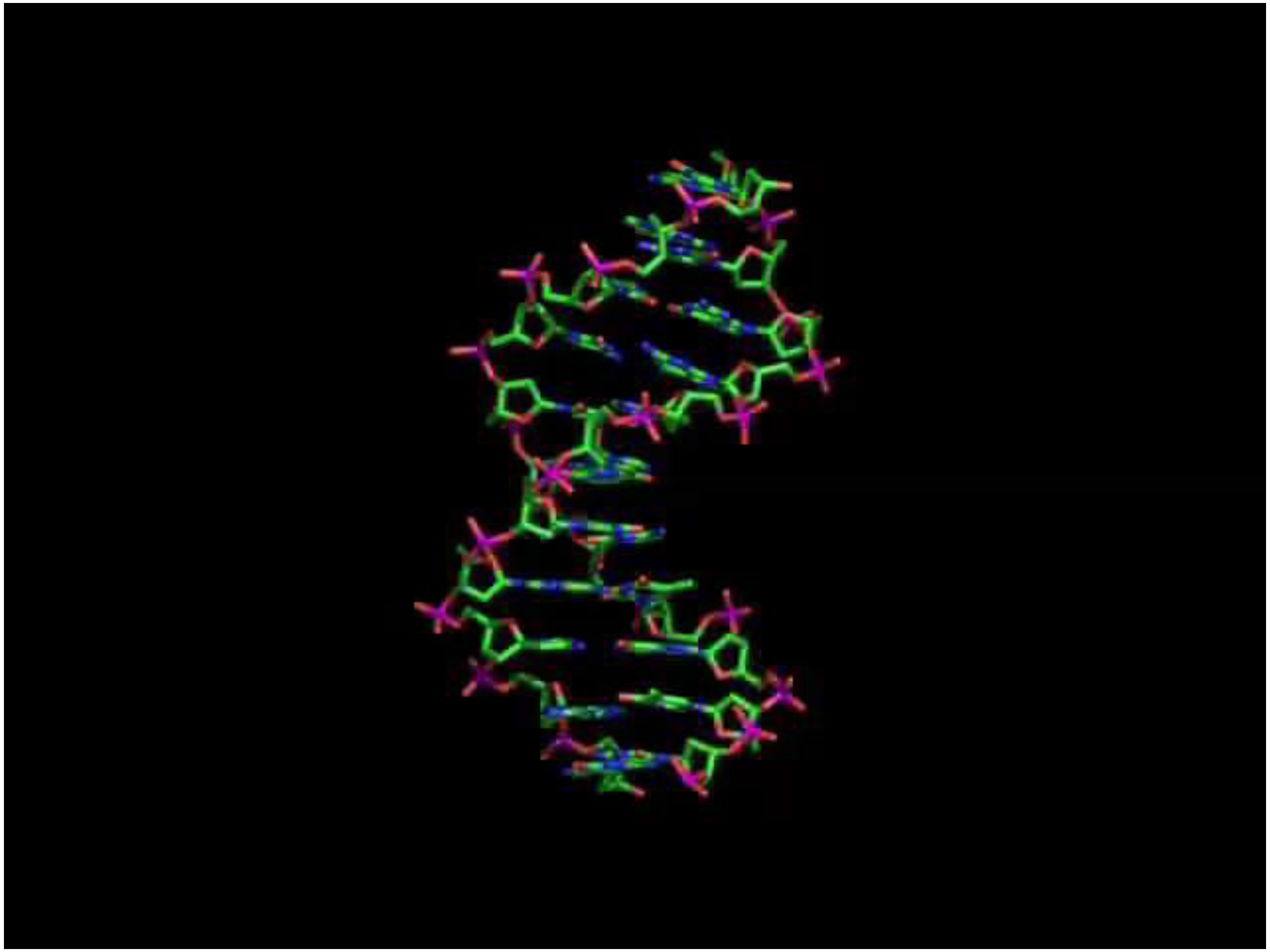
Figure 3.28-2



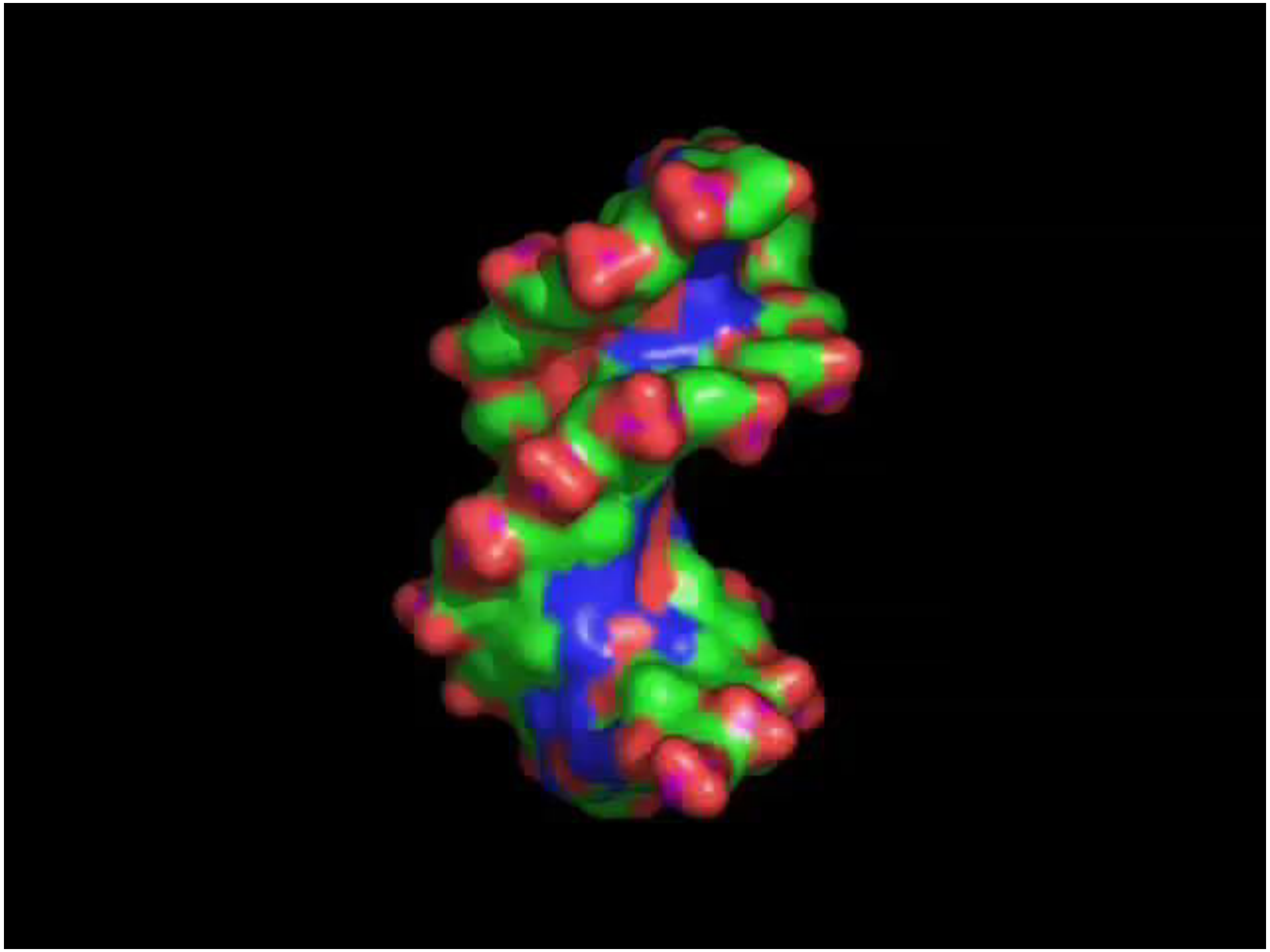
(b) Transfer RNA

Animation: DNA Double Helix

Video: DNA Stick Model



Video: DNA Surface Model



- The nitrogenous bases in DNA pair up and form hydrogen bonds: adenine (A) always with thymine (T), and guanine (G) always with cytosine (C)
- This is called complementary base pairing
- Complementary pairing can also occur between two RNA molecules or between parts of the same molecule
- In RNA, thymine is replaced by uracil (U), so A and U pair

Concept 3.7: Genomics and proteomics have transformed biological inquiry and applications

- The Human Genome Project was effectively completed in the early 2000s
- An unplanned benefit of the project was the development of faster, less expensive sequencing methods
- The first human genome took over 10 years to sequence
- Currently, a human genome could be completed in just a few days

Figure 3.29

- The number of genomes that have been fully sequenced has generated enormous amounts of data
- Bioinformatics is the use of computer software and other tools to analyze the data
- **Genomics** is the approach used to analyze large sets of genes or compare the genomes of different species
- Similar analysis of proteins is called **proteomics**

Figure 3.30

MAKE CONNECTIONS: Contributions of Genomics and Proteomics to Biology

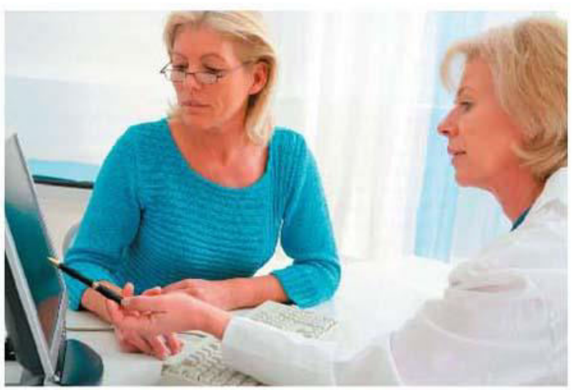
Paleontology

Evolution

Hippopotamus

Short-finned pilot whale

Medical Science



Conservation Biology

Species Interactions

Figure 3.30-1

Paleontology

Evolution

Hippopotamus

Short-finned pilot whale

Figure 3.30-2a

Evolution

Hippopotamus

Evolution

Short-finned pilot whale

Figure 3.30-3

Medical Science

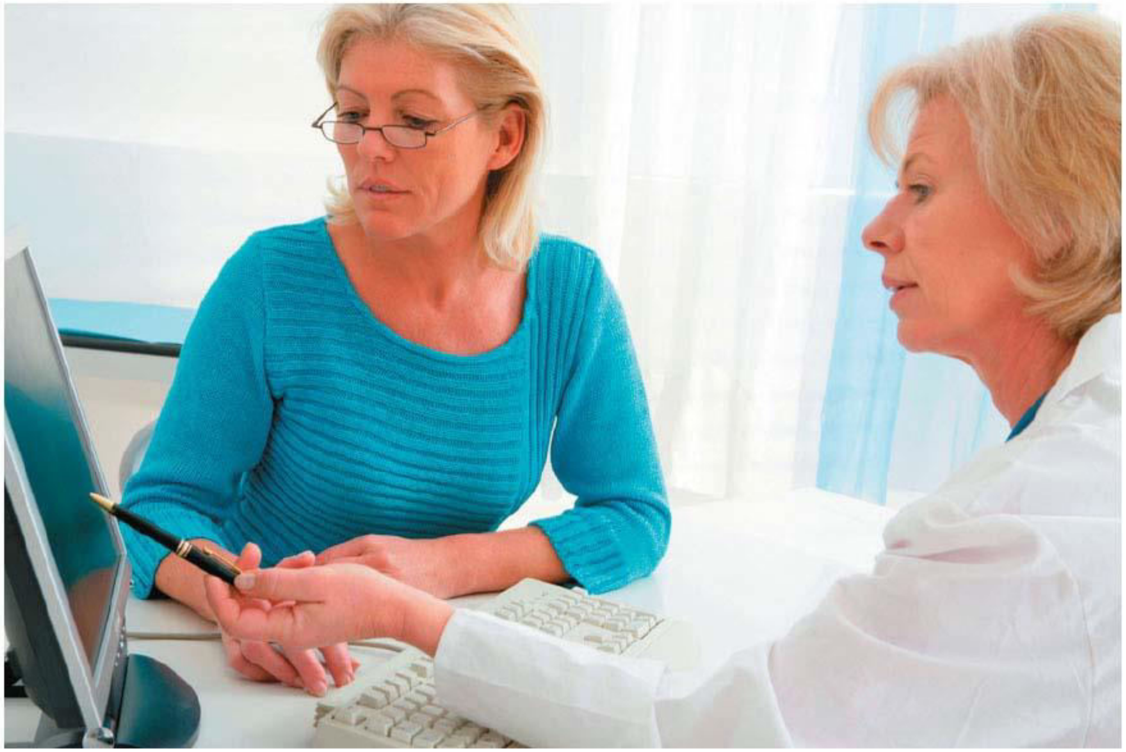
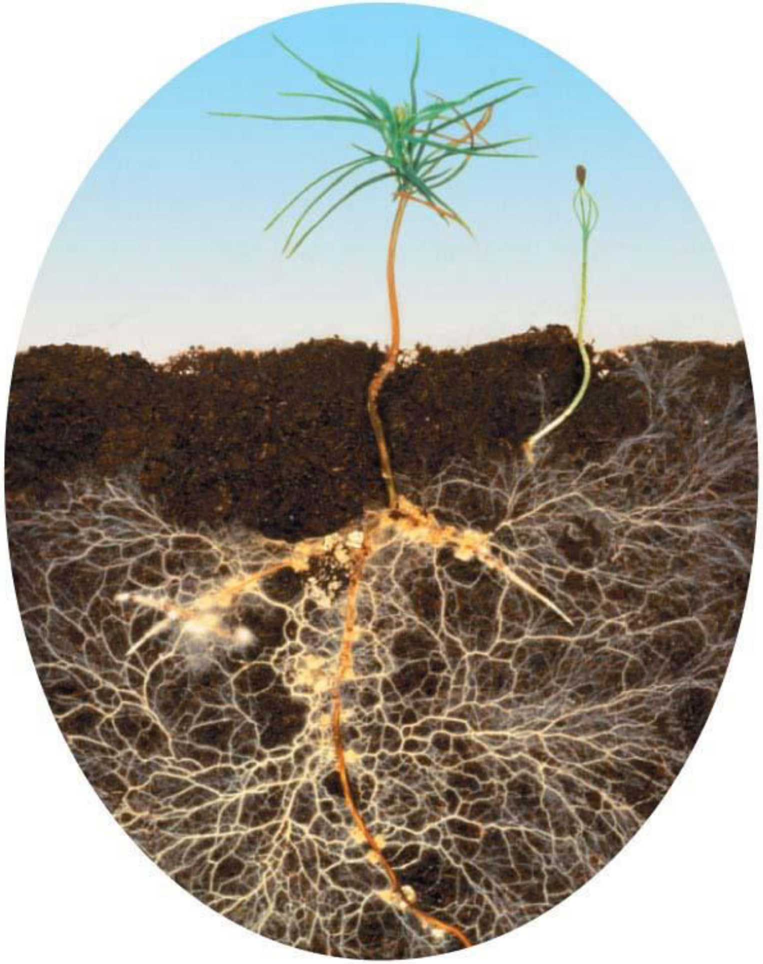


Figure 3.30-4

Conservation Biology

Figure 3.30-5

Species Interactions



DNA and Proteins as Tape Measures of Evolution

- The linear sequences of nucleotides in DNA molecules are passed from parents to offspring
- Two closely related species are more similar in DNA than are more distantly related species
- Molecular biology can be used to assess evolutionary kinship

Figure 3.UN04

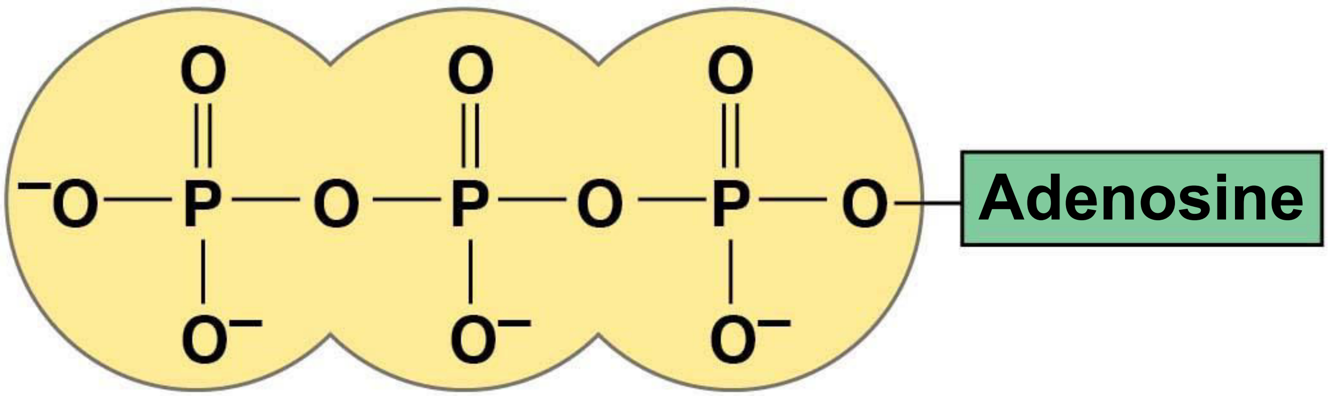


Figure 3.UN05

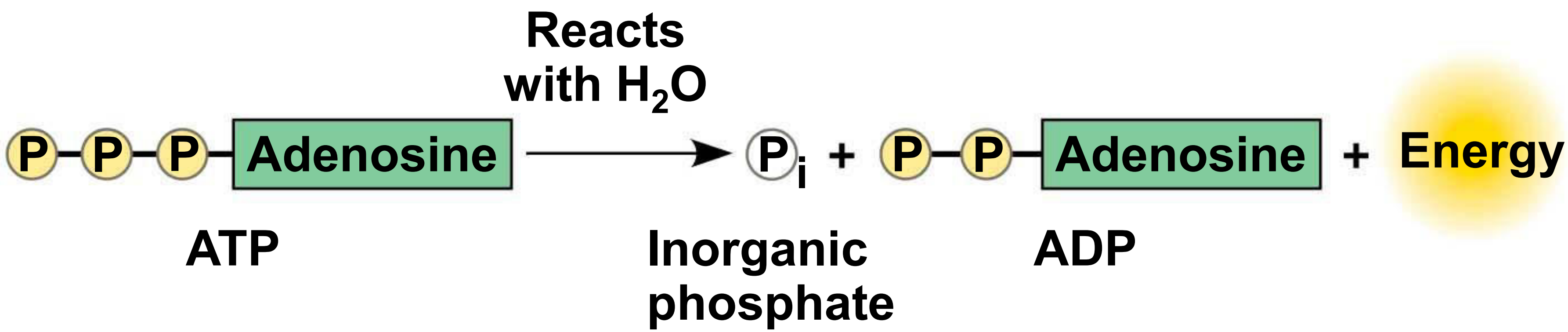


Figure 3.UN06

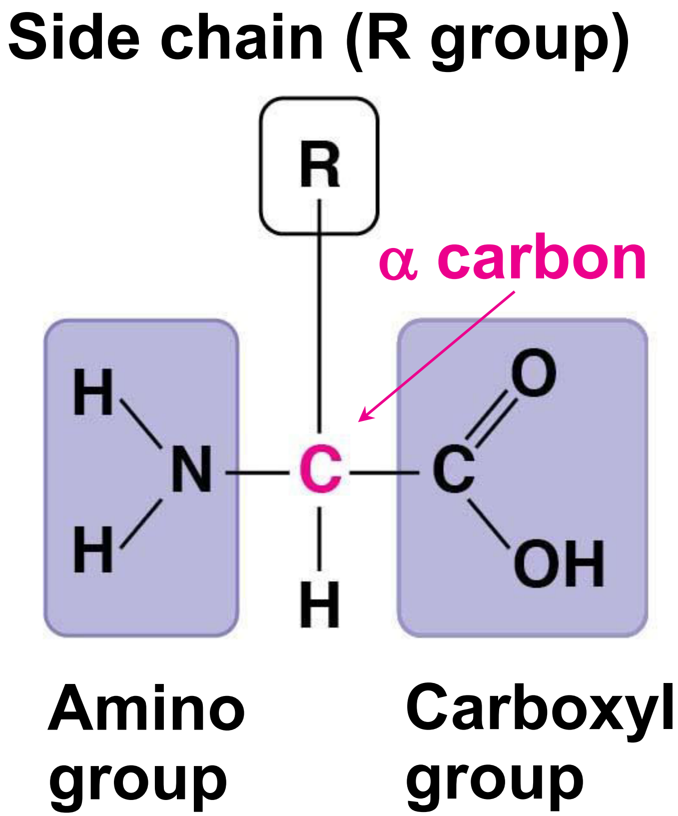
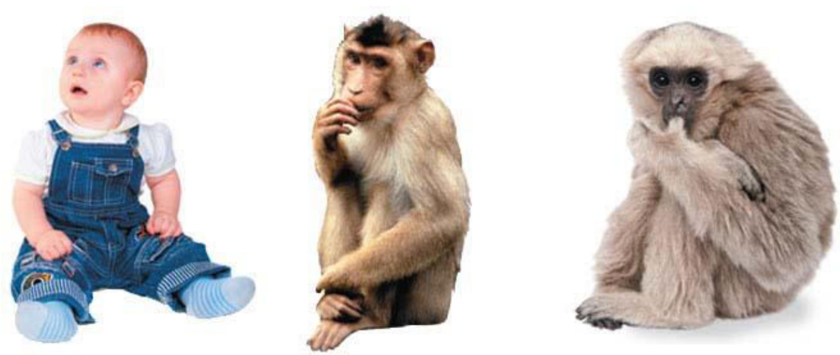


Figure 3.UN07-1

Species	Alignment of Amino Acid Sequences of β-globin
Human	1 VHLTPEEKSA VTALWGKVNV DEVGGEALGR LLVVYPWTQR FFESFGDLST
Monkey	1 VHLTPEEKNA VTTLWGKVNV DEVGGEALGR LLLVYPWTQR FFESFGDLSS
Gibbon	1 VHLTPEEKSA VTALWGKVNV DEVGGEALGR LLVVYPWTQR FFESFGDLST
Human	51 PDAVMGNPKV KAHGKKVLGA FSDGLAHLDN LKGTFATLSE LHCDKLHVDP
Monkey	51 PDAVMGNPKV KAHGKKVLGA FSDGLNHLDN LKGTFAQLSE LHCDKLHVDP
Gibbon	51 PDAVMGNPKV KAHGKKVLGA FSDGLAHLDN LKGTFAQLSE LHCDKLHVDP
Human	101 ENFRLLGNVL VCVLAHHFGK EFTPPVQAAY QKVVAGVANA LAHKYH
Monkey	101 ENFKLLGNVL VCVLAHHFGK EFTPQVQAAY QKVVAGVANA LAHKYH
Gibbon	101 ENFRLLGNVL VCVLAHHFGK EFTPQVQAAY QKVVAGVANA LAHKYH

Data from Human: http://www.ncbi.nlm.nih.gov/protein/AAA21113.1; rhesus monkey: http://www.ncbi.nlm.nih.gov/ protein/122634; gibbon: http://www.ncbi.nlm.nih.gov/protein/122616

Figure 3.UN07-2



▲ **Human** ▲ **Rhesus monkey** ▲ **Gibbon**

Figure 3.UN08

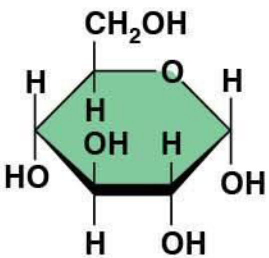
Components	Examples	Functions
 Monosaccharide monomer	Monosaccharides: glucose, fructose	Fuel; carbon sources that can be converted to other molecules or combined into polymers
	Disaccharides: lactose, sucrose	
	Polysaccharides: • Cellulose (plants) • Starch (plants) • Glycogen (animals) • Chitin (animals and fungi)	• Strengthens plant cell walls • Stores glucose for energy • Stores glucose for energy • Strengthens exoskeletons and fungal cell walls

Figure 3.UN09

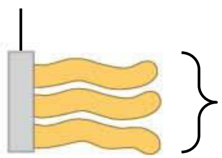
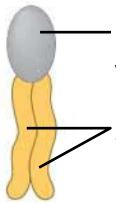
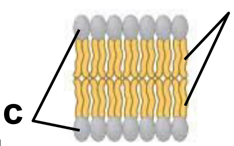
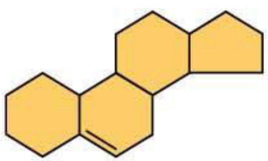
Components	Examples	Functions
	Triacylglycerols (fats or oils): glycerol + three fatty acids	Important energy source  
	Phospholipids: glycerol + phosphate group + two fatty acids	Lipid bilayers of membranes 
	Steroids: four fused rings with attached chemical groups	• Component of cell membranes (cholesterol) • Signaling molecules that travel through the body (hormones)

Figure 3.UN10

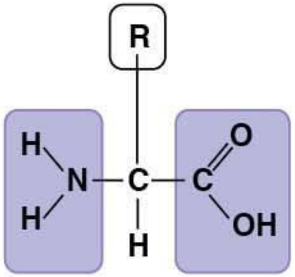
Components	Examples	Functions
 Amino acid monomer (20 types)	• Enzymes • Structural proteins • Storage proteins • Transport proteins • Hormones • Receptor proteins • Motor proteins • Defensive proteins	• Catalyze chemical reactions • Provide structural support • Store amino acids • Transport substances • Coordinate organismal responses • Receive signals from outside cell • Function in cell movement • Protect against disease

Figure 3.UN11

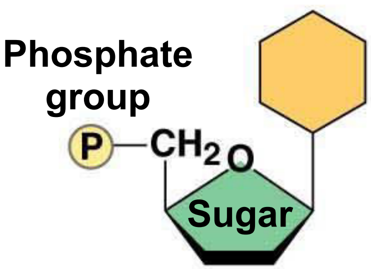
Components	Examples	Functions
Nitrogenous base  Nucleotide monomer	DNA:  • Sugar = deoxyribose • Nitrogenous bases = C, G, A, T • Usually double-stranded	Stores hereditary information
	RNA:  • Sugar = ribose • Nitrogenous bases = C, G, A, U • Usually single-stranded	Various functions in gene expression, including carrying instructions from DNA to ribosomes

Figure 3.UN12

Das Bild kann zurzeit nicht angezeigt werden.

