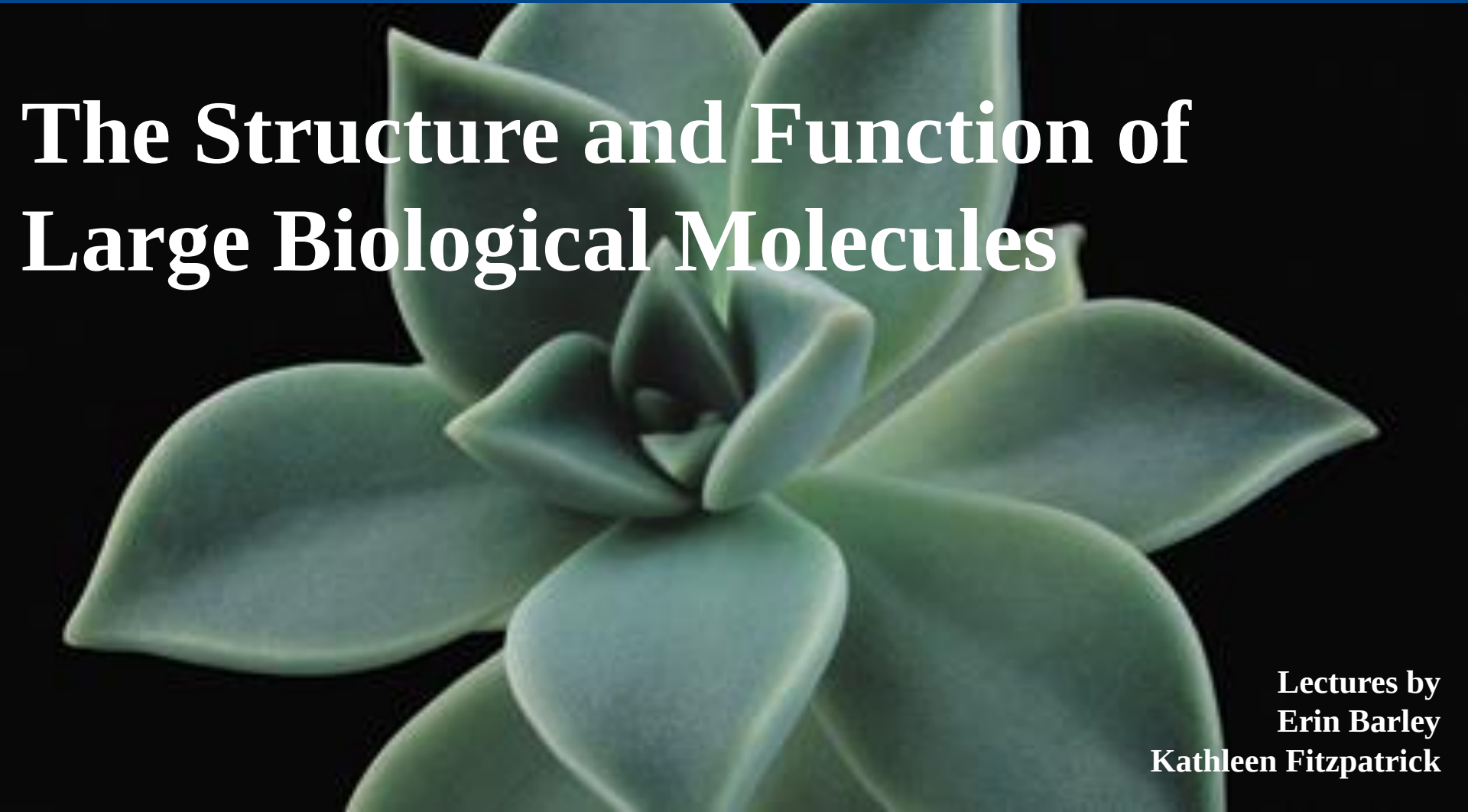


# Chapter 5

## The Structure and Function of Large Biological Molecules



**Lectures by  
Erin Barley  
Kathleen Fitzpatrick**

# Overview: The Molecules of Life

- All living things are made up of four classes of large biological molecules: carbohydrates, lipids, proteins, and nucleic acids
- **Macromolecules** are large molecules composed of thousands of covalently connected atoms
- Molecular structure and function are inseparable