Figure 3.UN13

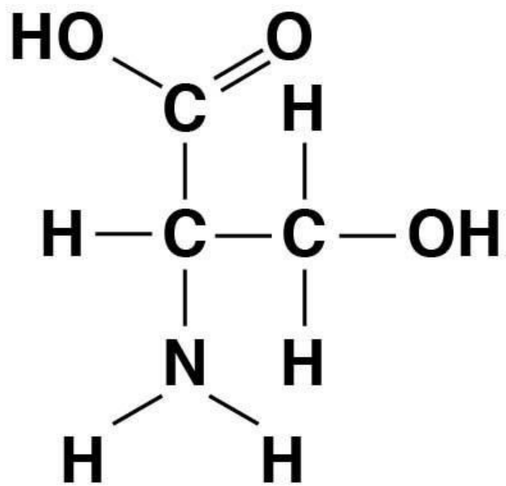


Figure 3.UN14

CAMPBELL BIOLOGY IN FOCUS

URRY • CAIN • WASSERMAN • MINORSKY • REECE

2

The Chemical Context of Life

Lecture Presentations by
Kathleen Fitzpatrick and
Nicole Tunbridge,
Simon Fraser University

SECOND EDITION

Overview: A Chemical Connection to Biology

- Biology is a multidisciplinary science
- Living organisms are subject to basic laws of physics and chemistry

Figure 2.1

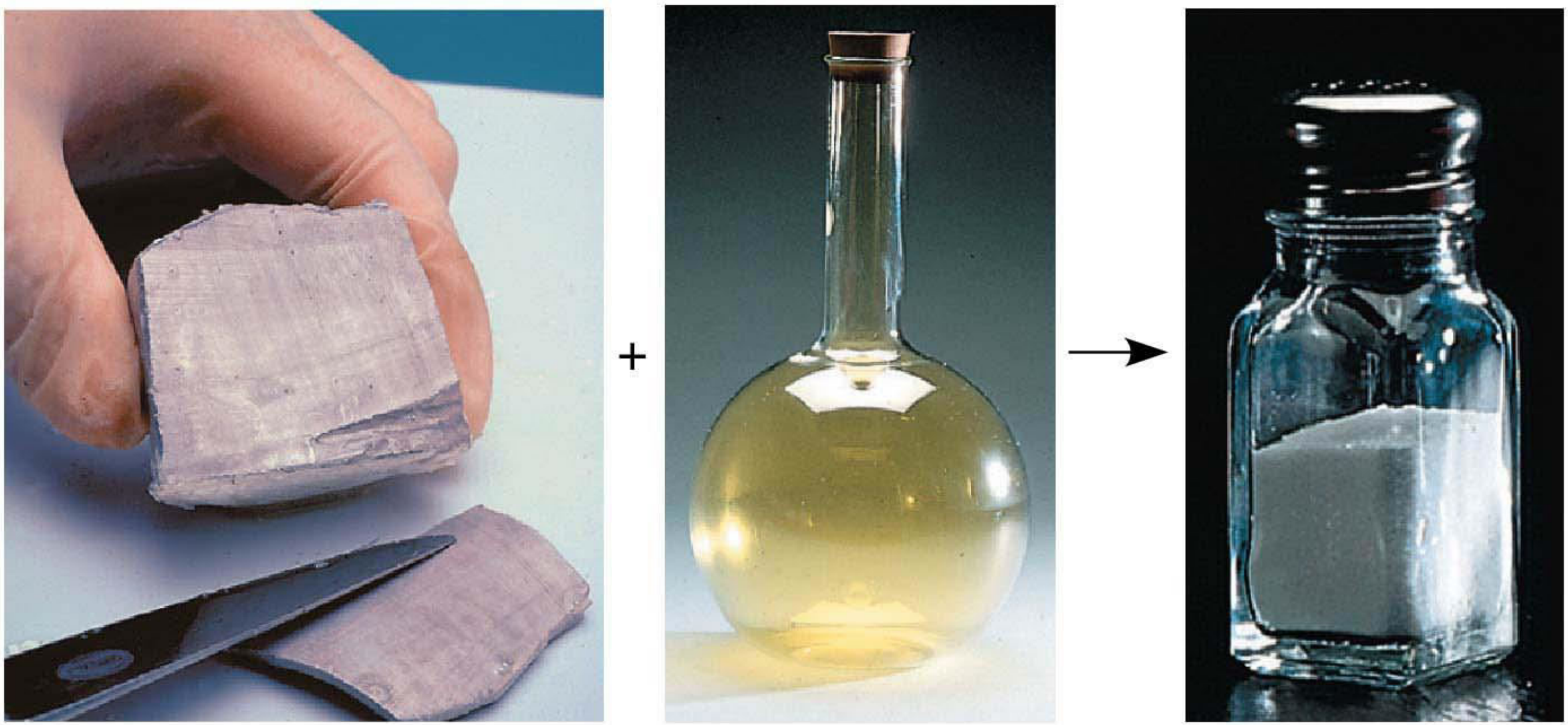
Concept 2.1: Matter consists of chemical elements in pure form and in combinations called compounds

- Organisms are composed of **matter**
- Matter is anything that takes up space and has mass

Elements and Compounds

- Matter is made up of elements
- An **element** is a substance that cannot be broken down to other substances by chemical reactions
- A **compound** is a substance consisting of two or more elements in a fixed ratio
- A compound has emergent properties, characteristics different from those of its elements

Figure 2.2

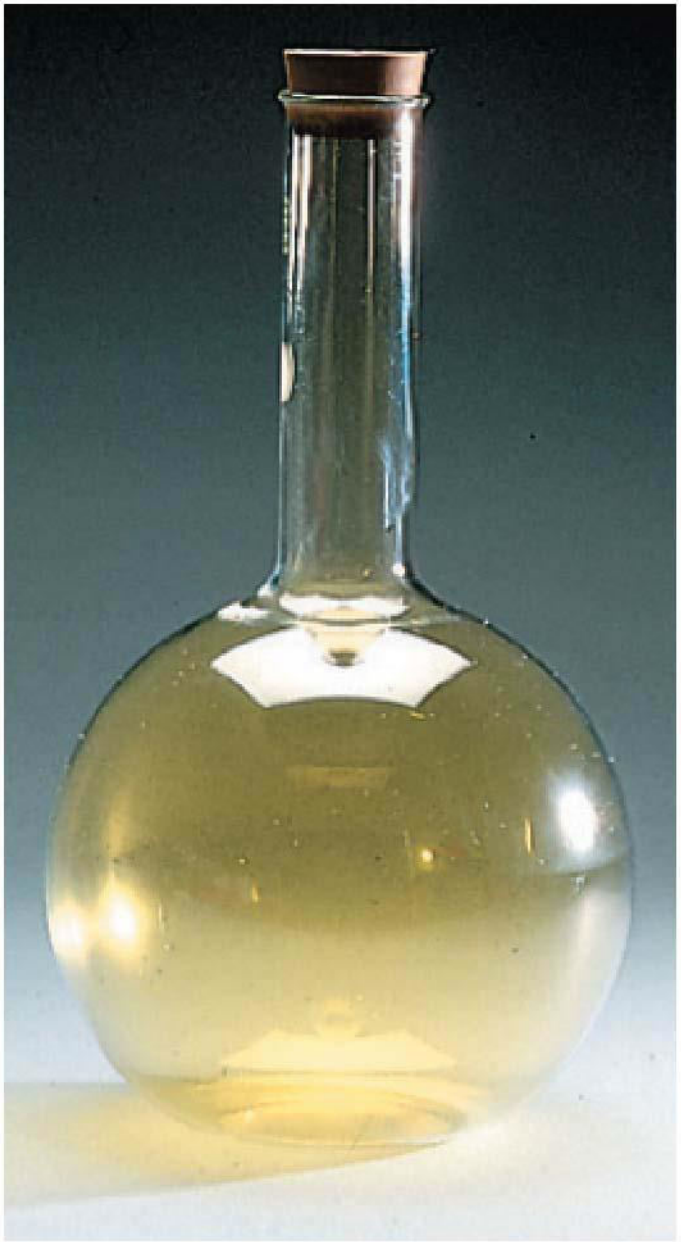


Sodium Chlorine Sodium chloride

Figure 2.2-1

Sodium

Figure 2.2-2



Chlorine

Figure 2.2-3

Sodium chloride

The Elements of Life

- Of 92 natural elements, about 20–25% are **essential elements**, needed by an organism to live a healthy life and reproduce
- **Trace elements** are required in only minute quantities
- For example, in vertebrates, iodine (I) is required for normal activity of the thyroid gland
- In humans, an iodine deficiency can cause goiter

Table 2.1

Table 2.1 Elements in the Human Body

Element	Symbol	Percentage of Body Mass (including water)	
Oxygen	O	65.0%	96.3%
Carbon	C	18.5%	
Hydrogen	H	9.5%	
Nitrogen	N	3.3%	
Calcium	Ca	1.5%	3.7%
Phosphorus	P	1.0%	
Potassium	K	0.4%	
Sulfur	S	0.3%	
Sodium	Na	0.2%	
Chlorine	Cl	0.2%	
Magnesium	Mg	0.1%	

Trace elements (less than 0.01% of mass): Boron (B), chromium (Cr), cobalt (Co), copper (Cu), fluorine (F), iodine (I), iron (Fe), manganese (Mn), molybdenum (Mo), selenium (Se), silicon (Si), tin (Sn), vanadium (V), zinc (Zn)

Evolution of Tolerance to Toxic Elements

- Some naturally occurring elements are toxic to organisms
- In humans, arsenic is linked to many diseases and can be lethal
- Some species have become adapted to environments containing elements that are usually toxic
  - For example, sunflower plants can take up lead, zinc, and other heavy metals in concentrations lethal to most organisms
  - Sunflower plants were used to detoxify contaminated soils after Hurricane Katrina

Concept 2.2: An element's properties depend on the structure of its atoms

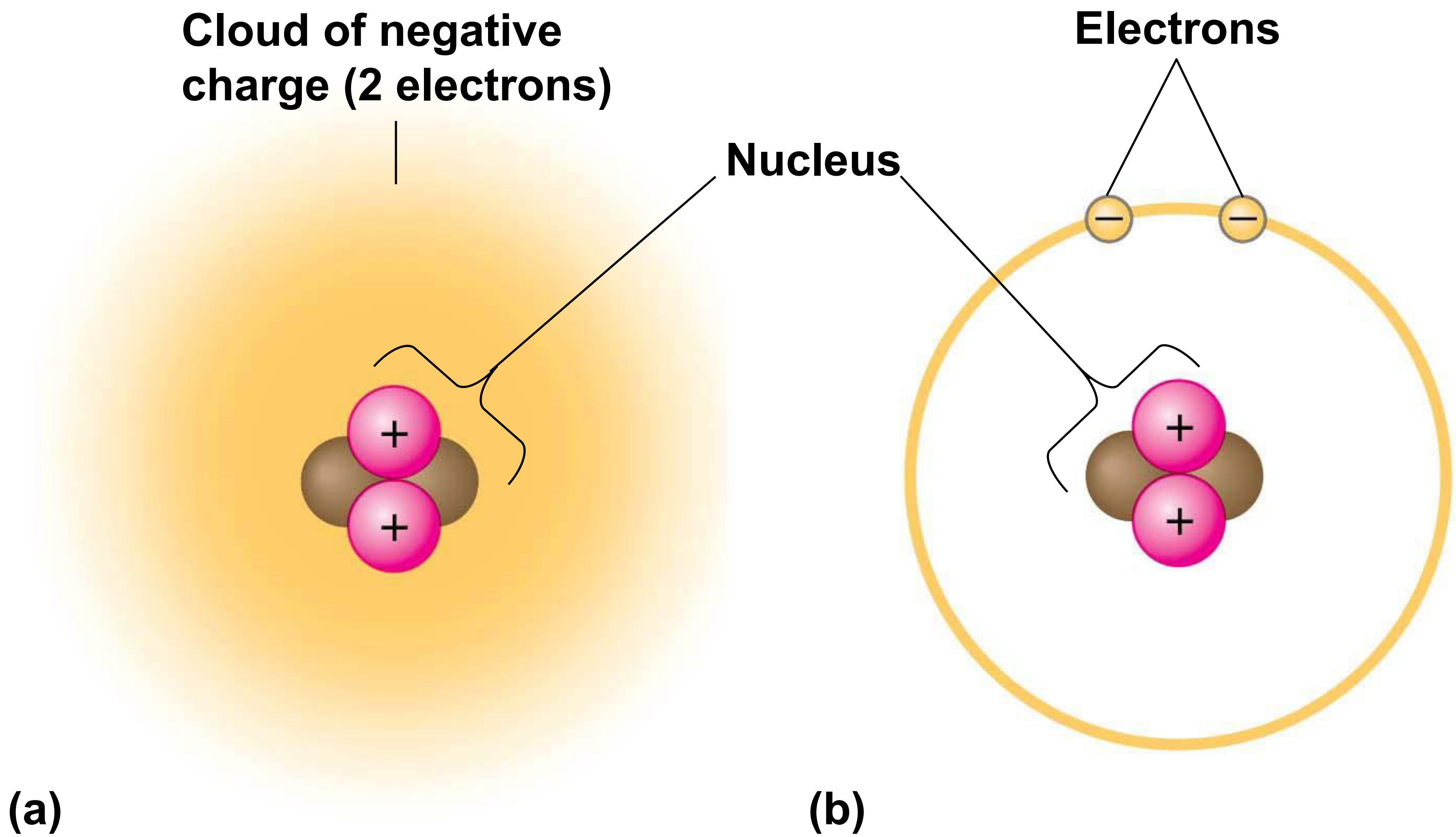
- Each element consists of a certain type of atom, different from the atoms of any other element
- An **atom** is the smallest unit of matter that still retains the properties of an element

Subatomic Particles

- Atoms are composed of smaller parts called subatomic particles
- Relevant subatomic particles include
  - **Neutrons** (no electrical charge)
  - **Protons** (positive charge)
  - **Electrons** (negative charge)

- Neutrons and protons form the atomic nucleus
- Electrons form a “cloud” around the nucleus
- Neutron mass and proton mass are almost identical and are measured in **daltons**

Figure 2.3



Atomic Number and Atomic Mass

- Atoms of the various elements differ in number of subatomic particles
- An element's **atomic number** is the number of protons in its nucleus
- An element's **mass number** is the sum of protons plus neutrons in the nucleus
- **Atomic mass**, the atom's total mass, can be approximated by the mass number

Mass number = number of protons + neutrons
= 23 for sodium

$^{23}_{11}\text{Na}$

Atomic number = number of protons
= 11 for sodium

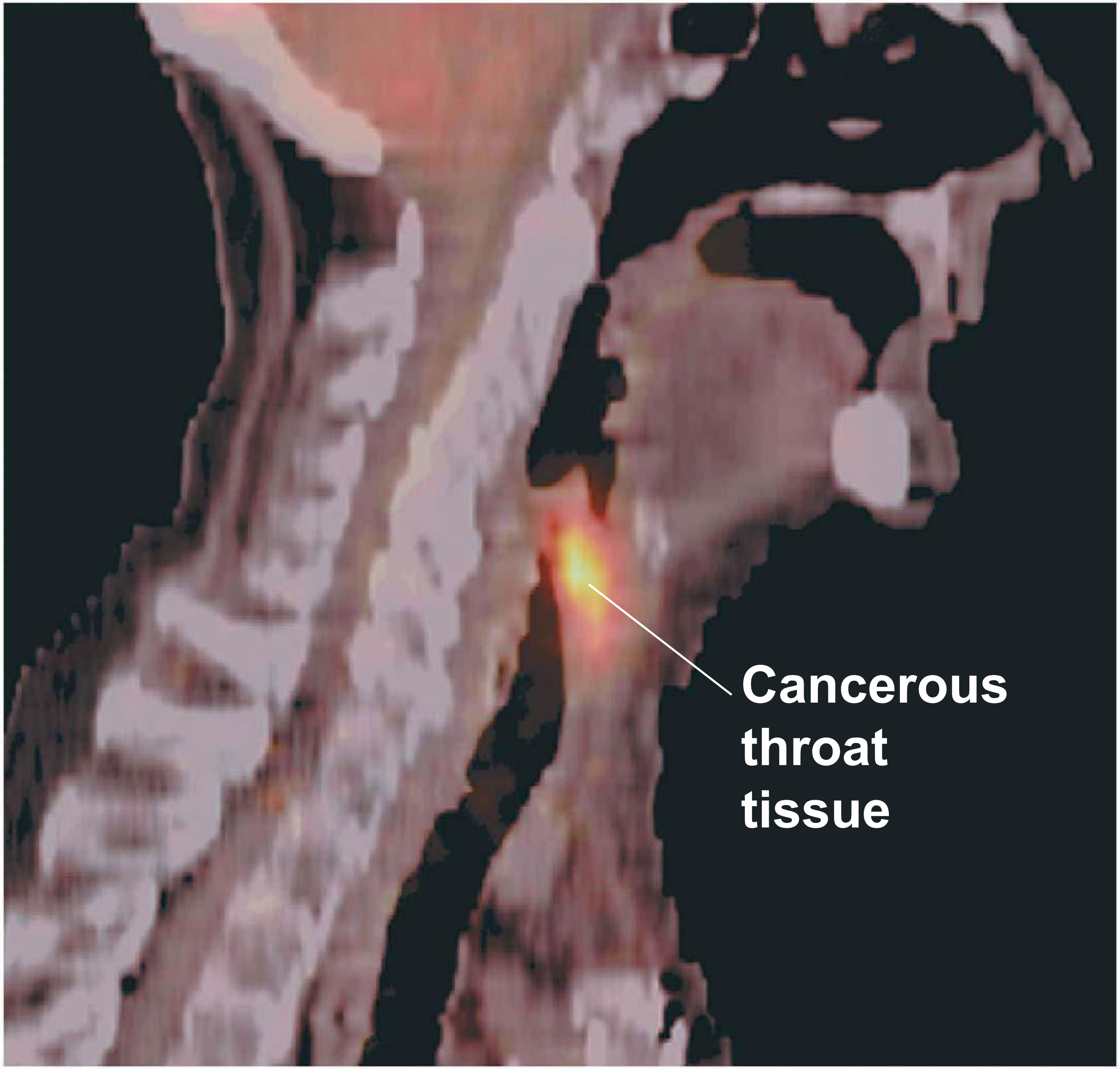
Because neutrons and protons each have a mass of approximately 1 dalton, we can estimate the **atomic mass** (total mass of one atom) of sodium as 23 daltons

Isotopes

- All atoms of an element have the same number of protons but may differ in number of neutrons
- **Isotopes** are two atomic forms of an element that differ in number of neutrons
- **Radioactive isotopes** decay spontaneously, giving off particles and energy

- Some applications of radioactive isotopes in biological research are
  - Dating fossils
  - Tracing atoms through metabolic processes
  - Diagnosing medical disorders

Figure 2.4



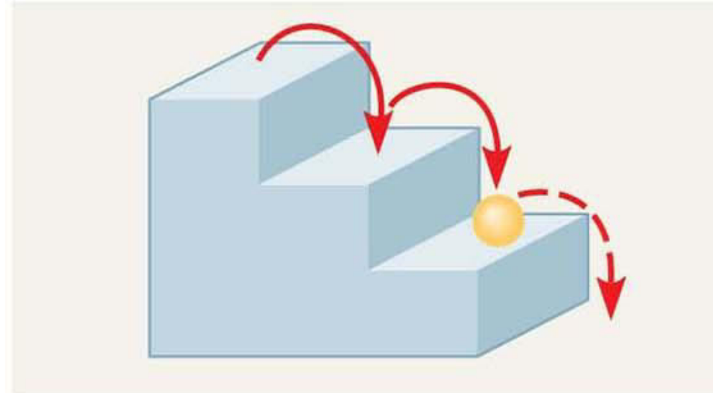
The Energy Levels of Electrons

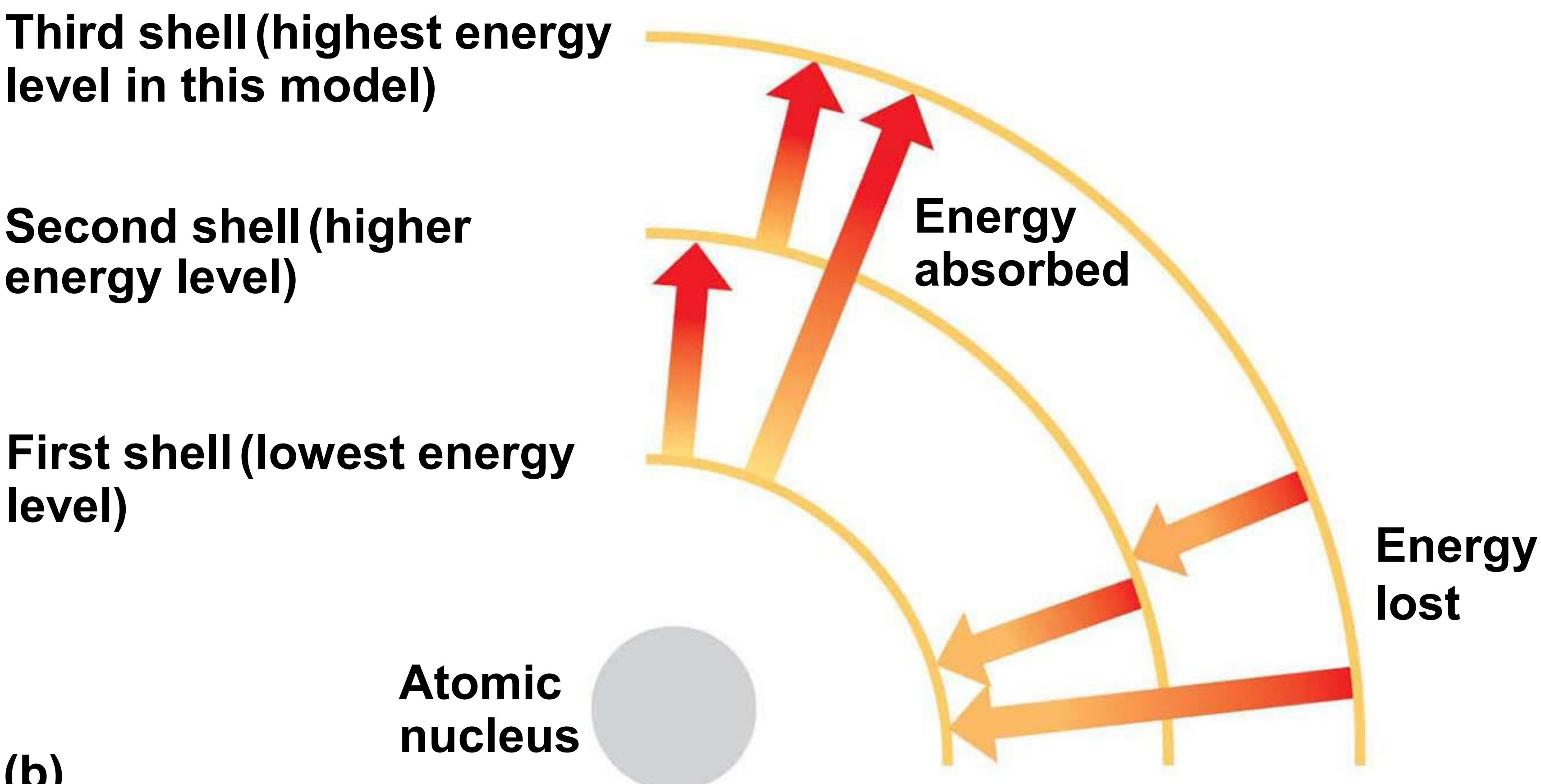
- **Energy** is the capacity to cause change
- **Potential energy** is the energy that matter has because of its location or structure
- The electrons of an atom have potential energy due to their distance from the nucleus
- Changes in potential energy occur in steps of fixed amounts
- An electron's energy level is correlated with its average distance from the nucleus

- Electrons are found in different **electron shells**, each with a characteristic average distance from the nucleus
- The energy level of each shell increases with distance from the nucleus
- Electrons can move to higher or lower shells by absorbing or releasing energy, respectively

Figure 2.5

(a) A ball bouncing down a flight of stairs can come to rest only on each step, not between steps.



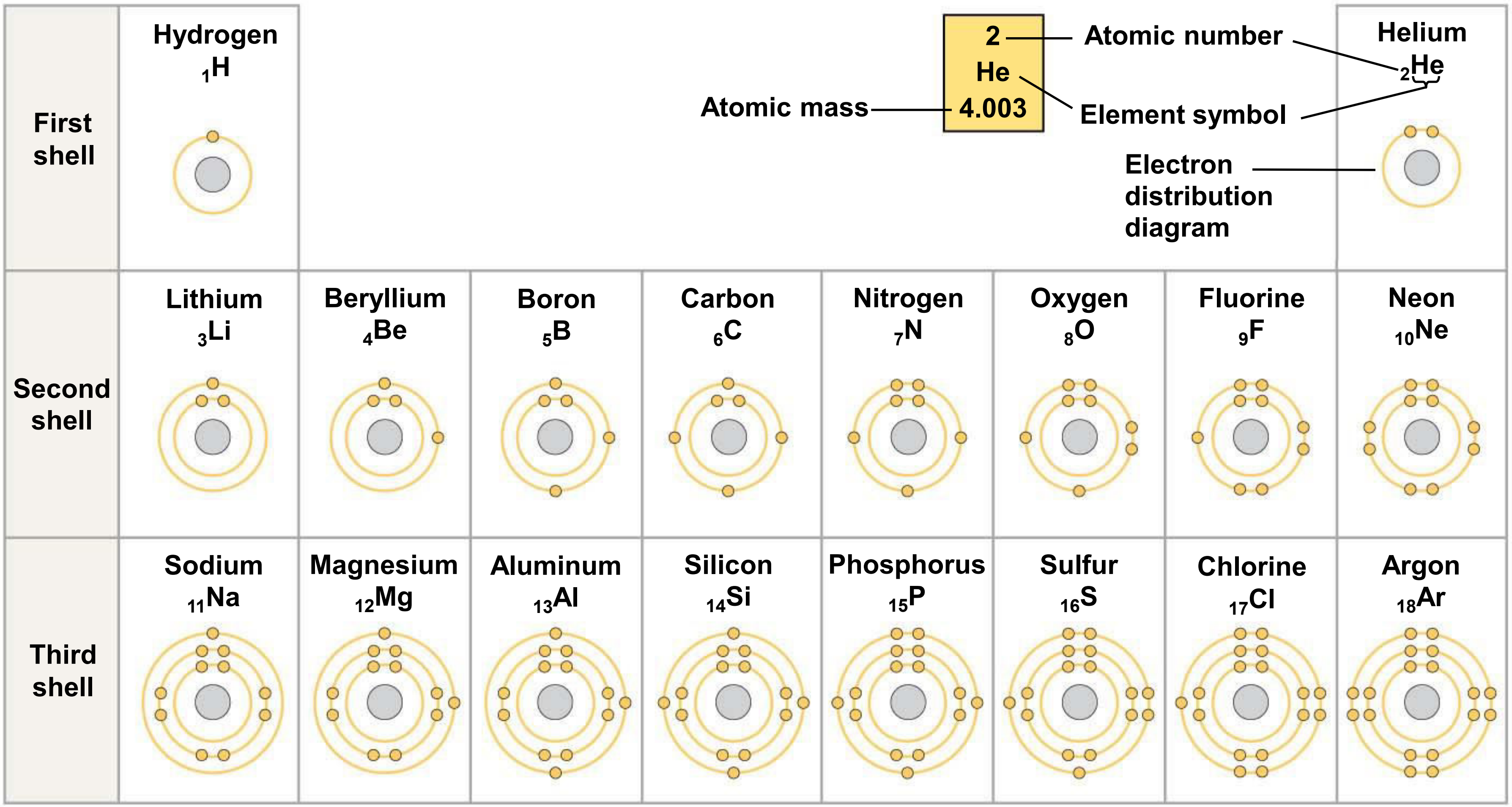


(b)

Electron Distribution and Chemical Properties

- The chemical behavior of an atom is determined by the distribution of electrons in electron shells
- The periodic table of the elements shows the electron distribution for each element

Figure 2.6



First shell
Second shell
Third shell
Hydrogen
1H
Helium
2He
2
He
4.003
Atomic number
Element symbol
Atomic mass
Electron distribution diagram
Lithium
3Li
Beryllium
4Be
Boron
5B
Carbon
6C
Nitrogen
7N
Oxygen
8O
Fluorine
9F
Neon
10Ne
Sodium
11Na
Magnesium
12Mg
Aluminum
13Al
Silicon
14Si
Phosphorus
15P
Sulfur
16S
Chlorine
17Cl
Argon
18Ar

Figure 2.6-1

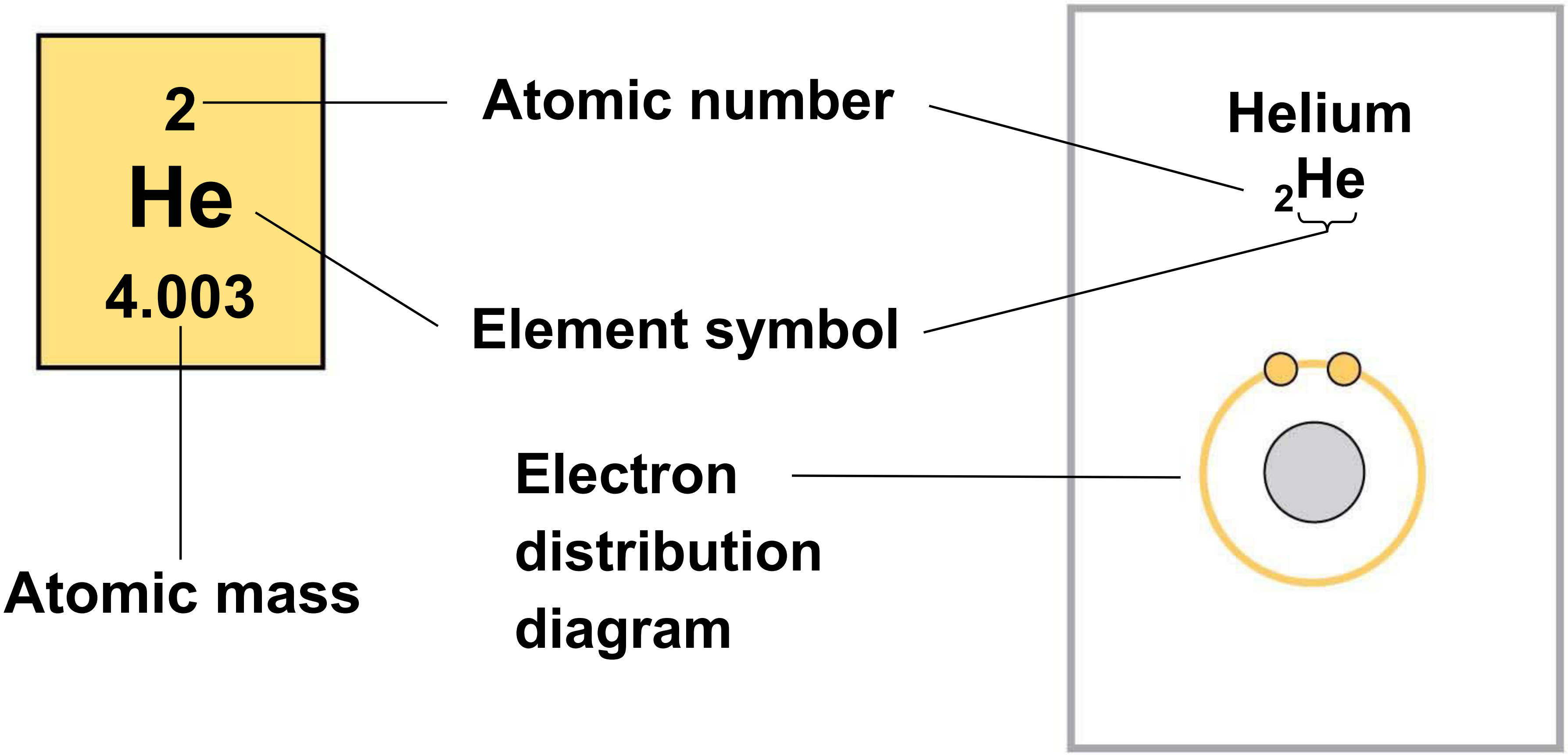

2
He
4.003
Atomic number
Element symbol
Atomic mass
Helium
$_2$He
Electron
distribution
diagram

Figure 2.6-2

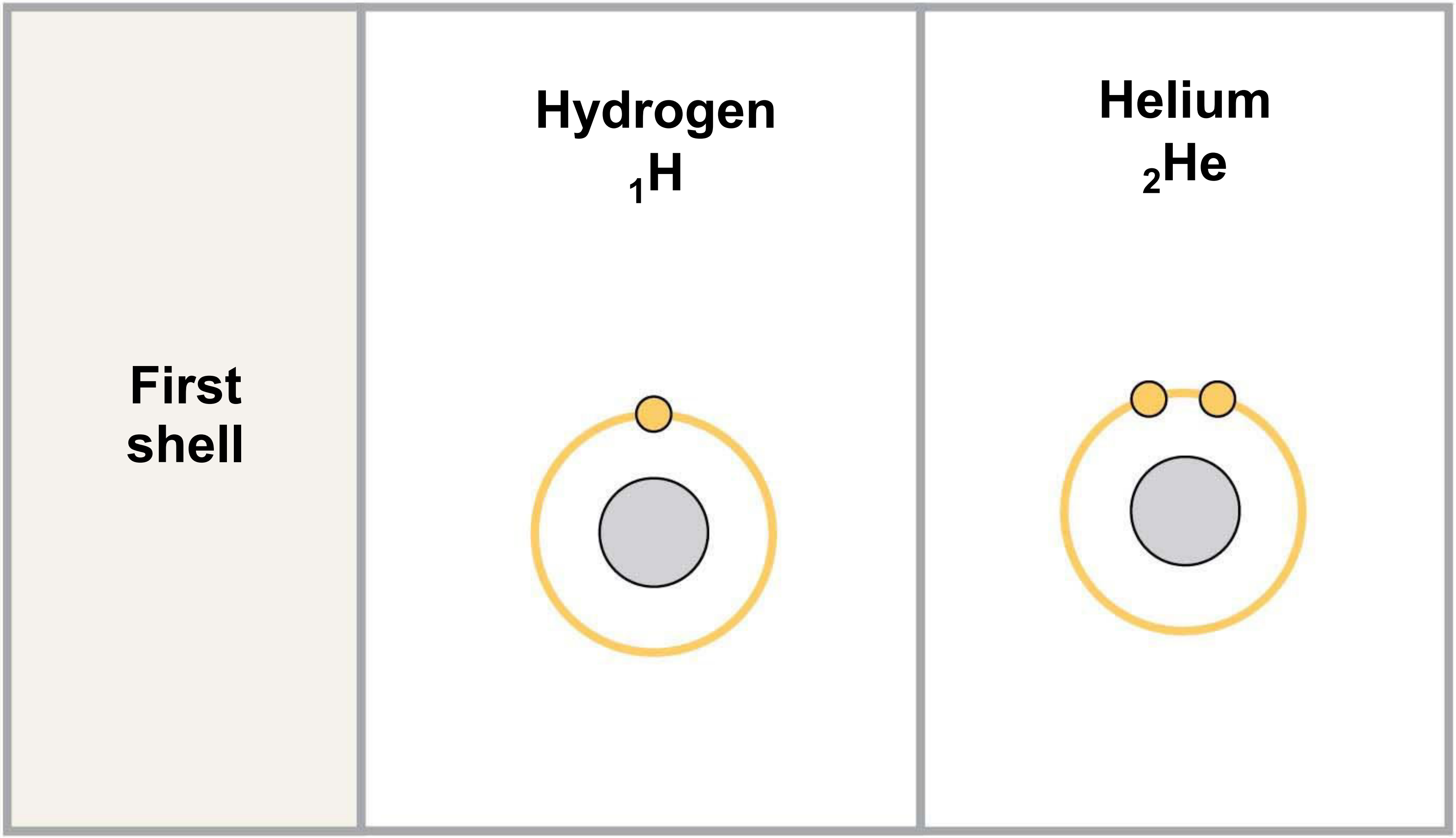


Figure 2.6-3

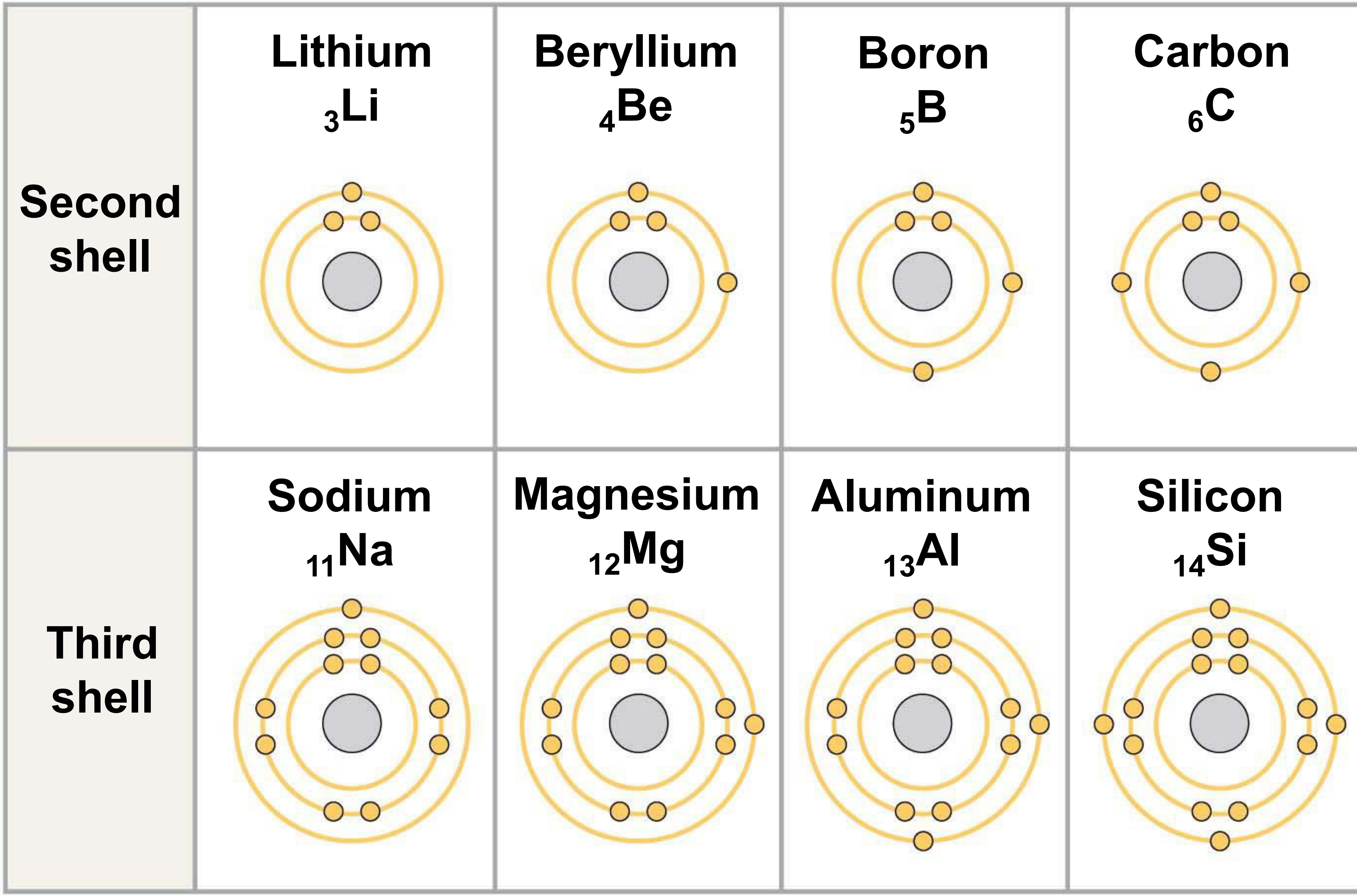
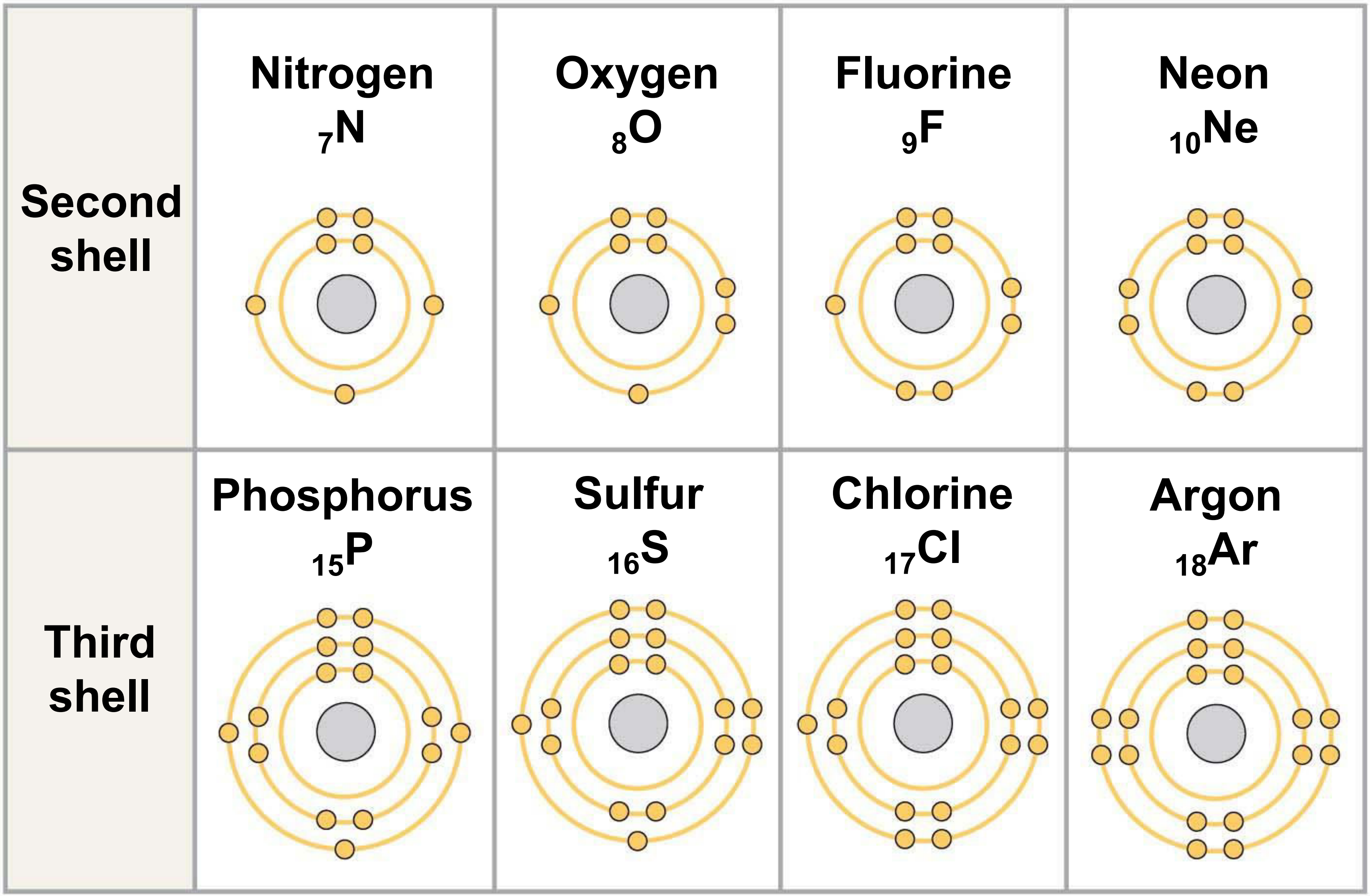

Lithium
$_3$Li
Beryllium
$_4$Be
Boron
$_5$B
Carbon
$_6$C
Second shell
Sodium
$_{11}$Na
Magnesium
$_{12}$Mg
Aluminum
$_{13}$Al
Silicon
$_{14}$Si
Third shell

Figure 2.6-4


Second shell
Nitrogen
$_{7}$N
Oxygen
$_{8}$O
Fluorine
$_{9}$F
Neon
$_{10}$Ne
Third shell
Phosphorus
$_{15}$P
Sulfur
$_{16}$S
Chlorine
$_{17}$Cl
Argon
$_{18}$Ar

- Chemical behavior of an atom depends mostly on the number of electrons in its outermost shell, or **valence shell**
- **Valence electrons** are those that occupy the valence shell
- The reactivity of an atom arises from the presence of one or more unpaired electrons in the valence shell
- Atoms with completed valence shells are unreactive, or inert

Concept 2.3: The formation and function of molecules depend on chemical bonding between atoms

- Atoms with incomplete valence shells can share or transfer valence electrons with certain other atoms
- This usually results in atoms staying close together, held by attractions called **chemical bonds**

Covalent Bonds

- A **covalent bond** is the sharing of a pair of valence electrons by two atoms
- In a covalent bond, the shared electrons count as part of each atom's valence shell
- Two or more atoms held together by covalent bonds constitute a **molecule**