# Concept 5.1: Macromolecules are polymers, built from monomers

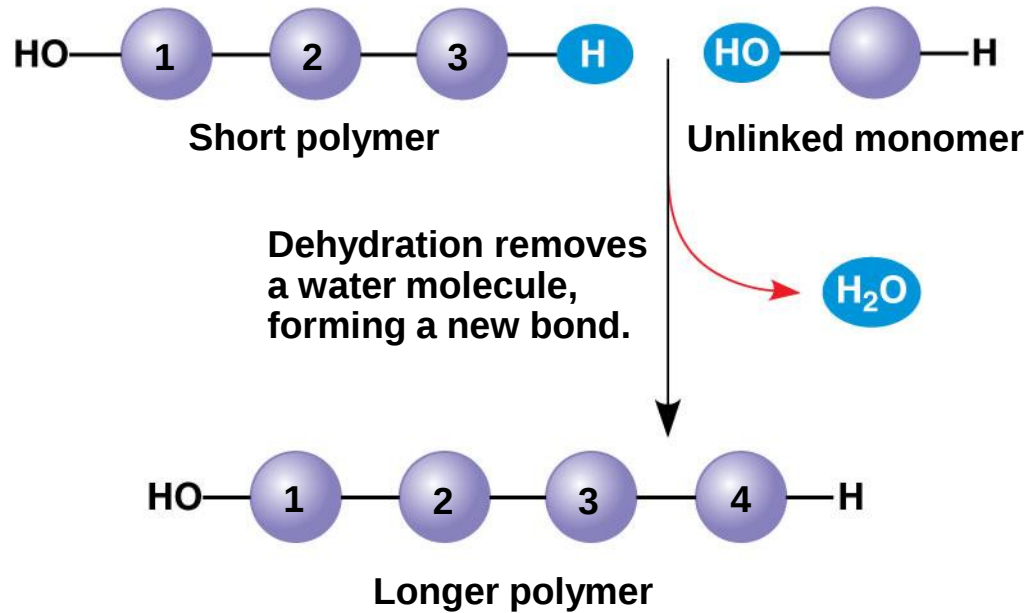
- A **polymer** is a long molecule consisting of many similar building blocks
- These small building-block molecules are called **monomers**
- Three of the four classes of life's organic molecules are polymers
  - Carbohydrates
  - Proteins
  - Nucleic acids

# The Synthesis and Breakdown of Polymers

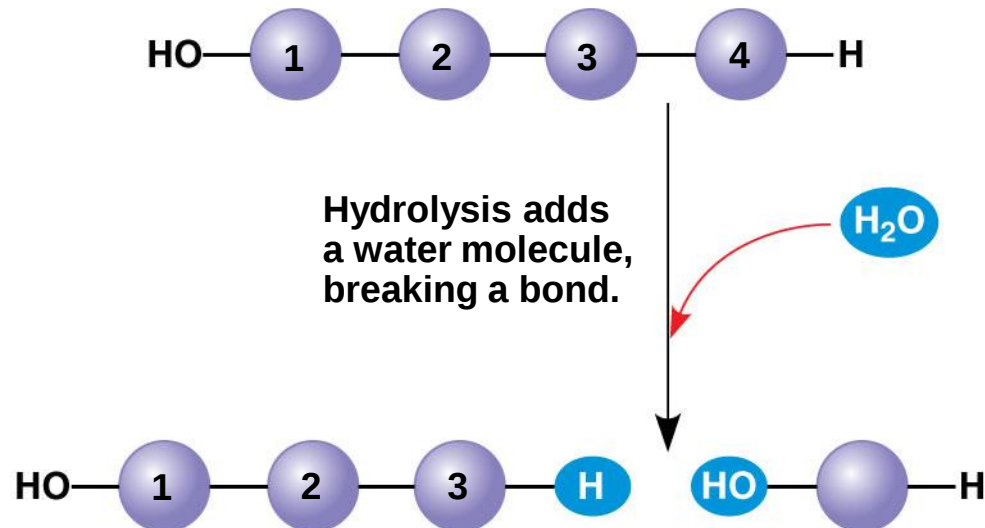
- A **dehydration reaction** occurs when two monomers bond together through the loss of a water molecule
- Polymers are disassembled to monomers by **hydrolysis**, a reaction that is essentially the reverse of the dehydration reaction