Figure 2.7-s1

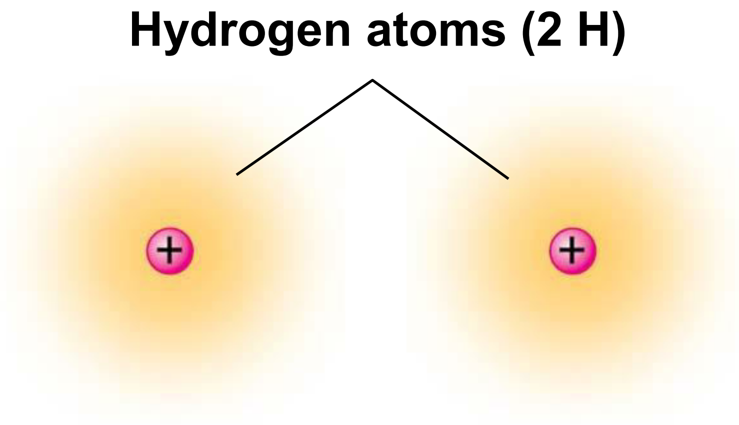


Figure 2.7-s2

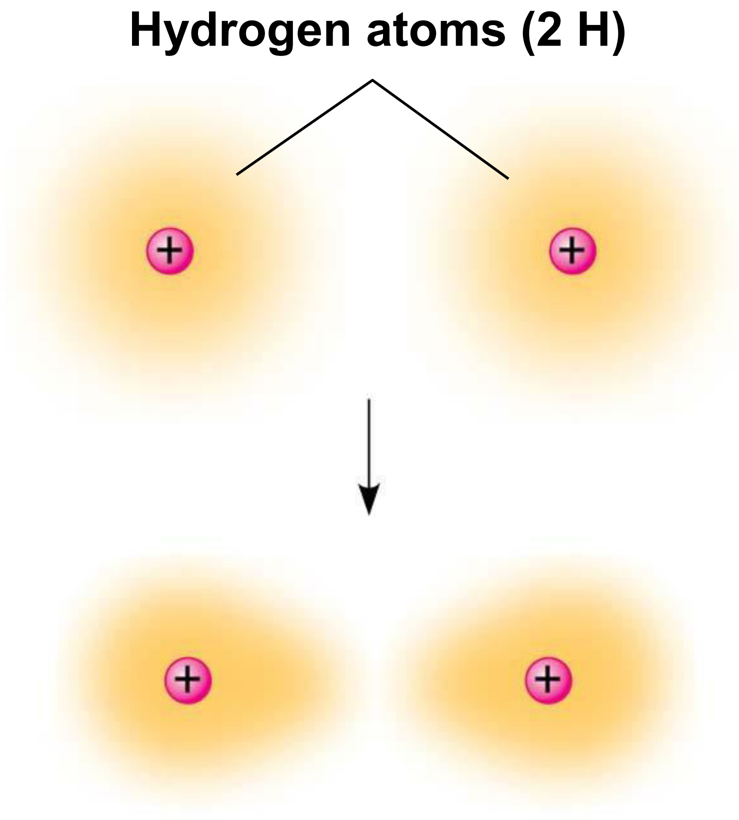
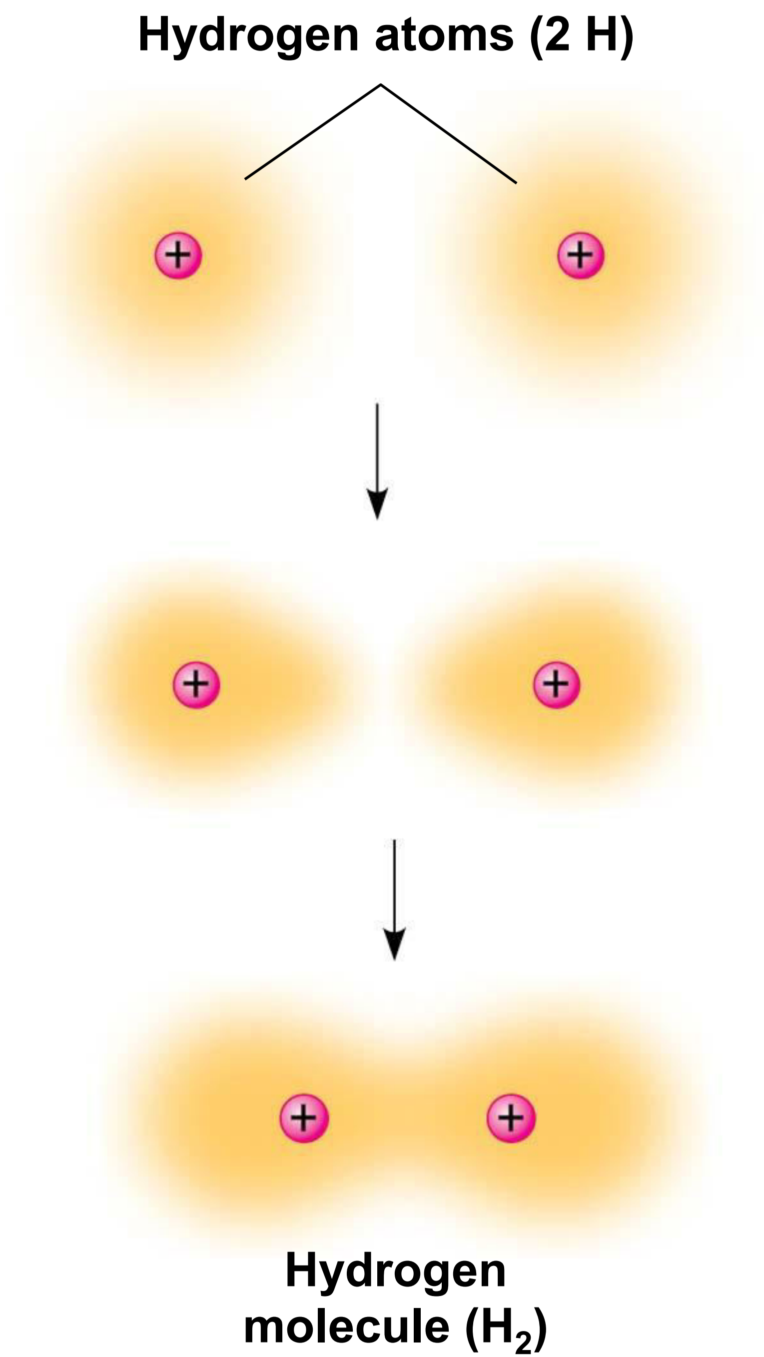


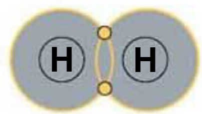
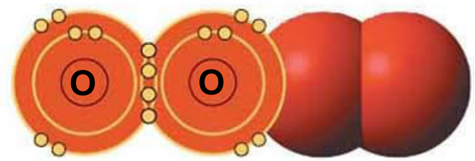
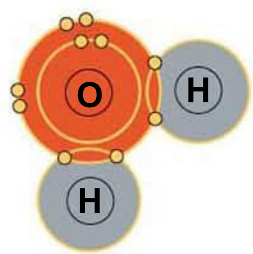
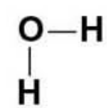
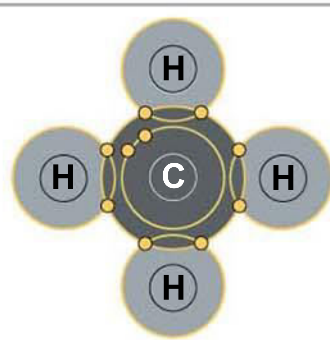
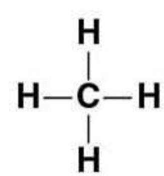
Figure 2.7-s3



- The notation used to represent atoms and bonding is called a structural formula
  - For example, H—H
- This can be abbreviated further with a molecular formula
  - For example, H_2

- In a structural formula, a **single bond**, the sharing of one pair of electrons, is indicated by a single line between the atoms
  - For example, H—H
- A **double bond**, the sharing of two pairs of electrons, is indicated by a double line between atoms
  - For example, O═O

Figure 2.8

Name and Molecular Formula	Electron Distribution Diagram	Structural Formula	Space-Filling Model
(a) Hydrogen (H_2)	 	H—H	
(b) Oxygen (O_2)	 	O═O	
(c) Water (H_2O)	 	 	
(d) Methane (CH_4)	 	 	

- Each atom that can share valence electrons has a bonding capacity, the number of bonds that the atom can form
- Bonding capacity, or **valence**, usually corresponds to the number of electrons required to complete the atom

- Pure elements are composed of molecules of one type of atom, such as H_2 and O_2
- Molecules composed of a combination of two or more types of atoms, such as H_2O or CH_4, are called compounds

- Atoms in a molecule attract electrons to varying degrees
- **Electronegativity** is an atom's attraction for the electrons of a covalent bond
- The more electronegative an atom, the more strongly it pulls shared electrons toward itself

- In a **nonpolar covalent bond**, the atoms share the electrons equally
- In a **polar covalent bond**, one atom is more electronegative, and the atoms do not share the electron equally
- Unequal sharing of electrons causes a partial positive or negative charge for each atom or molecule

Animation: Covalent Bonds

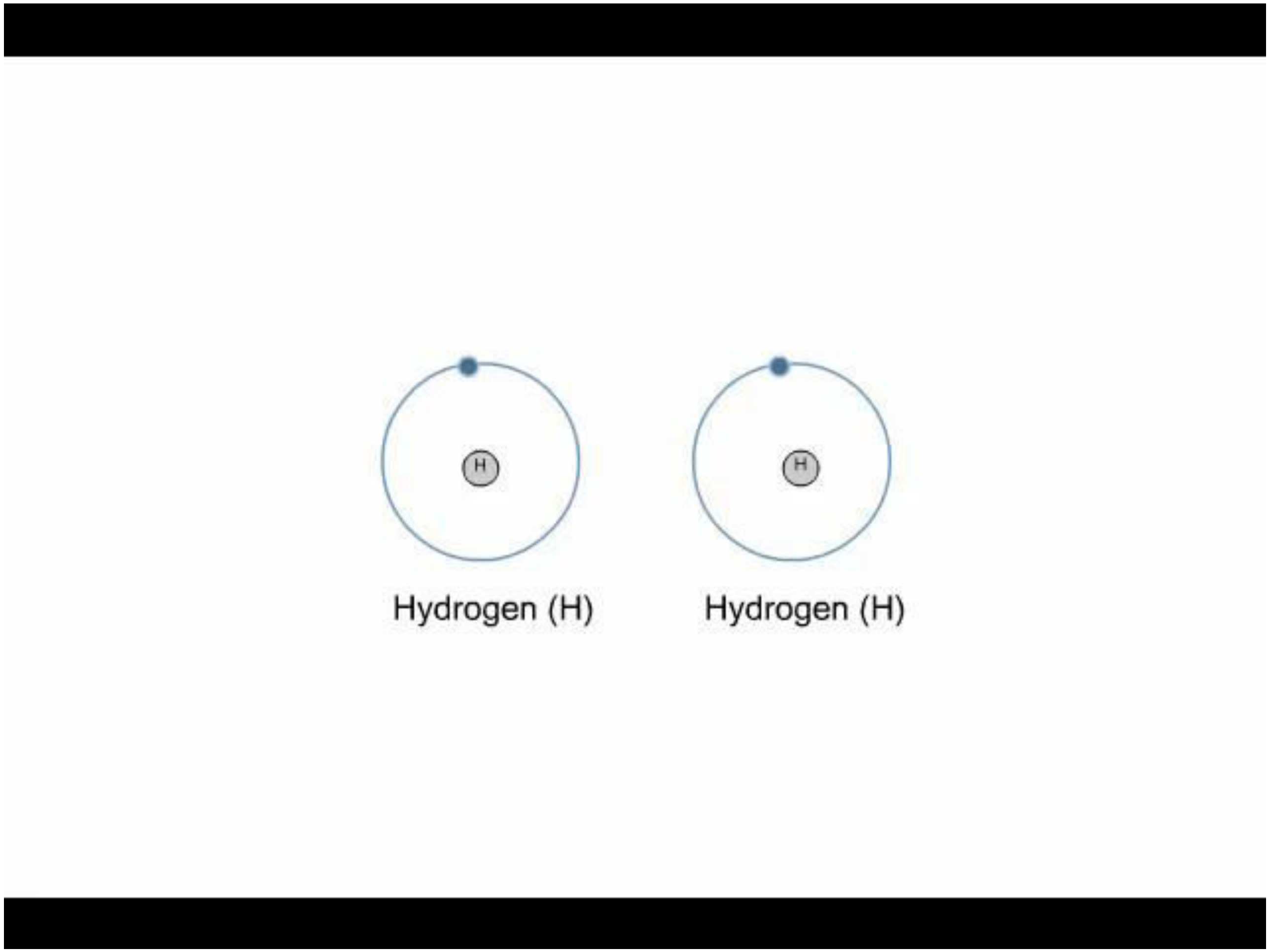
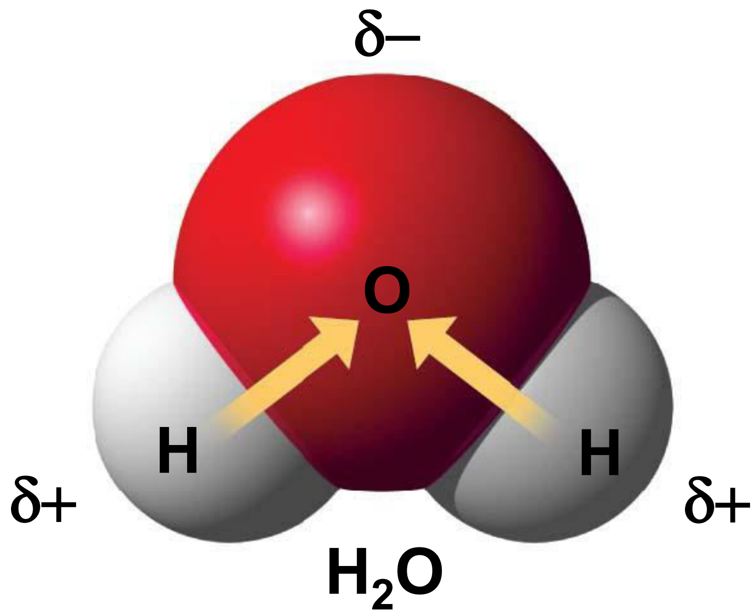


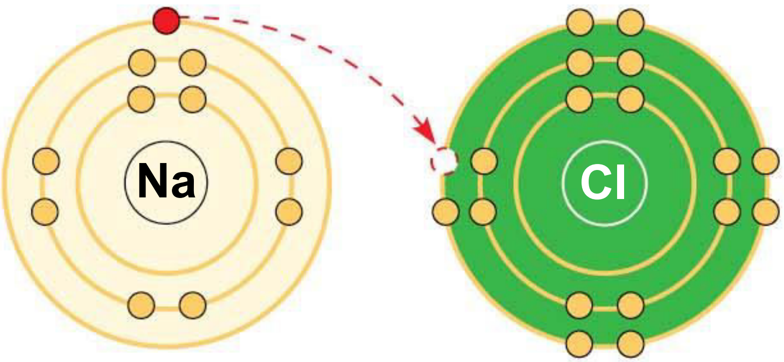
Figure 2.9



Ionic Bonds

- Atoms sometimes strip electrons from their bonding partners
- An example is the transfer of an electron from sodium to chlorine
- After the transfer of an electron, both atoms have charges and are called **ions**
- Both atoms also have complete valence shells

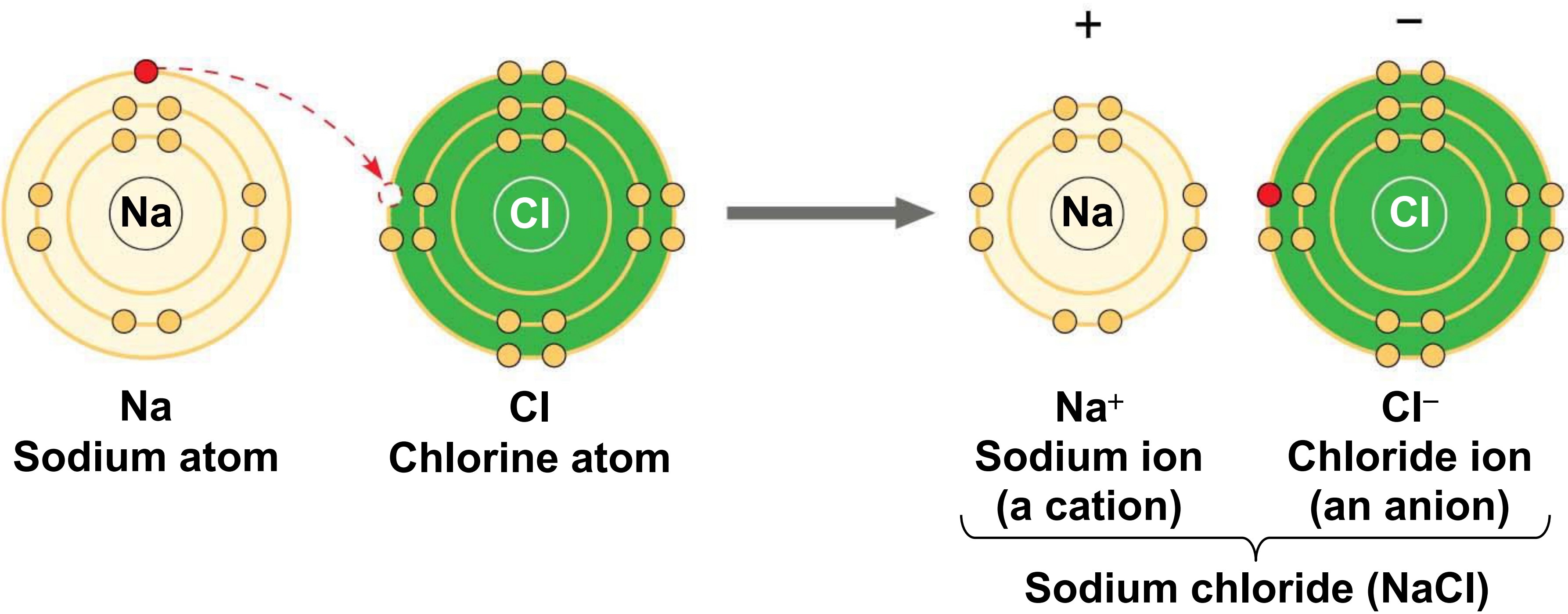
Figure 2.10-s1



Na
Sodium atom

Cl
Chlorine atom

Figure 2.10-s2



- A **cation** is a positively charged ion
- An **anion** is a negatively charged ion
- An **ionic bond** is an attraction between an anion and a cation

- Compounds formed by ionic bonds are called **ionic compounds**, or **salts**
- Salts, such as sodium chloride (table salt), are often found in nature as crystals

Animation: Ionic Bonds

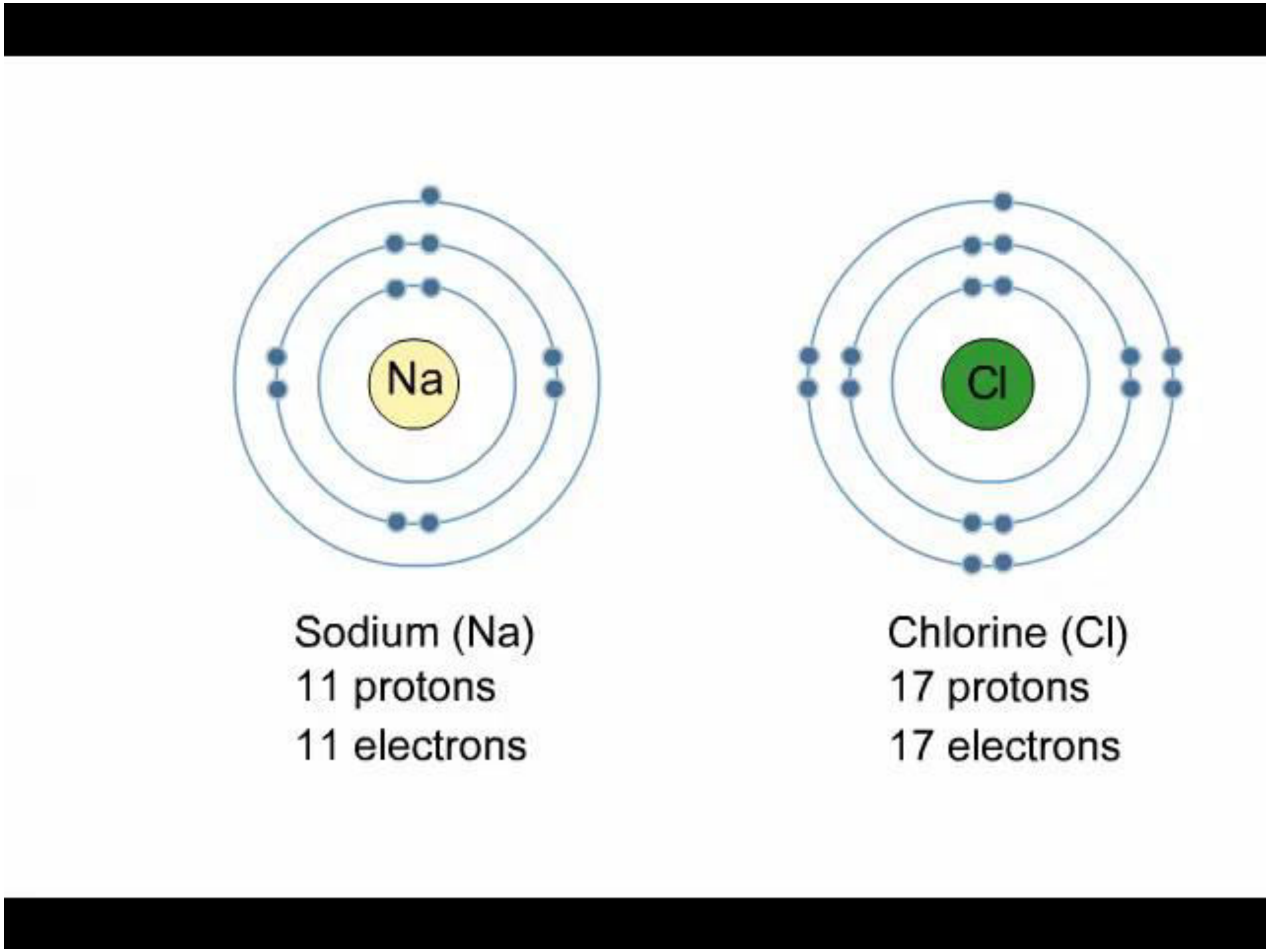


Figure 2.11

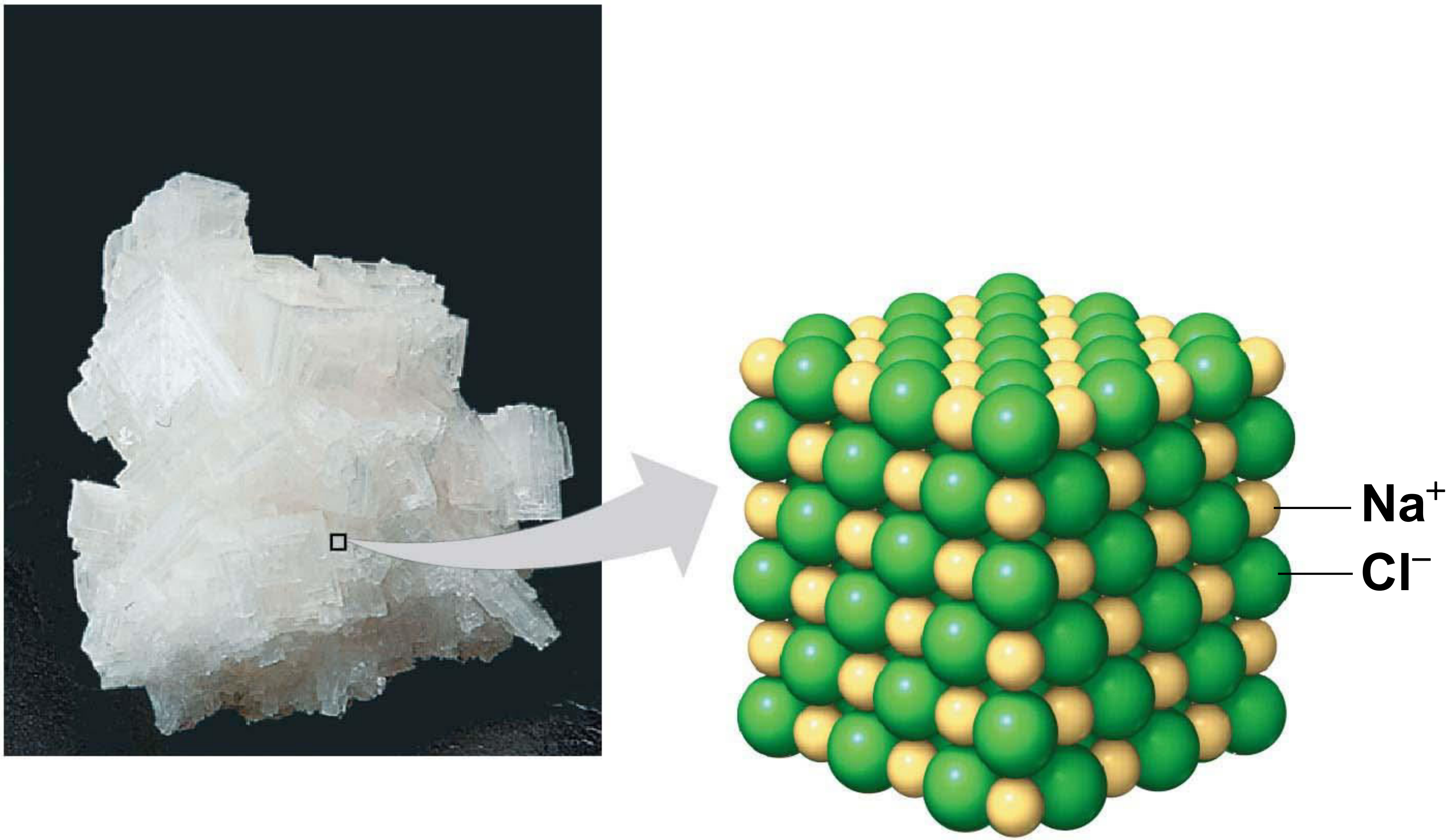


Figure 2.11-1

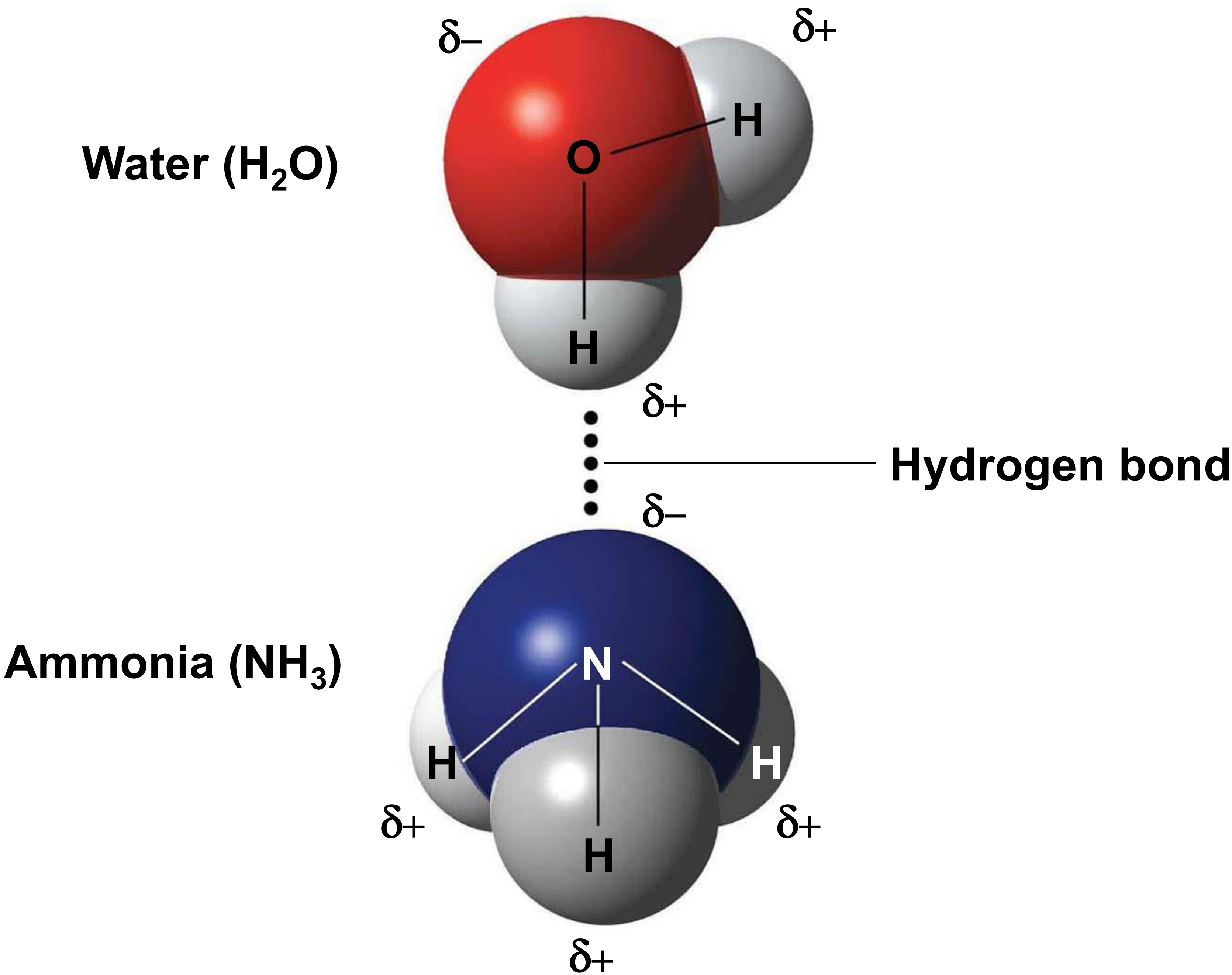
Weak Chemical Bonds

- Most of the strongest bonds in organisms are covalent bonds that form a cell's molecules
- Many large biological molecules are held in their functional form by weak bonds
- Weak chemical bonds include ionic bonds, hydrogen bonds, and van der Waals interactions

Hydrogen Bonds

- A **hydrogen bond** forms when a hydrogen atom covalently bonded to one electronegative atom is also attracted to another electronegative atom
- In living cells, the electronegative partners are usually oxygen or nitrogen atoms

Figure 2.12



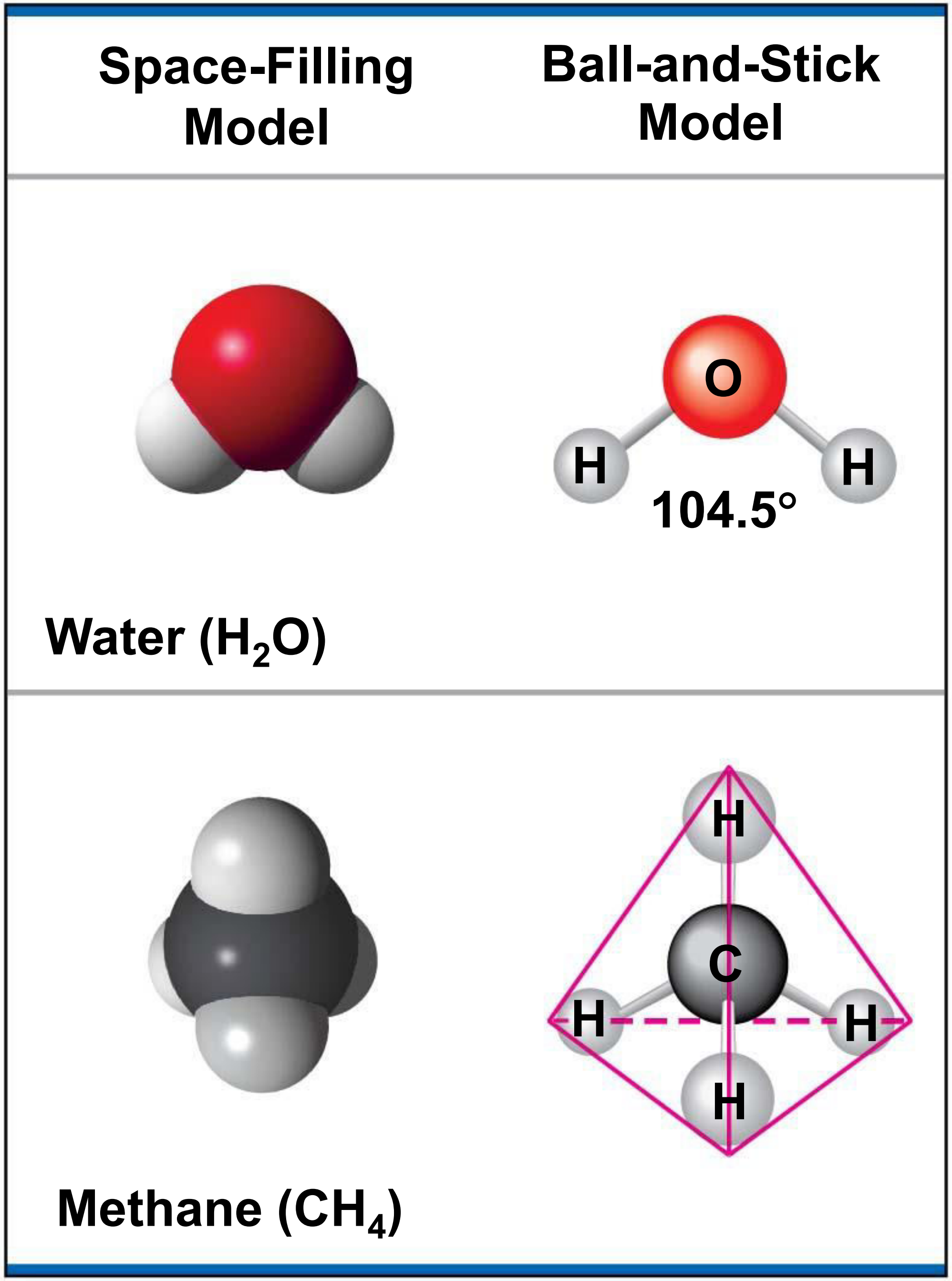
Van der Waals Interactions

- Electrons may be distributed asymmetrically in molecules or atoms
- The resulting regions of positive or negative charge enable all atoms and molecules to stick to one another
- These weak **van der Waals interactions** occur only when atoms and molecules are very close together
- Collectively, such interactions can be strong, as between molecules of a gecko's toe hairs and a wall surface

Molecular Shape and Function

- A molecule's shape is key to its function in the cell
- Molecular shape determines how biological molecules recognize and respond to one another

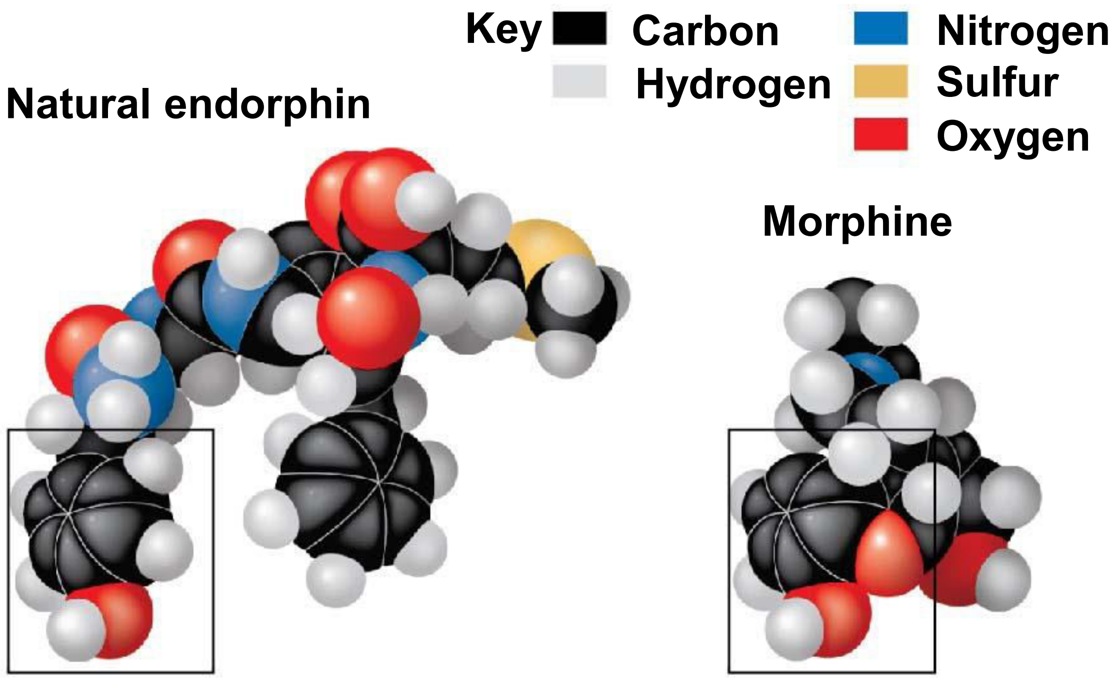
Figure 2.13



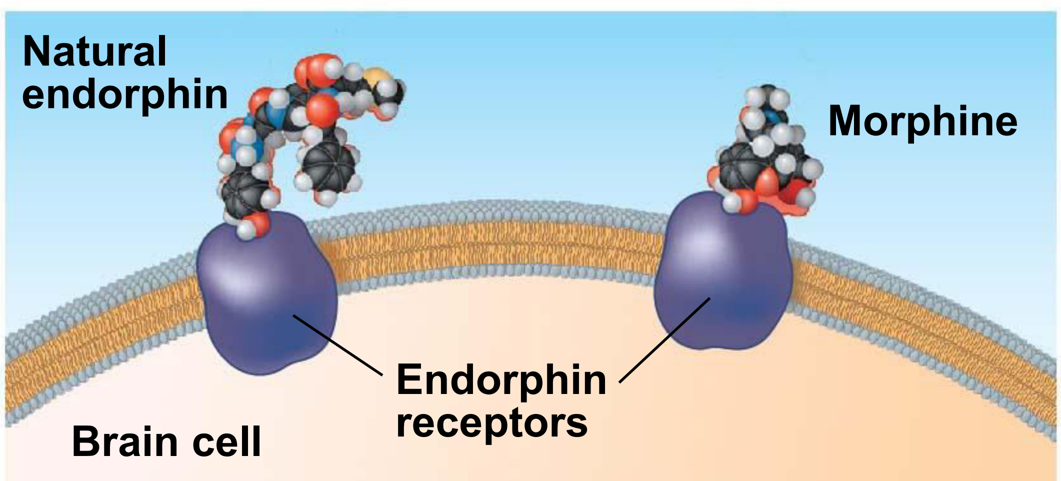
Space-Filling Model
Ball-and-Stick Model
O
H
H
104.5°
Water (H_2O)
H
C
H
H
H
Methane (CH_4)

- Biological molecules recognize and interact with each other with a specificity based on molecular shape
- Molecules with similar shapes can have similar biological effects

Figure 2.14

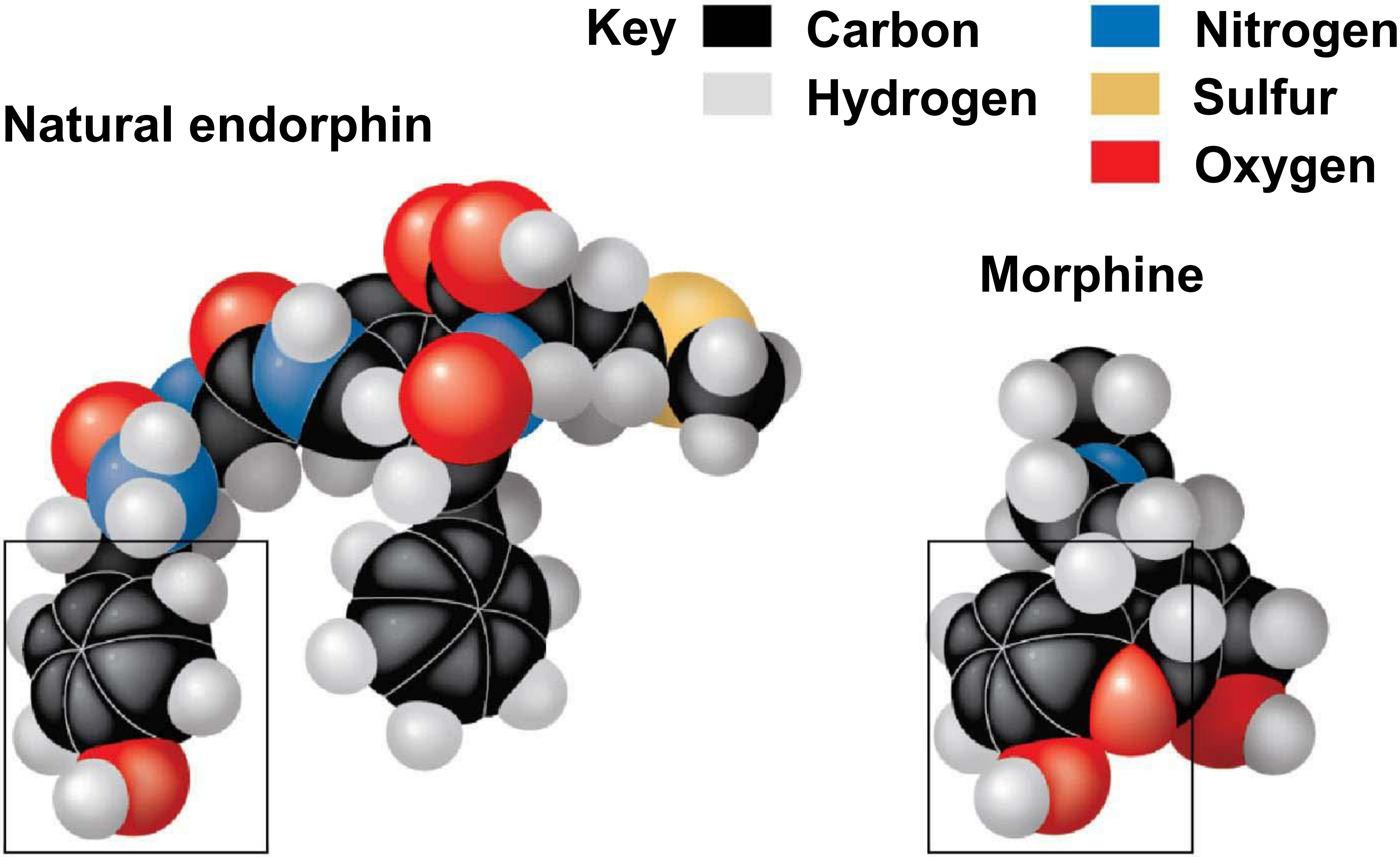


(a) Structures of endorphin and morphine



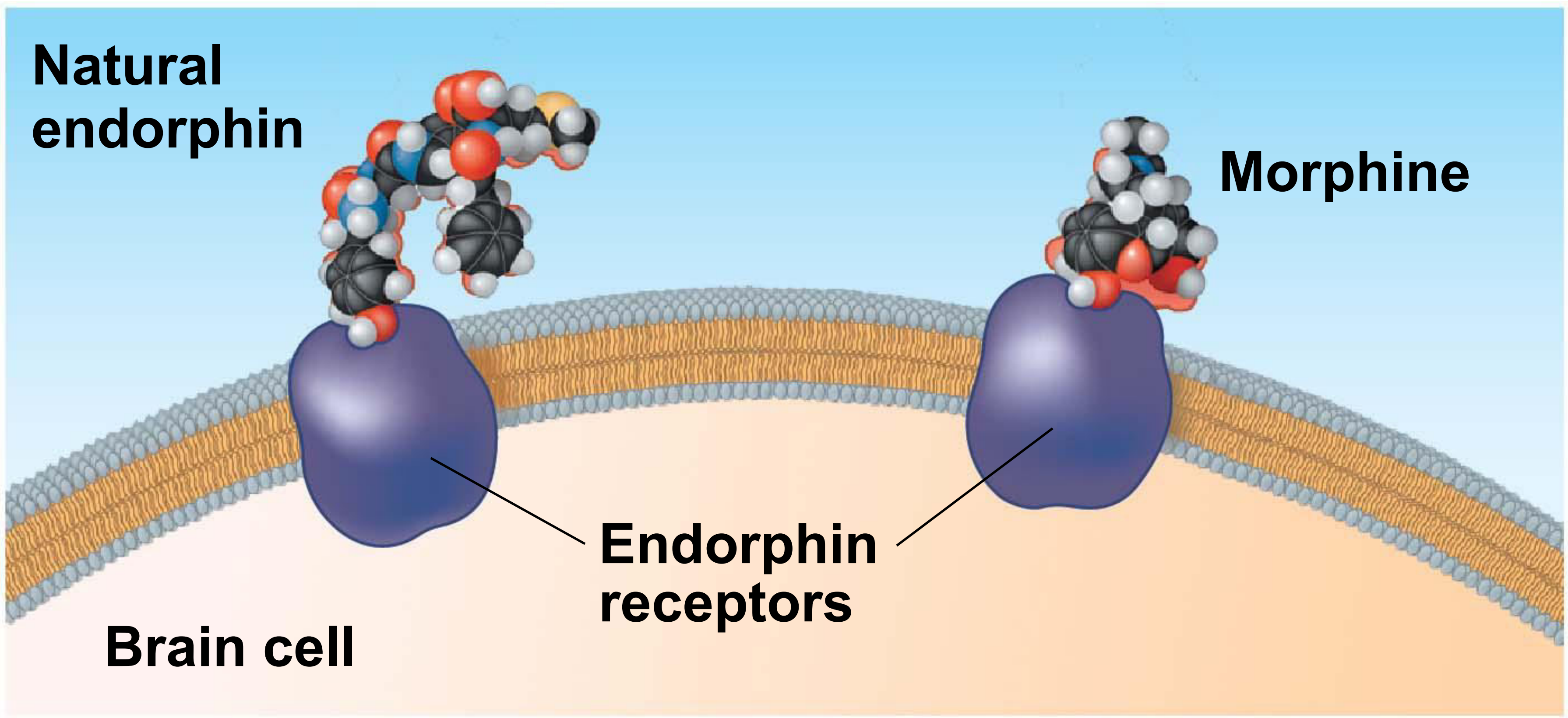
(b) Binding to endorphin receptors

Figure 2.14-1



(a) Structures of endorphin and morphine

Figure 2.14-2

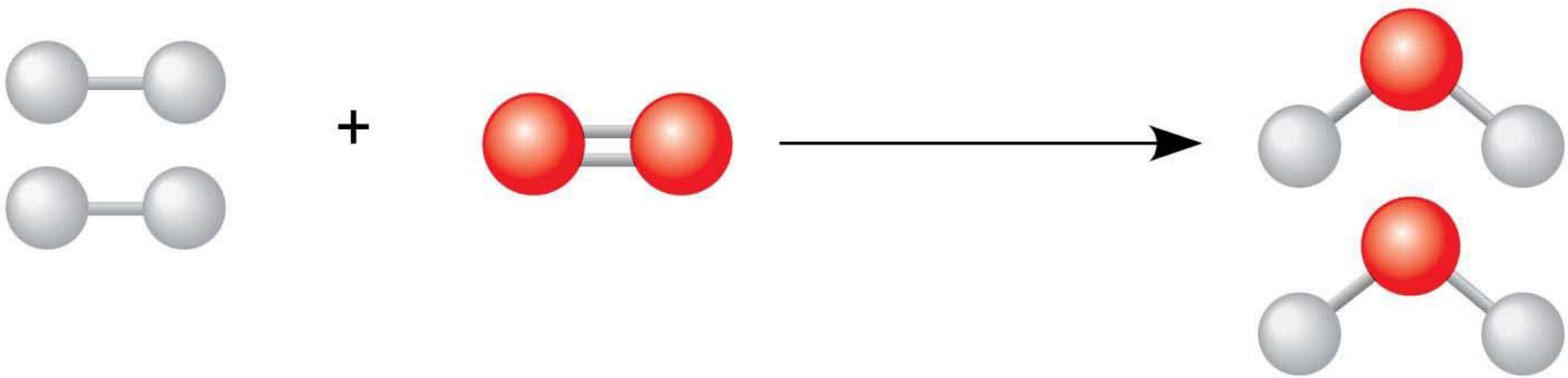


(b) Binding to endorphin receptors

Concept 2.4: Chemical reactions make and break chemical bonds

- **Chemical reactions** are the making and breaking of chemical bonds
- The starting molecules of a chemical reaction are called **reactants**
- The final molecules of a chemical reaction are called **products**

Figure 2.UN02



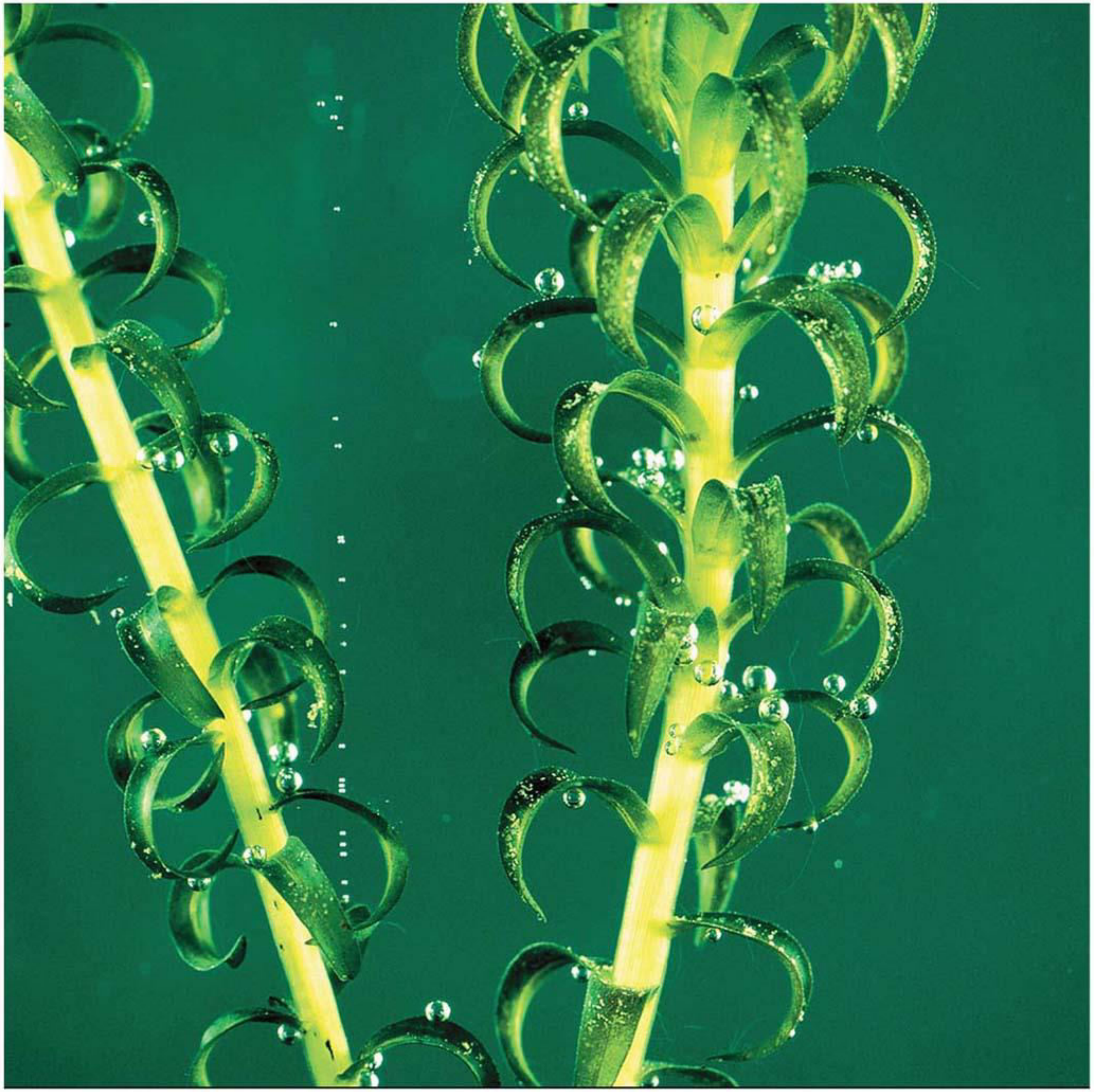
$2\,H_2 + O_2 \longrightarrow 2\,H_2O$

Reactants Reaction Products

- Photosynthesis is an important chemical reaction
- Sunlight powers the conversion of carbon dioxide and water to glucose and oxygen

$$6\ CO_2 + 6\ H_2O \rightarrow C_6H_{12}O_6 + 6\ O_2$$

Figure 2.15

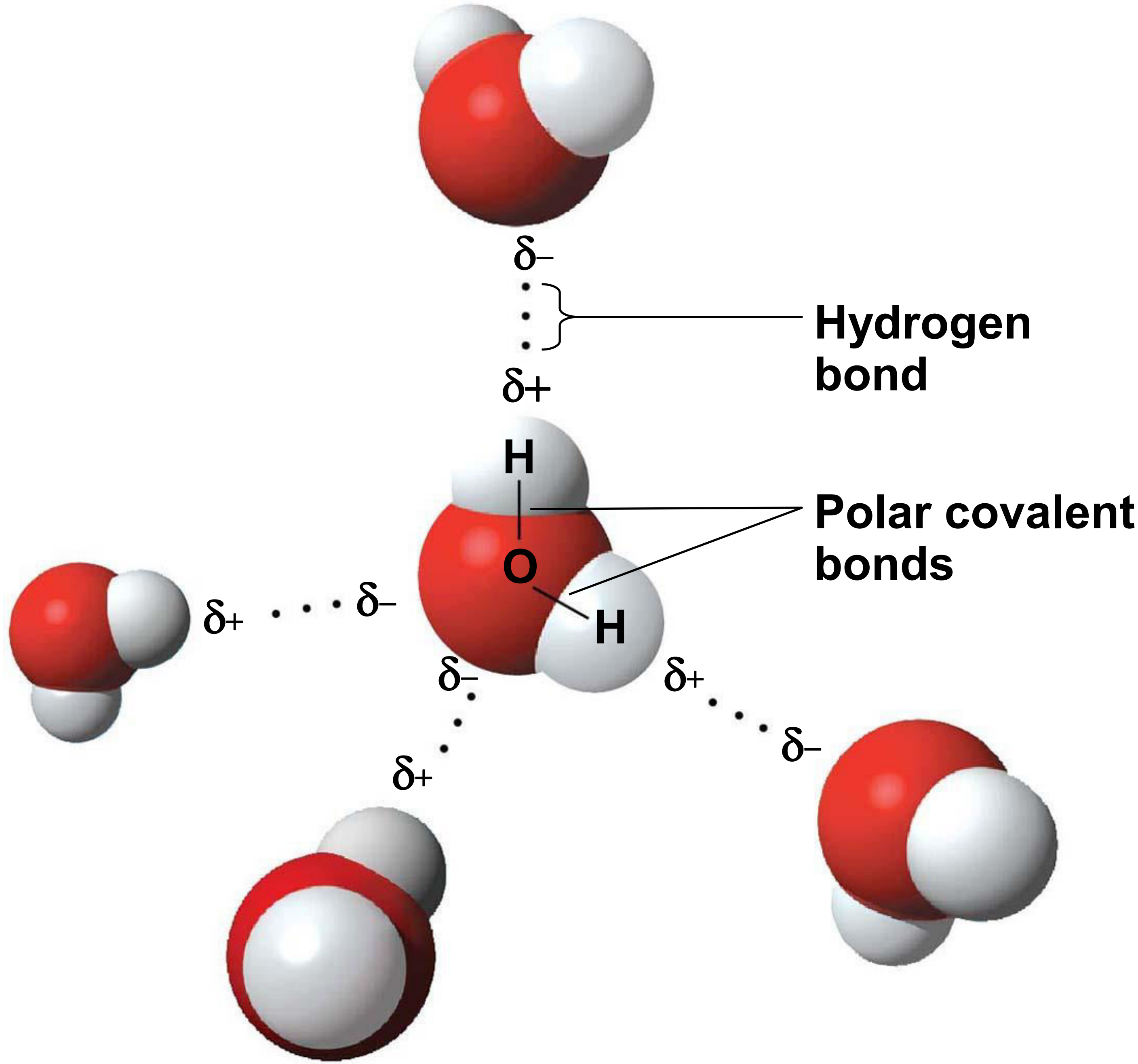


- All chemical reactions are reversible: Products of the forward reaction become reactants for the reverse reaction
- **Chemical equilibrium** is reached when the forward and reverse reaction rates are equal

Concept 2.5: Hydrogen bonding gives water properties that help make life possible on Earth

- All organisms are made mostly of water and live in an environment dominated by water
- Water molecules are **polar molecules**, with the oxygen region having a partial negative charge ($\delta-$) and the hydrogen region a slight positive charge ($\delta+$)
- Two water molecules are held together by a hydrogen bond

Figure 2.16



- Four emergent properties of water contribute to Earth’s suitability for life:
  - Cohesive behavior
  - Ability to moderate temperature
  - Expansion upon freezing
  - Versatility as a solvent

Cohesion of Water Molecules

- Water molecules are linked by multiple hydrogen bonds
- The molecules stay close together because of this; it is called **cohesion**

- Cohesion due to hydrogen bonding contributes to the transport of water and nutrients against gravity in plants
- **Adhesion**, the clinging of one substance to another, also plays a role

Animation: Water Structure

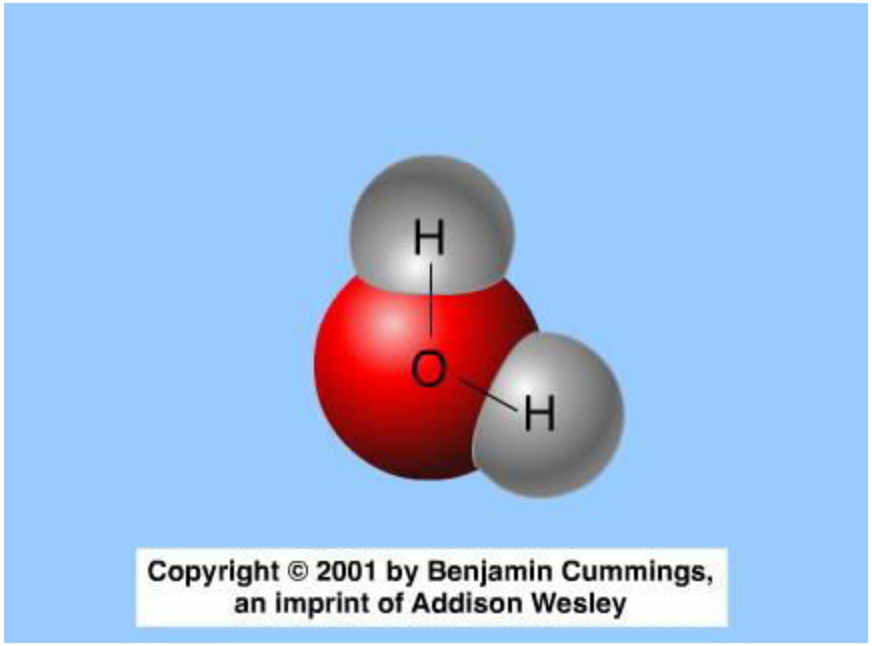
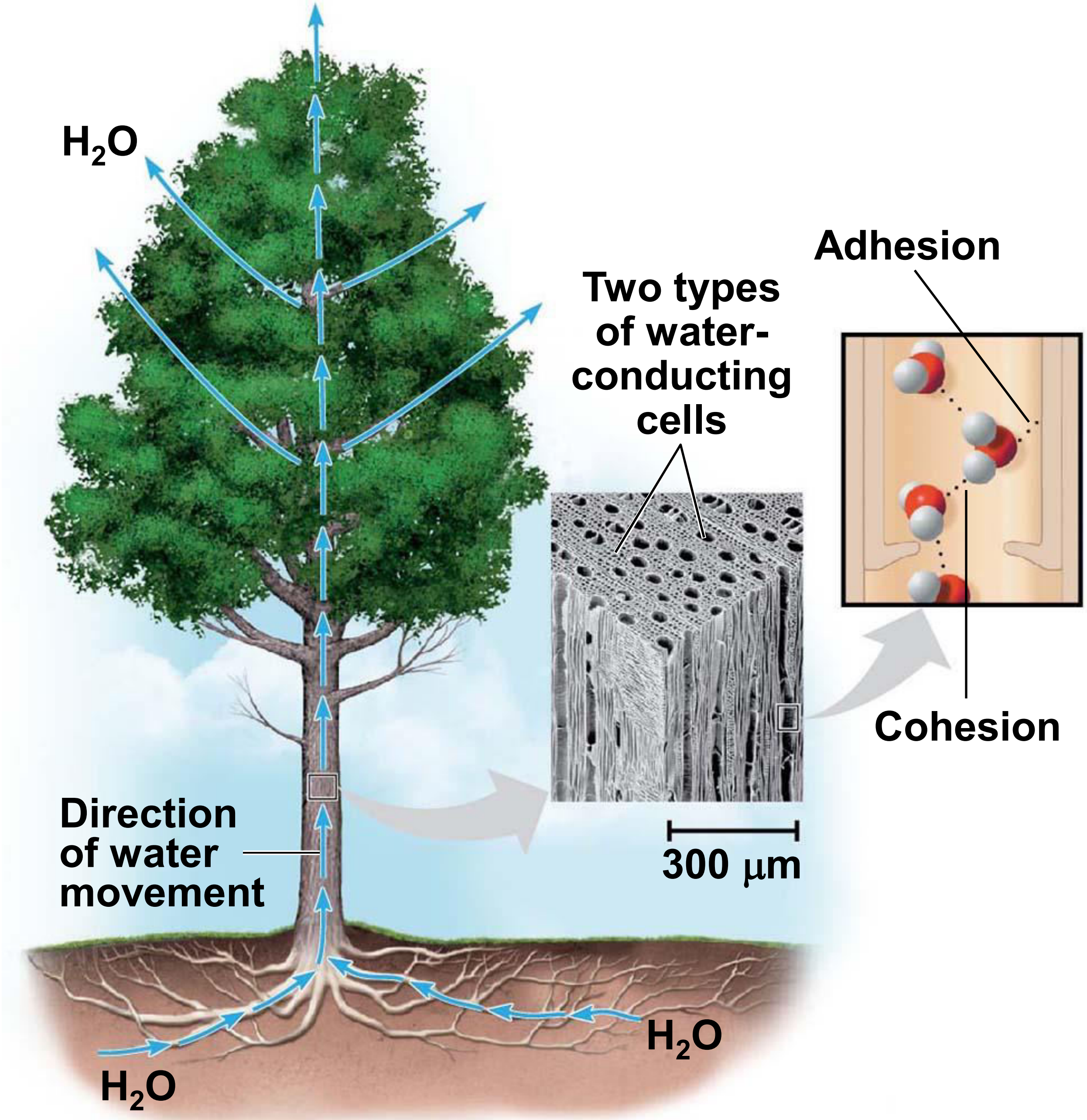


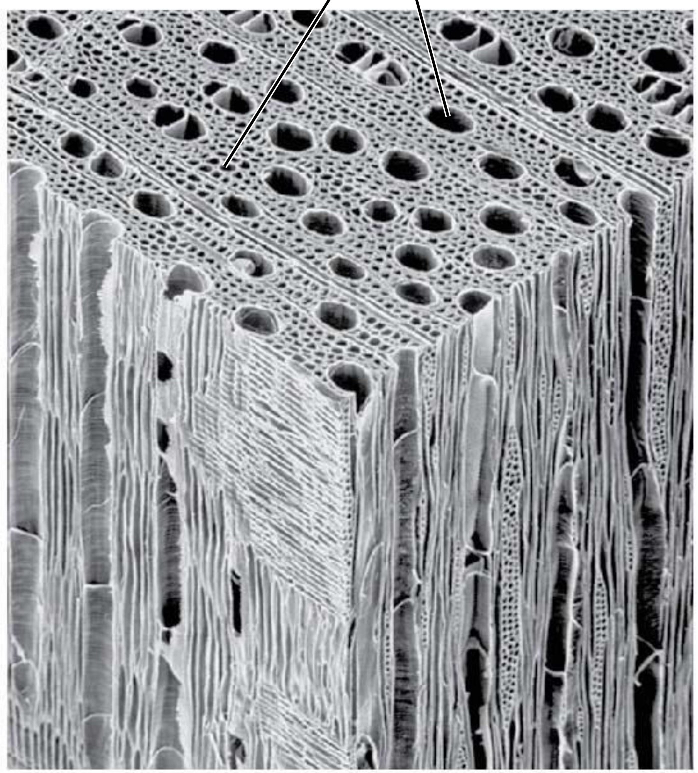
Figure 2.17



H_2O
Adhesion
Two types of water-conducting cells
Cohesion
Direction of water movement
300 μm
H_2O
H_2O

Figure 2.17-1

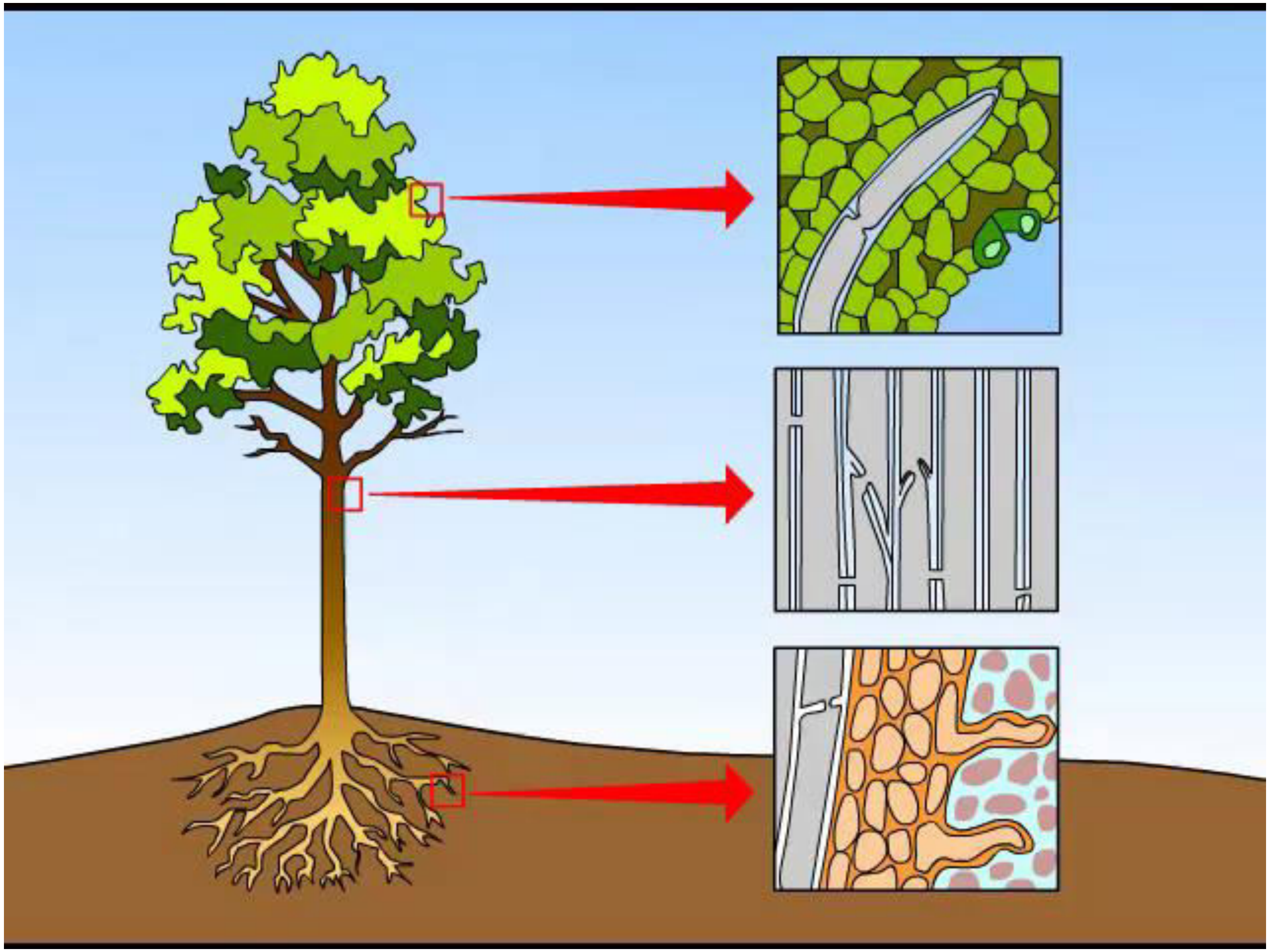
Two types of water-conducting cells



300 μm

- **Surface tension** is a measure of how hard it is to break the surface of a liquid
- Surface tension is related to cohesion

Animation: Water Transport



BioFlix: Water Transport In Plants

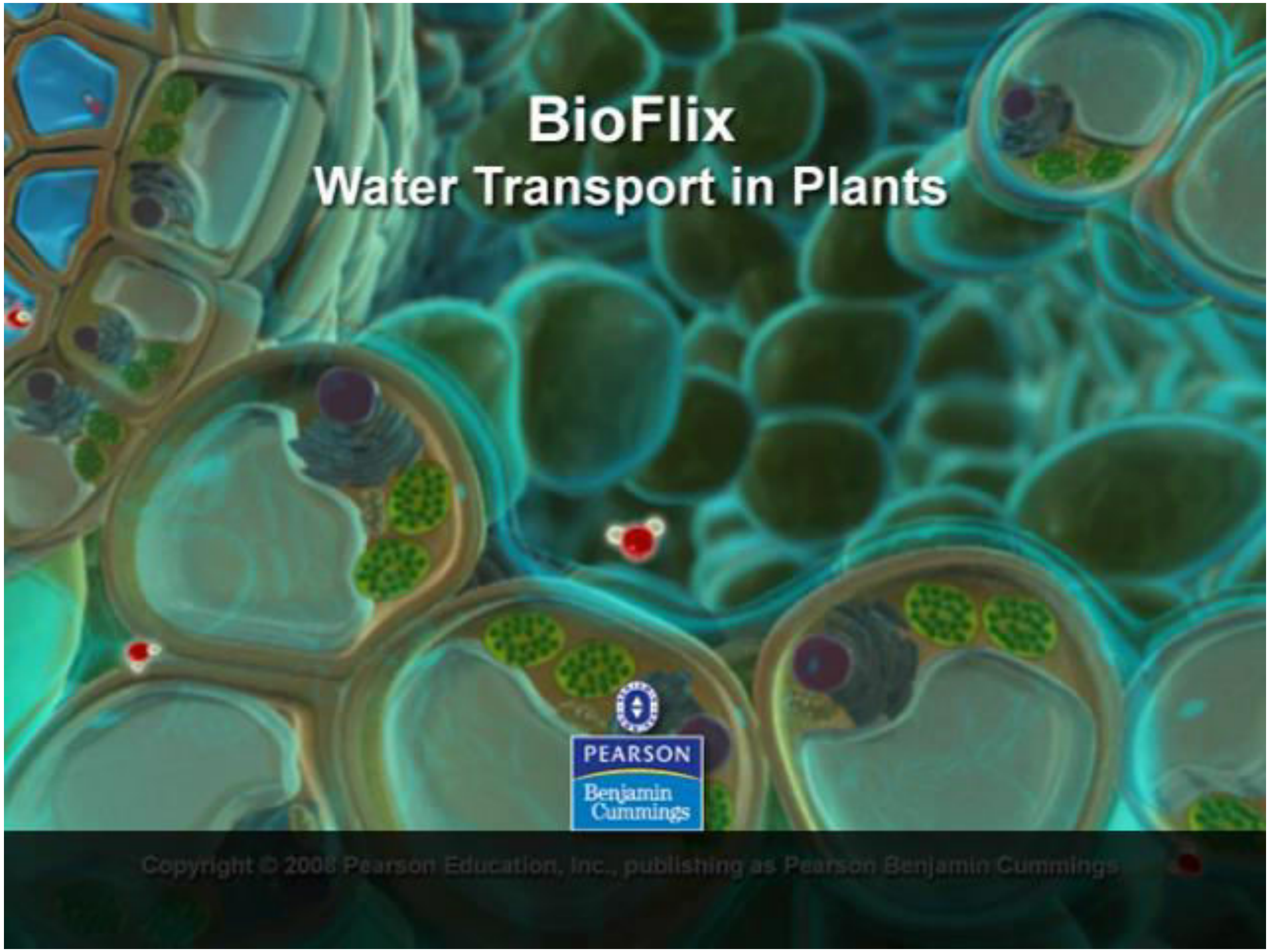


Figure 2.18

Moderation of Temperature by Water

- Water absorbs heat from warmer air and releases stored heat to cooler air
- Water can absorb or release a large amount of heat with only a slight change in its own temperature

Temperature and Heat

- **Kinetic energy** is the energy of motion
- **Thermal energy** is a measure of the total amount of kinetic energy due to molecular motion
- **Temperature** represents the average kinetic energy of molecules
- Thermal energy in transfer from one body of matter to another is defined as **heat**

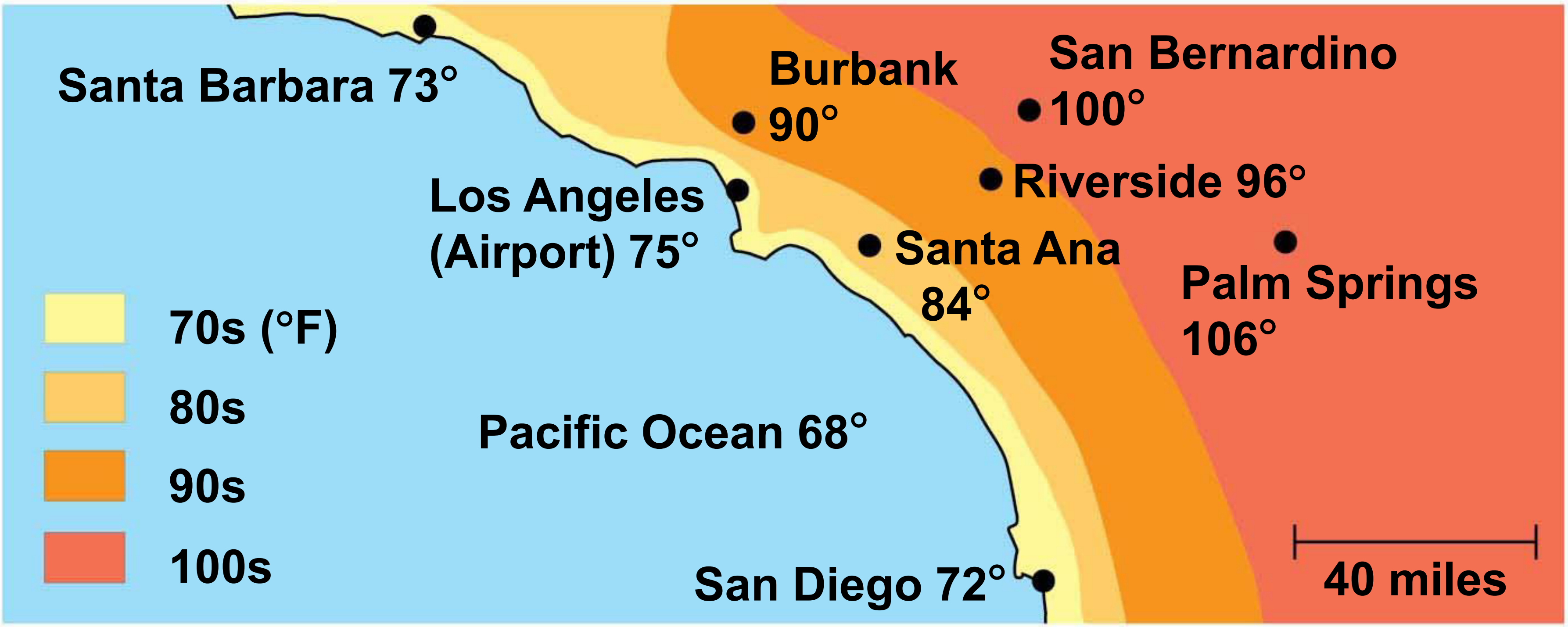
- A **calorie (cal)** is the amount of heat required to raise the temperature of 1 g of water by 1°C
- The "calories" on food packages are actually **kilocalories (kcal),** where 1 kcal = 1,000 cal
- The **joule (J)** is another unit of energy, where 1 J = 0.239 cal, or 1 cal = 4.184 J

Water's High Specific Heat

- The **specific heat** of a substance is the amount of heat that must be absorbed or lost for 1 g of that substance to change its temperature by 1°C
- The specific heat of water is 1 cal/(g · °C)
- Water resists changing its temperature because of its high specific heat

- Water’s high specific heat can be traced to hydrogen bonding
  - Heat is absorbed when hydrogen bonds break
  - Heat is released when hydrogen bonds form
- The high specific heat of water keeps temperature fluctuations within limits that permit life

Figure 2.19


Santa Barbara 73°
Burbank
90°
San Bernardino
100°
Riverside 96°
Los Angeles
(Airport) 75°
Santa Ana
84°
Palm Springs
106°
70s (°F)
80s
90s
100s
Pacific Ocean 68°
San Diego 72°
40 miles

Evaporative Cooling

- Evaporation (vaporization) is transformation of a substance from liquid to gas
- **Heat of vaporization** is the heat a liquid must absorb for 1 g to be converted to gas
- As a liquid evaporates, its remaining surface cools, a process called **evaporative cooling**
- Evaporative cooling of water helps stabilize temperatures in bodies or water and organisms

Floating of Ice on Liquid Water

- Ice floats in liquid water because hydrogen bonds in ice are more "ordered," making ice less dense
- Water reaches its greatest density at 4°C
- If ice sank, all bodies of water would eventually freeze solid, making life impossible on Earth

Figure 2.20

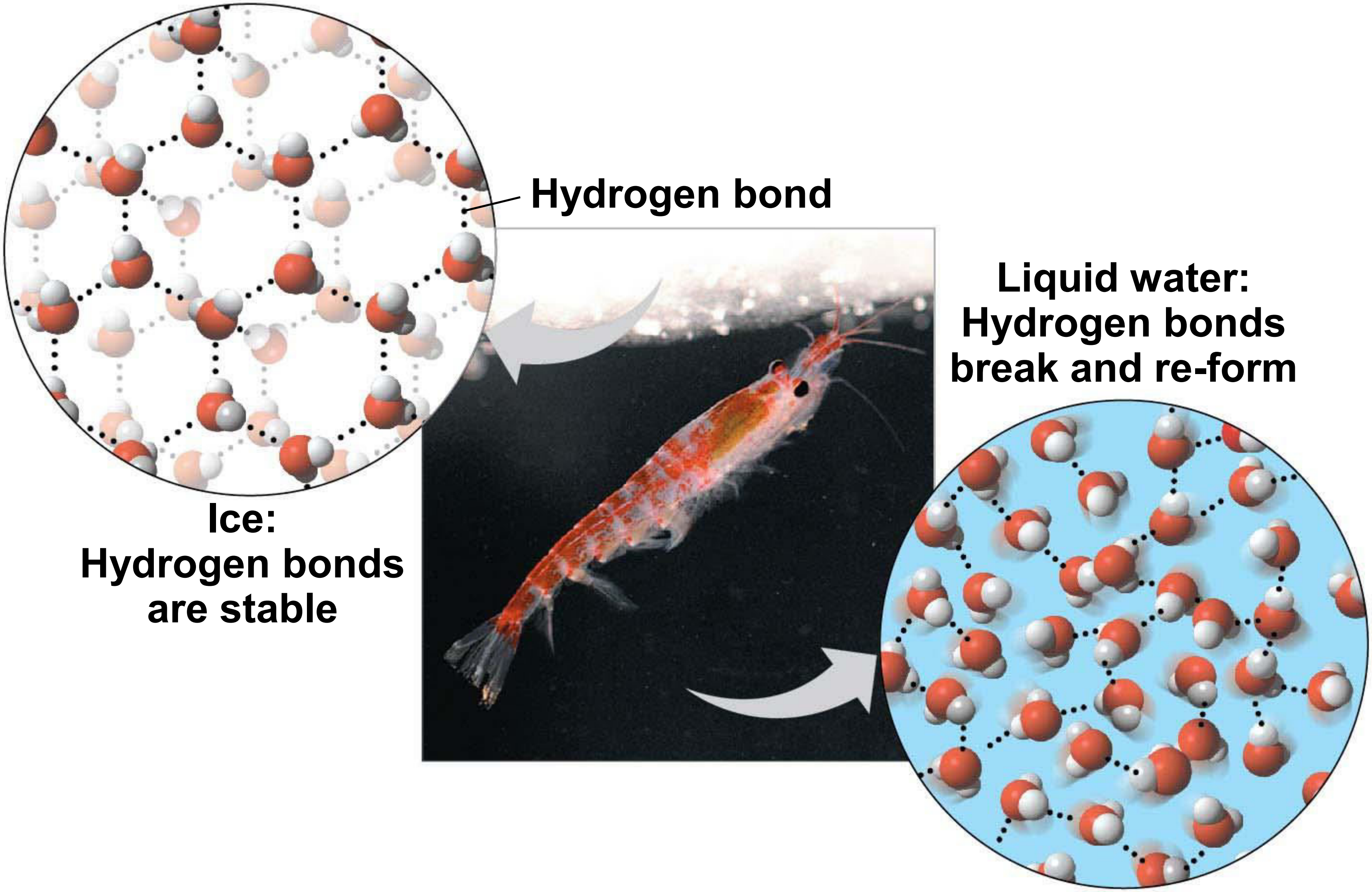

Hydrogen bond
Liquid water:
Hydrogen bonds
break and re-form
Ice:
Hydrogen bonds
are stable

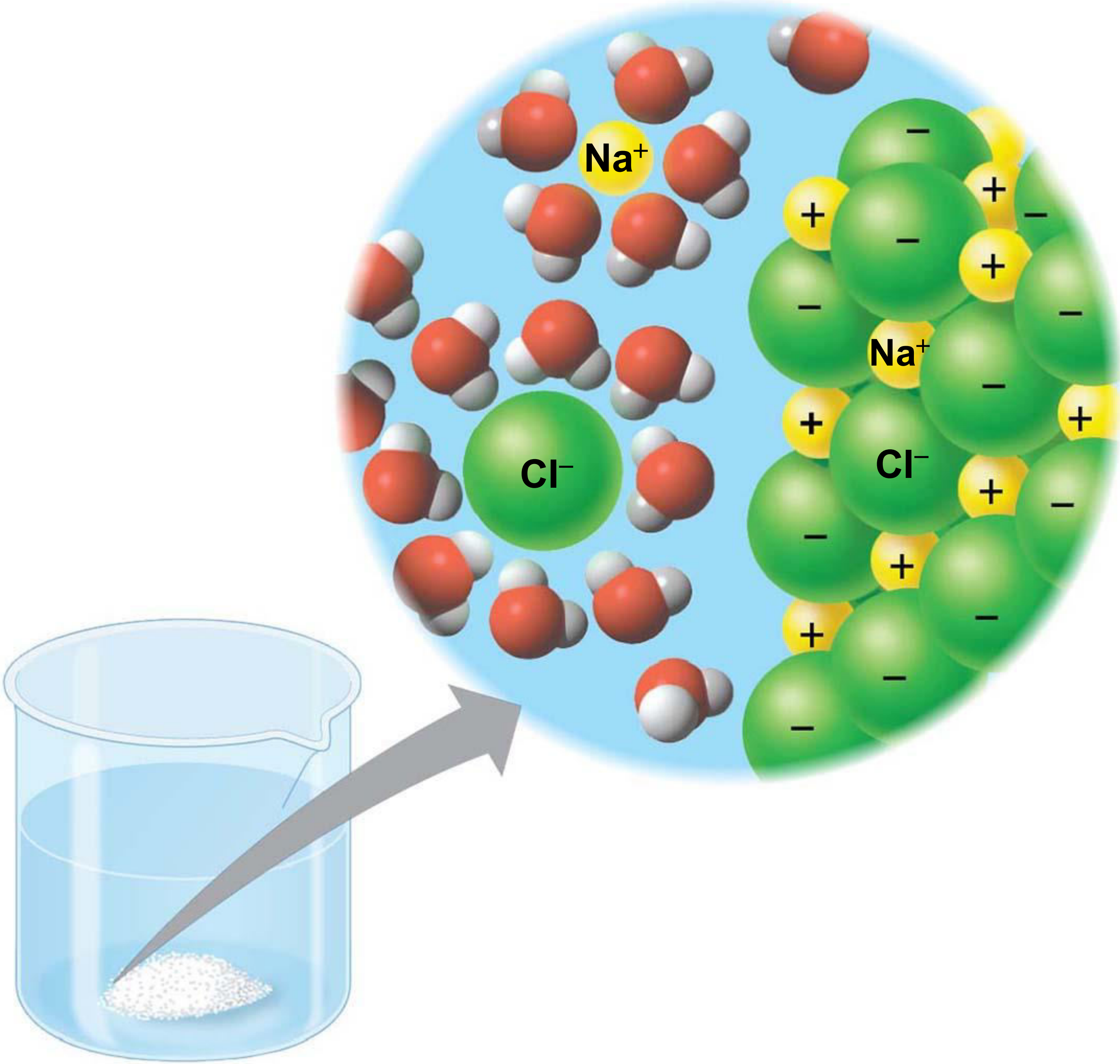
Figure 2.20-1

Water: The Solvent of Life

- A **solution** is a liquid that is a homogeneous mixture of substances
- A **solvent** is the dissolving agent of a solution
- The **solute** is the substance that is dissolved
- An **aqueous solution** is one in which water is the solvent

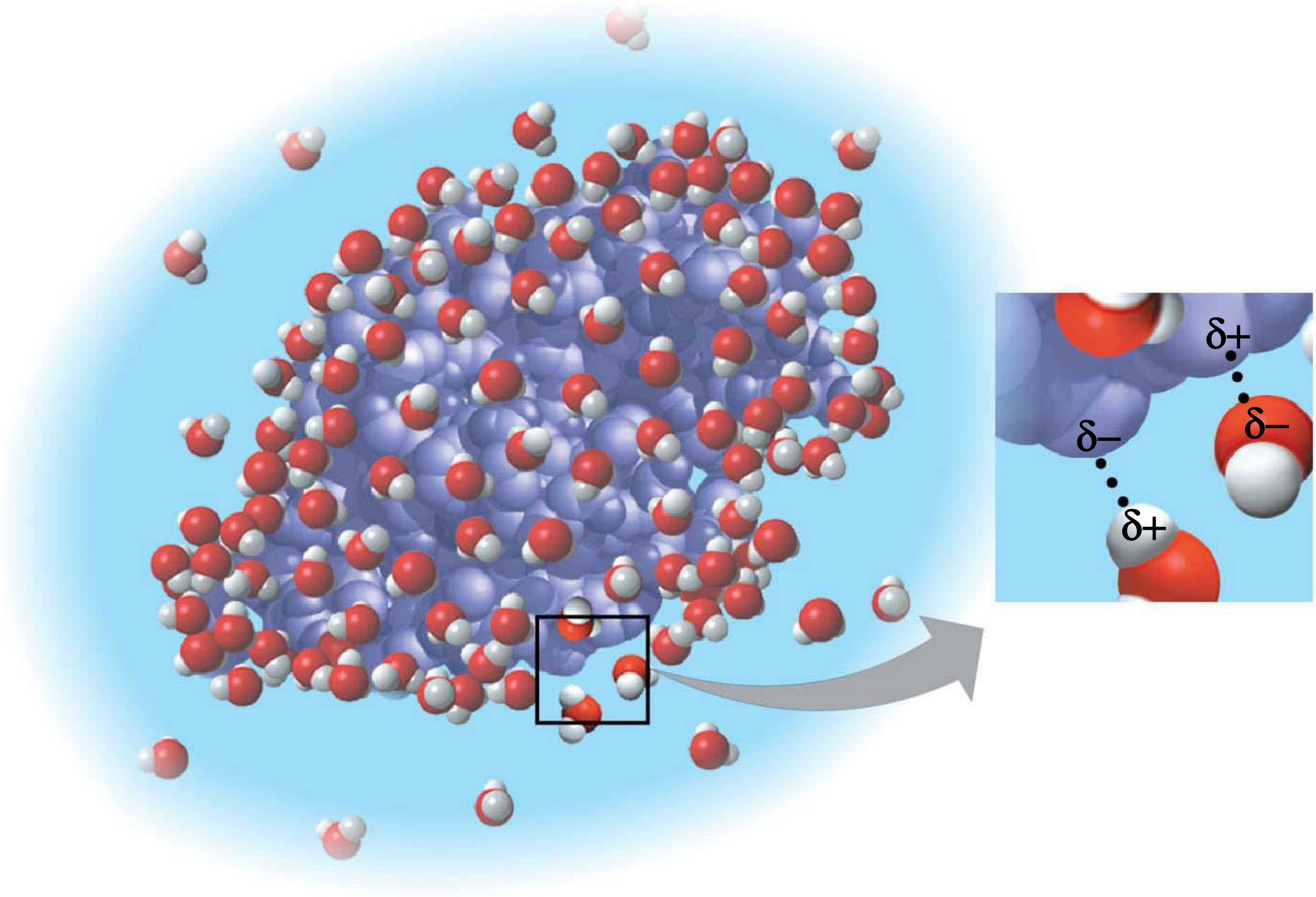
- Water is a versatile solvent due to its polarity, which allows it to form hydrogen bonds easily
- When an ionic compound is dissolved in water, each ion is surrounded by a sphere of water molecules called a **hydration shell**

Figure 2.21



- Water can also dissolve compounds made of nonionic polar molecules
- Even large polar molecules such as proteins can dissolve in water if they have ionic and polar regions

Figure 2.22



Hydrophilic and Hydrophobic Substances

- A **hydrophilic** substance is one that has an affinity for water
- A **hydrophobic** substance is one that does not have an affinity for water
- Oil molecules are hydrophobic because they have relatively nonpolar covalent bonds

Solute Concentration in Aqueous Solutions

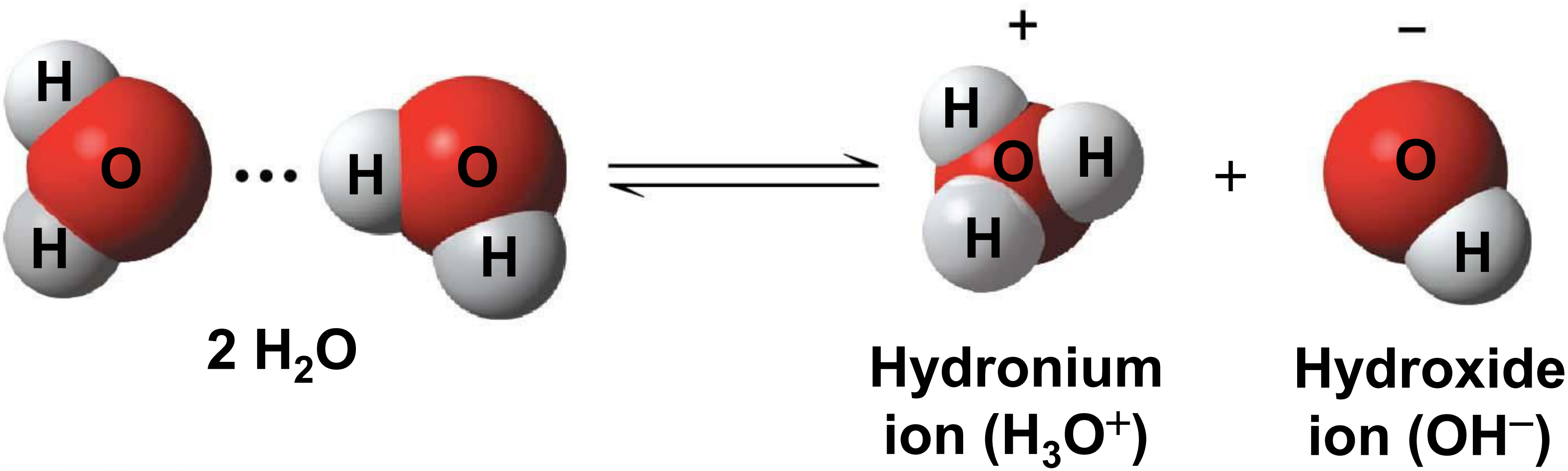
- Most chemical reactions in organisms involve solutes dissolved in water
- Chemical reactions depend on the concentration of solutes, or the number of molecules in a volume of an aqueous solution

- **Molecular mass** is the sum of all masses of all atoms in a molecule
- Numbers of molecules are usually measured in moles, where 1 **mole** (**mol**) = 6.02×10^{23} molecules
- Avogadro's number and the unit *dalton* were defined such that 6.02×10^{23} daltons = 1 g
- **Molarity** (***M***) is the number of moles of solute per liter of solution

Acids and Bases

- Sometimes a **hydrogen ion** (H^+) is transferred from one water molecule to another, leaving behind a **hydroxide ion** (OH^-)
- The proton (H^+) binds to the other water molecule, forming a **hydronium ion** (H_3O^+)
- By convention, H^+ is used to represent the hydronium ion

Figure 2.UN03



- Though water dissociation is rare and reversible, it is important in the chemistry of life
- H^+ and OH^- are very reactive
- Solutes called acids and bases disrupt the balance between H^+ and OH^- in pure water
- **Acids** increase the H^+ concentration in water, while **bases** reduce the concentration of H^+

- A strong acid like hydrochloric acid, HCl, dissociates completely into H^+ and Cl^- in water:

$$HCl \rightarrow H^+ + Cl^-$$

- Ammonia, NH_3, acts as a relatively weak base when it attracts a hydrogen ion from the solution and forms ammonium, NH_4^+
- This is a reversible reaction, as shown by the double arrows:

$$NH_3 + H^+ \rightleftharpoons NH_4^+$$

- Sodium hydroxide, NaOH, acts as a strong base indirectly by dissociating completely to form hydroxide ions:

$$NaOH \rightarrow Na^{+} + OH^{-}$$

- The hydroxide ions then combine with hydrogen ions to form water

- Weak acids act reversibly and accept back hydrogen ions
- Carbonic acid, H_2CO_3, acts as a weak acid:

$$H_2CO_3 \rightleftharpoons HCO_3^- + H^+$$

The pH Scale

- In any aqueous solution at 25°C, the product of H^+ and OH^- is constant and can be written as

$$[H^+][OH^-] = 10^{-14}$$

- The **pH** of a solution is defined as the negative logarithm of H^+ concentration, written as

$$pH = -\log [H^+]$$

- For a neutral aqueous solution, $[H^+]$ is 10^{-7} *M*, so

$$-\log [H^+] = -(-7) = 7$$

- Acidic solutions have pH values less than 7
- Basic solutions have pH values greater than 7
- Most biological fluids have pH values in the range of 6 to 8

Figure 2.23

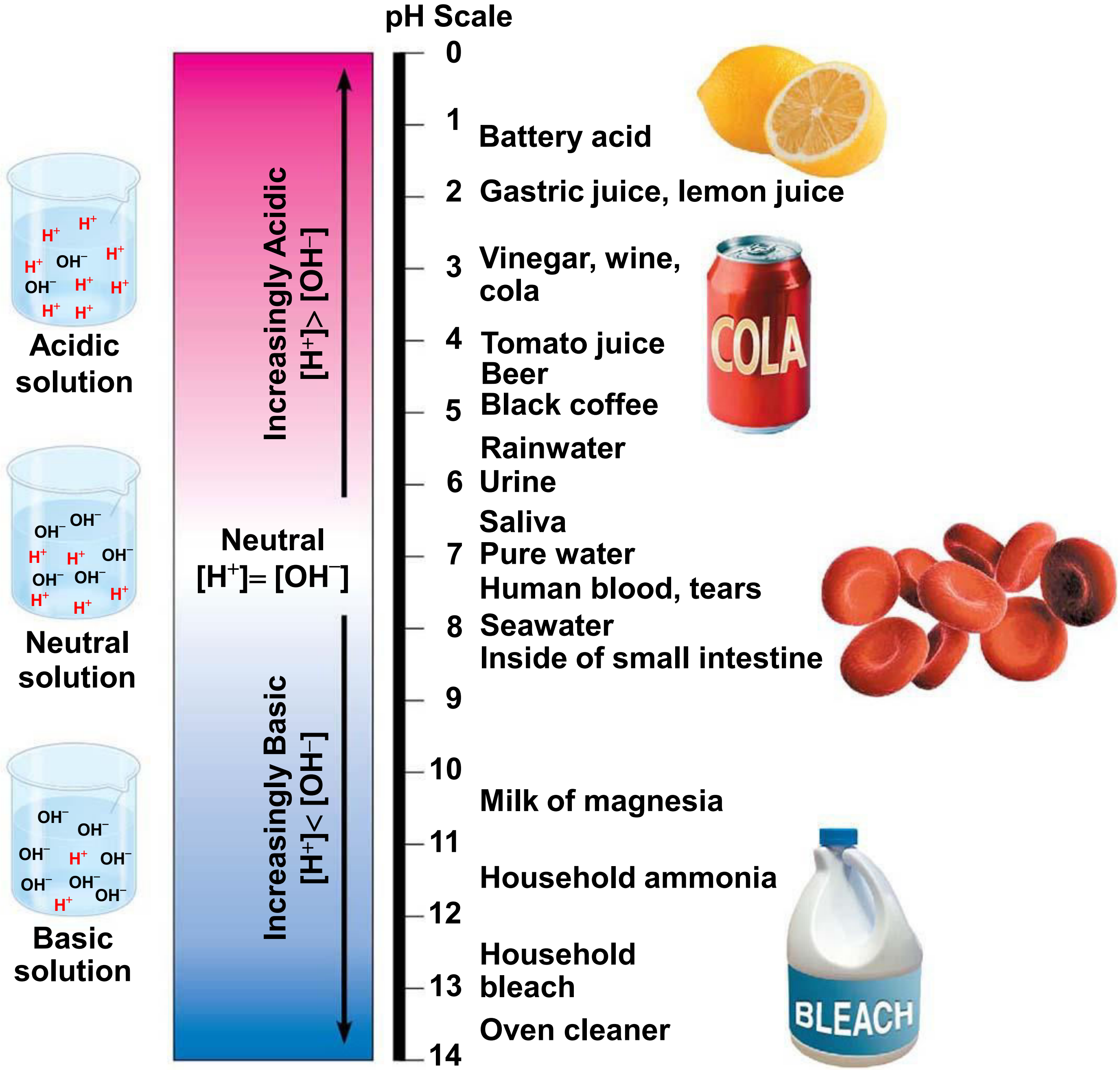
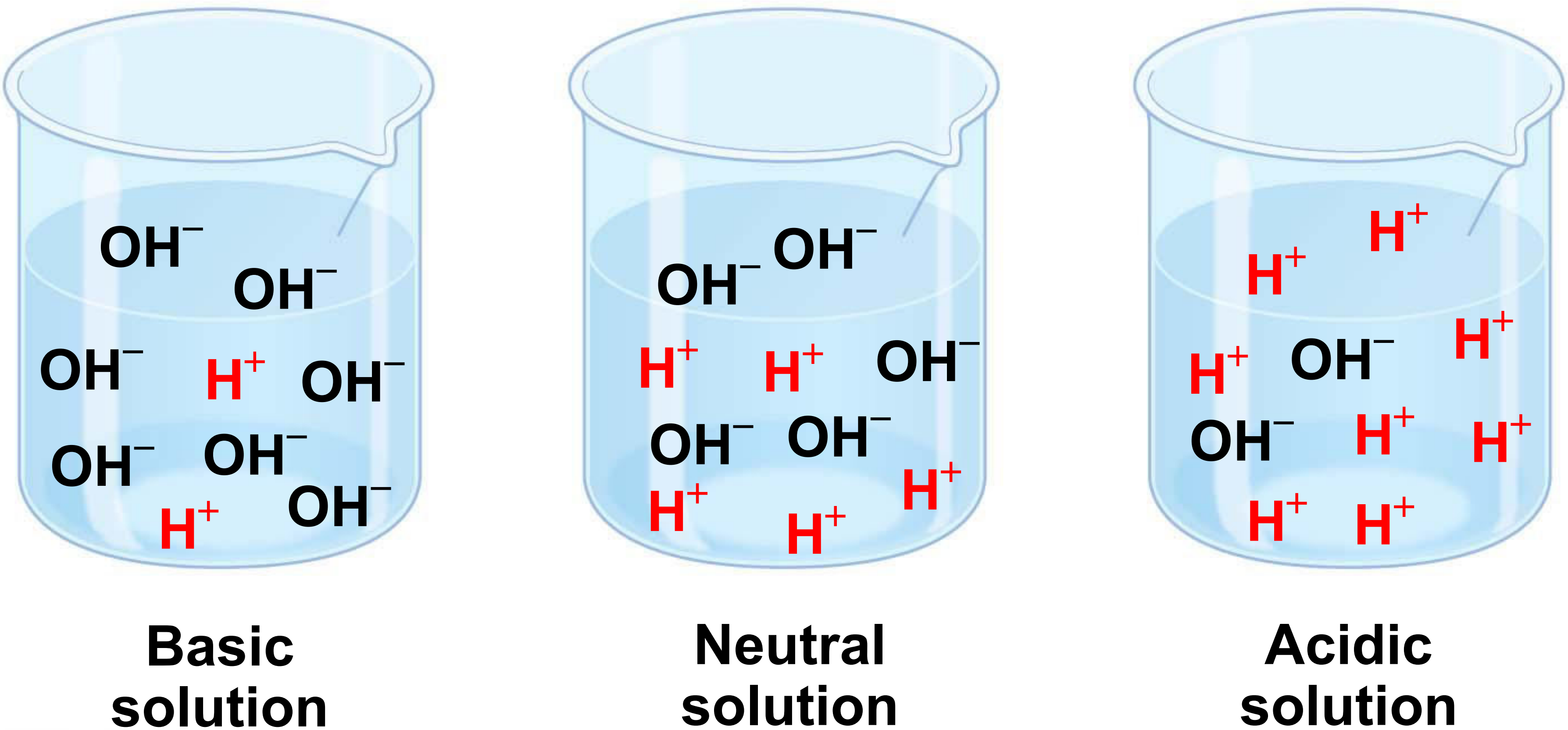

pH Scale
0
1 Battery acid
2 Gastric juice, lemon juice
3 Vinegar, wine, cola
4 Tomato juice
Beer
5 Black coffee
Rainwater
6 Urine
Saliva
7 Pure water
Human blood, tears
8 Seawater
Inside of small intestine
9
10
Milk of magnesia
11
Household ammonia
12
Household bleach
13
Oven cleaner
14
Increasingly Acidic
[H+] > [OH−]
Neutral
[H+] = [OH−]
Increasingly Basic
[H+] < [OH−]
Acidic solution
Neutral solution
Basic solution
COLA
BLEACH

Figure 2.23-1


OH–
OH–
OH–
H+
OH–
OH–
OH–
OH–
H+
Basic solution
OH–
OH–
H+
H+
OH–
OH–
OH–
H+
H+
H+
Neutral solution
H+
H+
H+
OH–
H+
OH–
H+
H+
H+
H+
Acidic solution

Buffers

- The internal pH of most living cells must remain close to pH 7
- **Buffers** are substances that minimize changes in concentrations of H^+ and OH^- in a solution
- Most buffer solutions contain a weak acid and its corresponding base, which combine reversibly with H^+

- Carbonic acid is a buffer that contributes to pH stability in human blood:

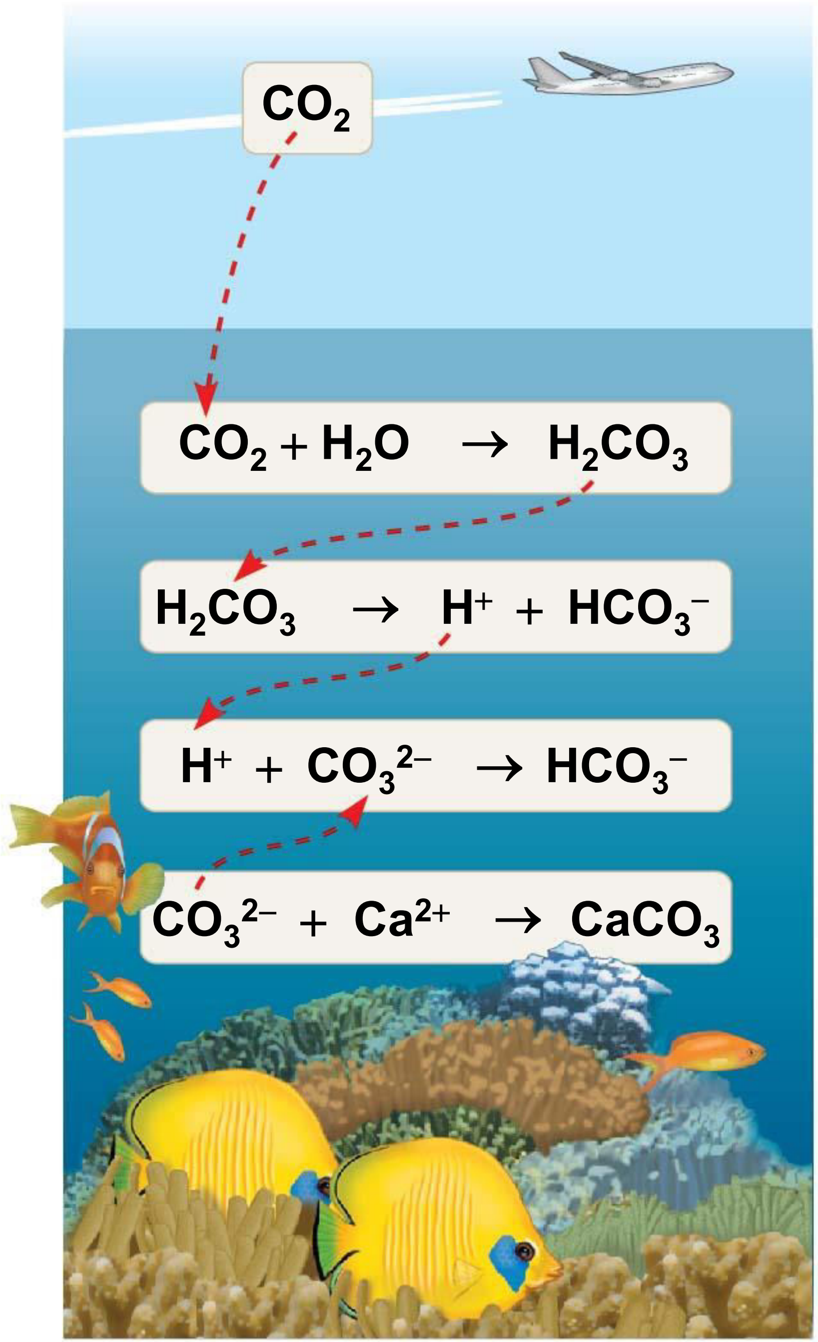
H_2CO_3	Response to a rise in PH $\rightleftharpoons$ Response to a drop in pH	HCO_3^-	+	H^+
H^+ donor (acid)		H^+ acceptor (base)		Hydrogen ion

Acidification: A Threat to Our Oceans

- Human activities such as burning fossil fuels threaten water quality
- CO_2 is a product of fossil fuel combustion
- About 25% of human-generated CO_2 is absorbed by the oceans
- CO_2 dissolved in seawater forms carbonic acid; this causes **ocean acidification**

- As seawater acidifies, hydrogen ions combine with carbonate ions to form bicarbonate ions (HCO_3^-)
- It is predicted that carbonate ion concentrations will decline by 40% by the year 2100
- This is a concern because organisms that build coral reefs or shells require carbonate ions

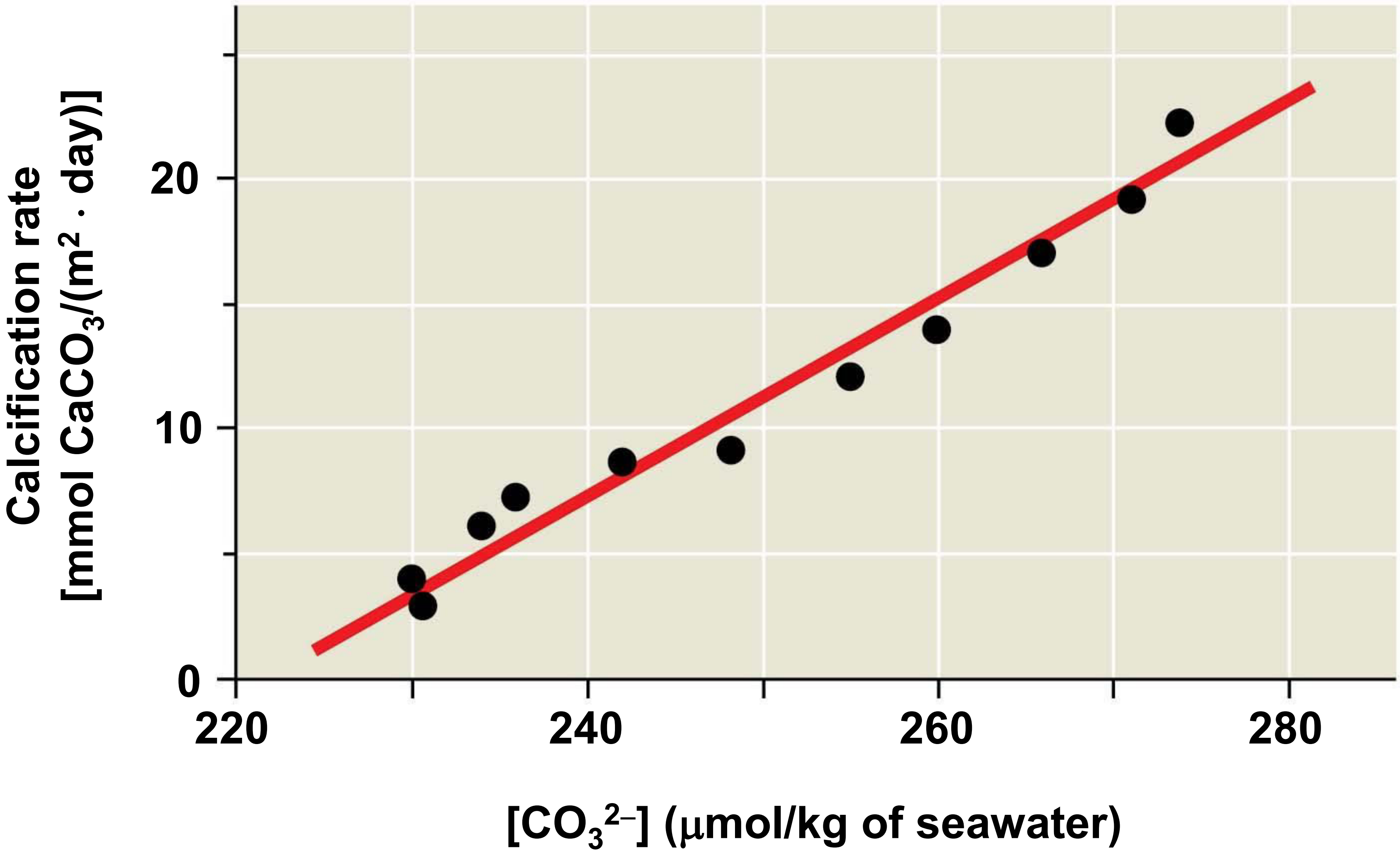
Figure 2.24



CO_2
$CO_2 + H_2O \rightarrow H_2CO_3$
$H_2CO_3 \rightarrow H^+ + HCO_3^-$
$H^+ + CO_3^{2-} \rightarrow HCO_3^-$
$CO_3^{2-} + Ca^{2+} \rightarrow CaCO_3$

Figure 2.UN01

Figure 2.UN04-1



Data from C. Langdon et al., Effect of calcium carbonate saturation state on the calcification rate of an experimental coral reef, *Global Biogeochemical Cycles* 14:639–654 (2000).

Figure 2.UN04-2

Figure 2.UN05

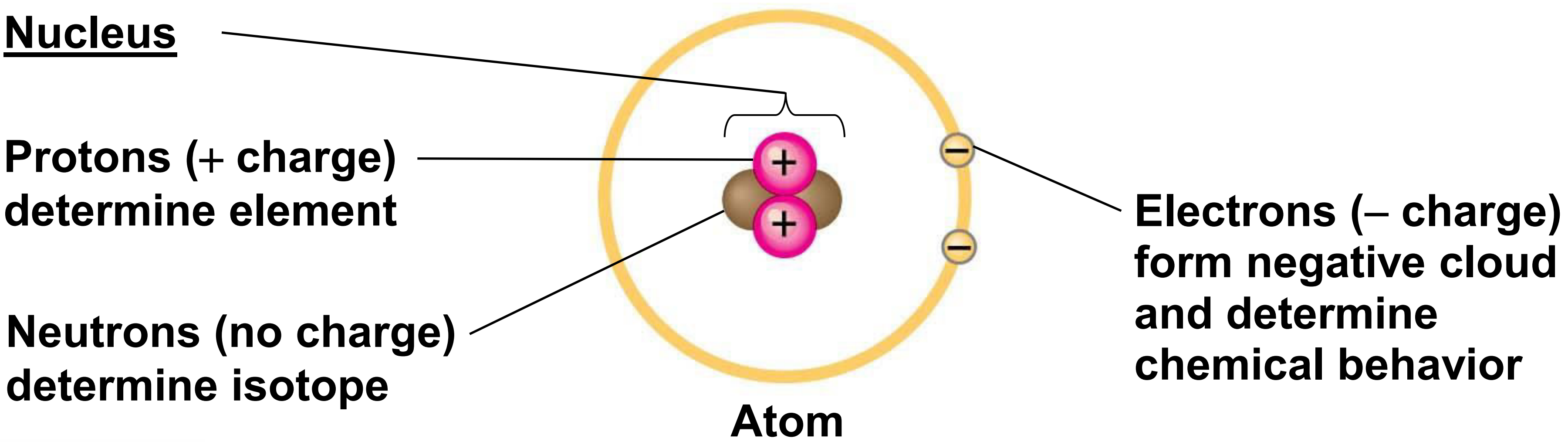


Figure 2.UN06

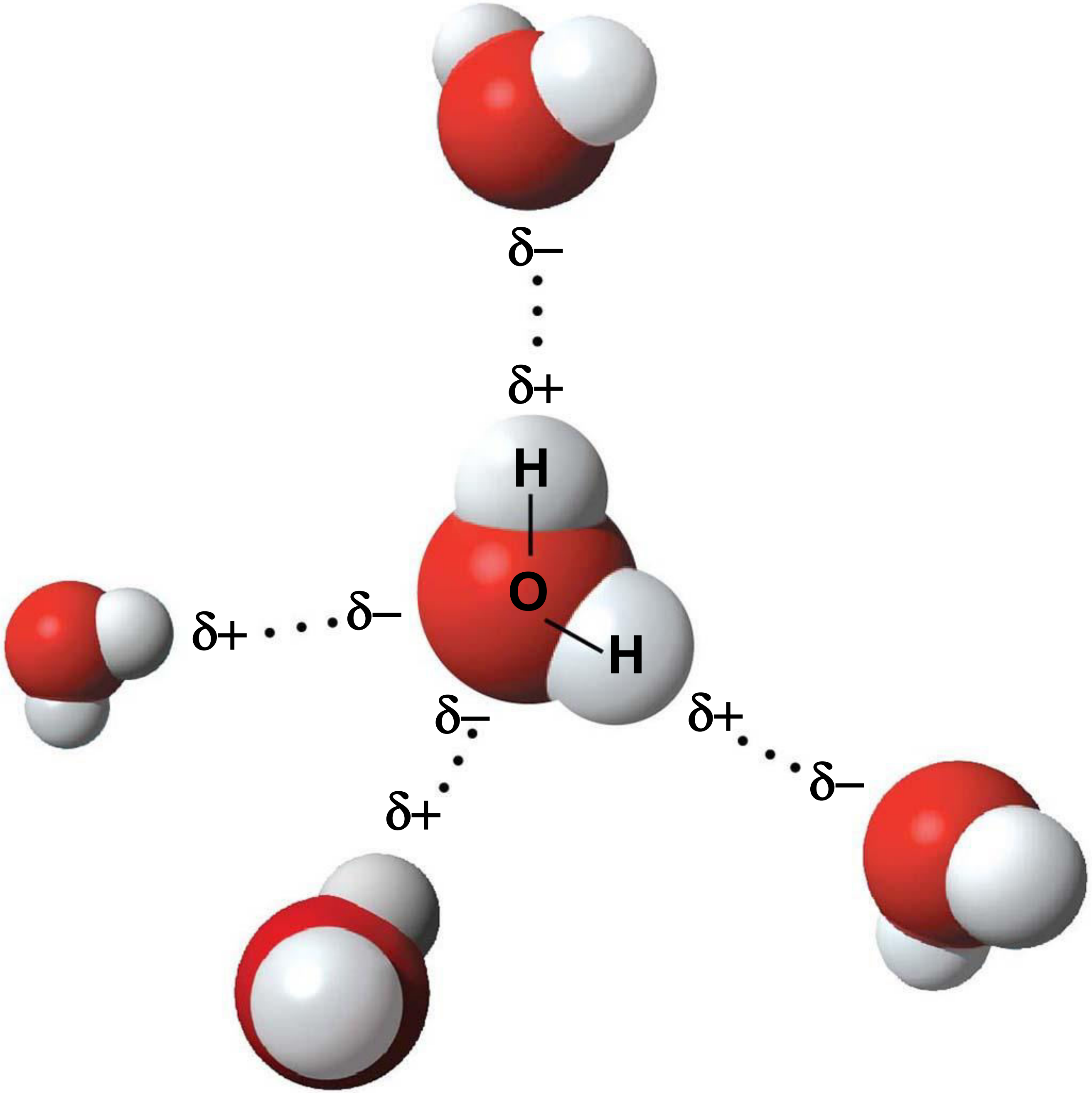
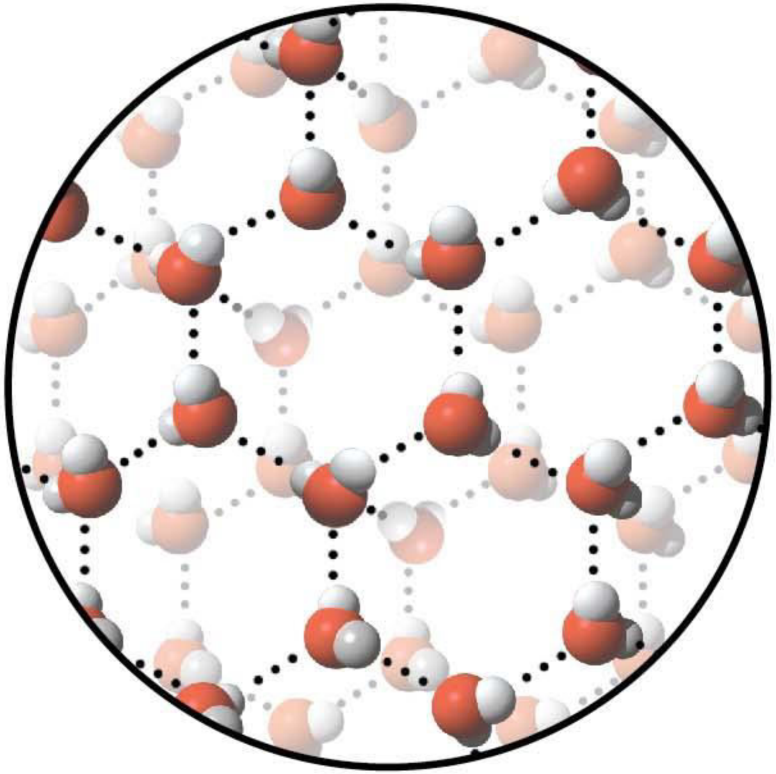
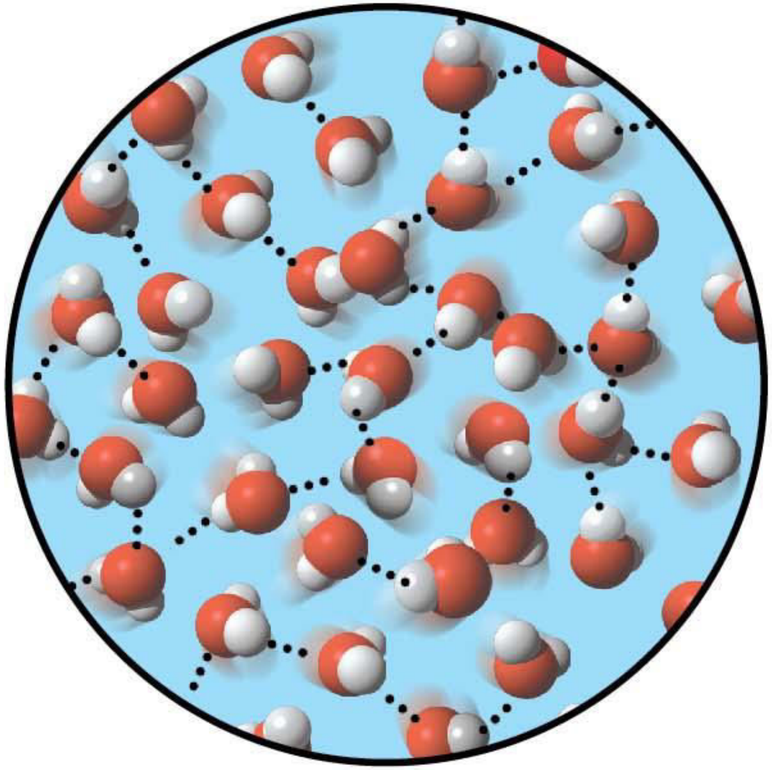


Figure 2.UN07



Ice: stable hydrogen bonds



Liquid water: transient hydrogen bonds

Figure 2.UN08

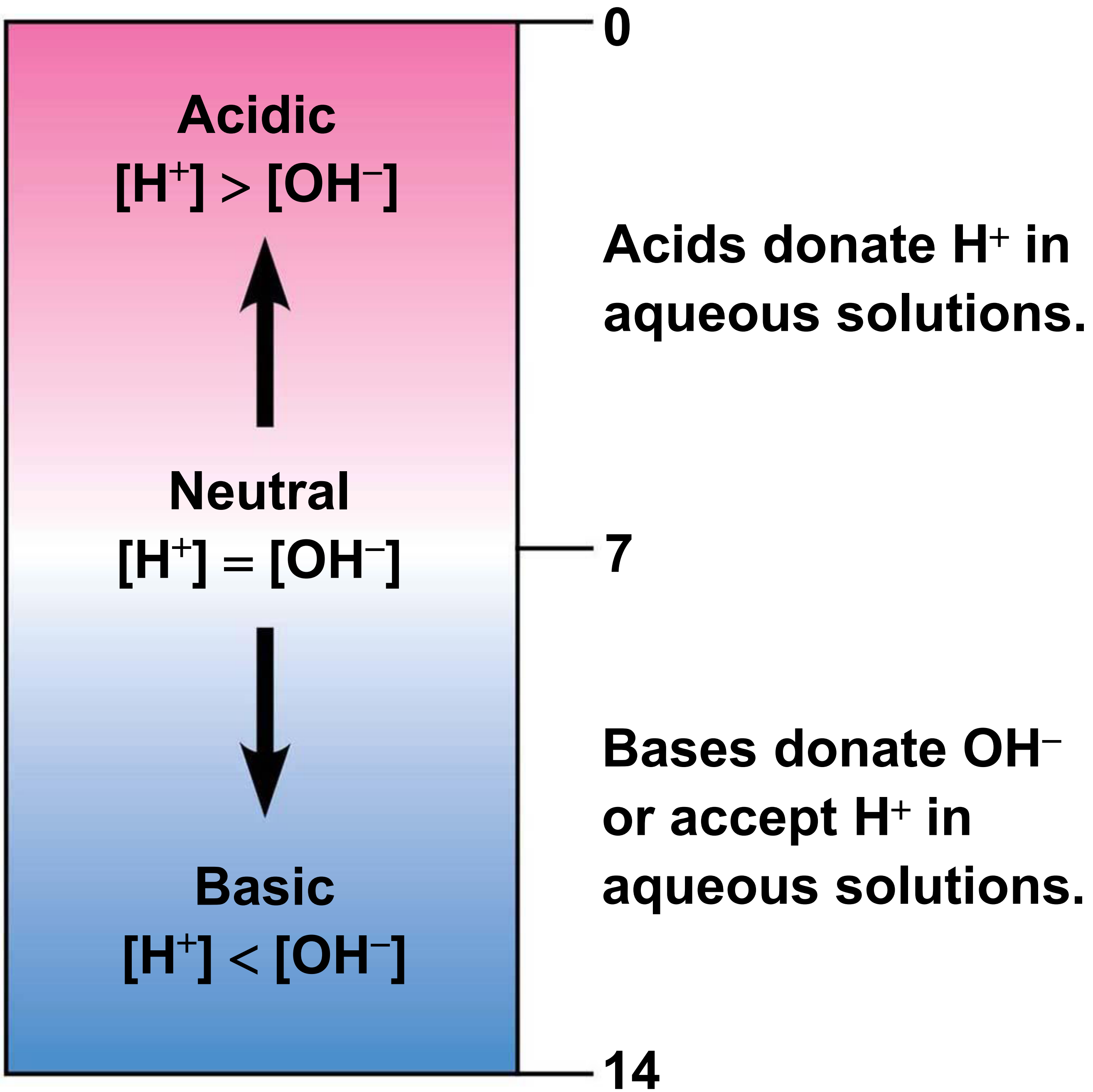


Figure 2.UN09

Figure 2.UN10