Figure 5.2

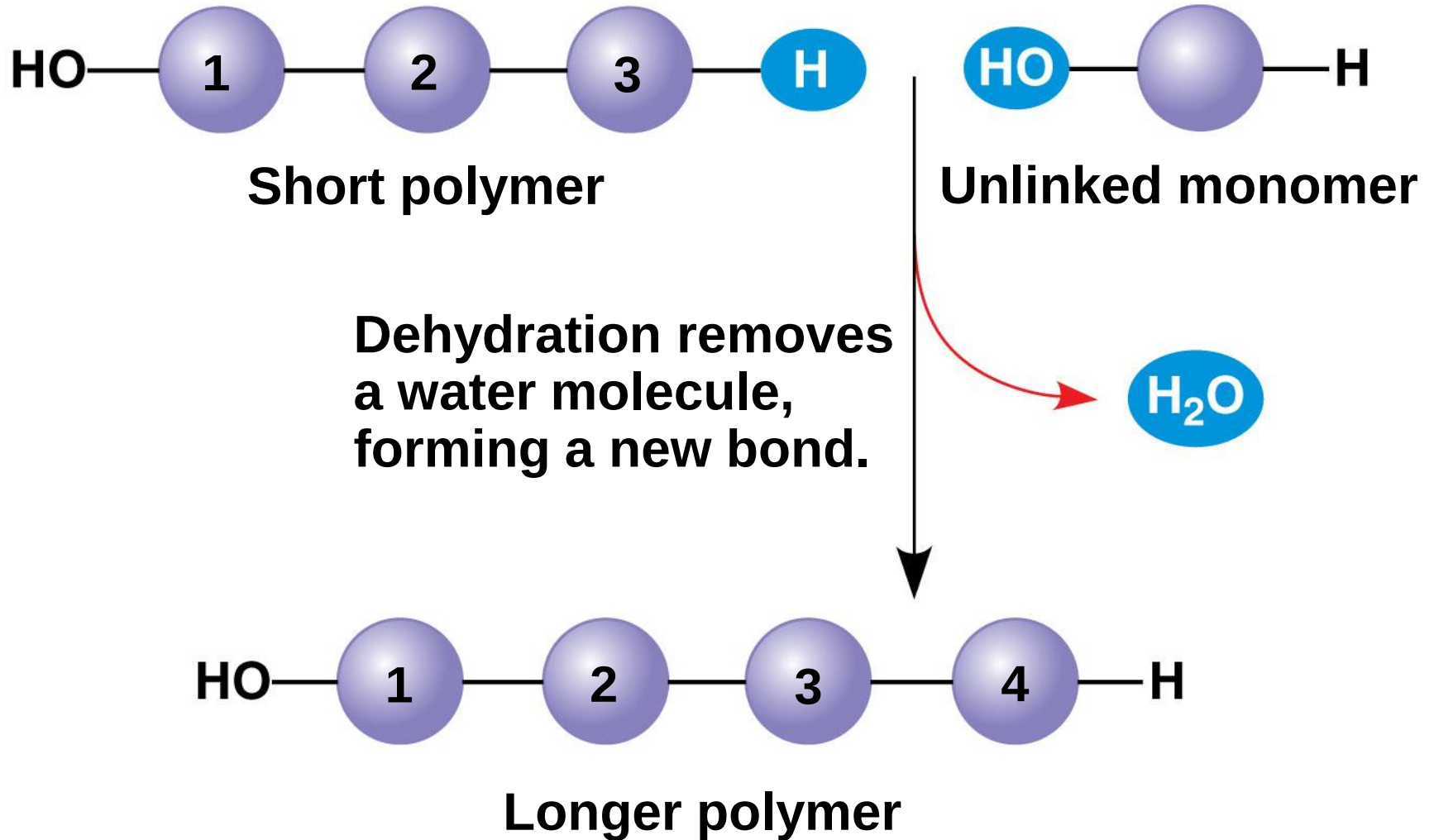
**(a) Dehydration reaction: synthesizing a polymer**



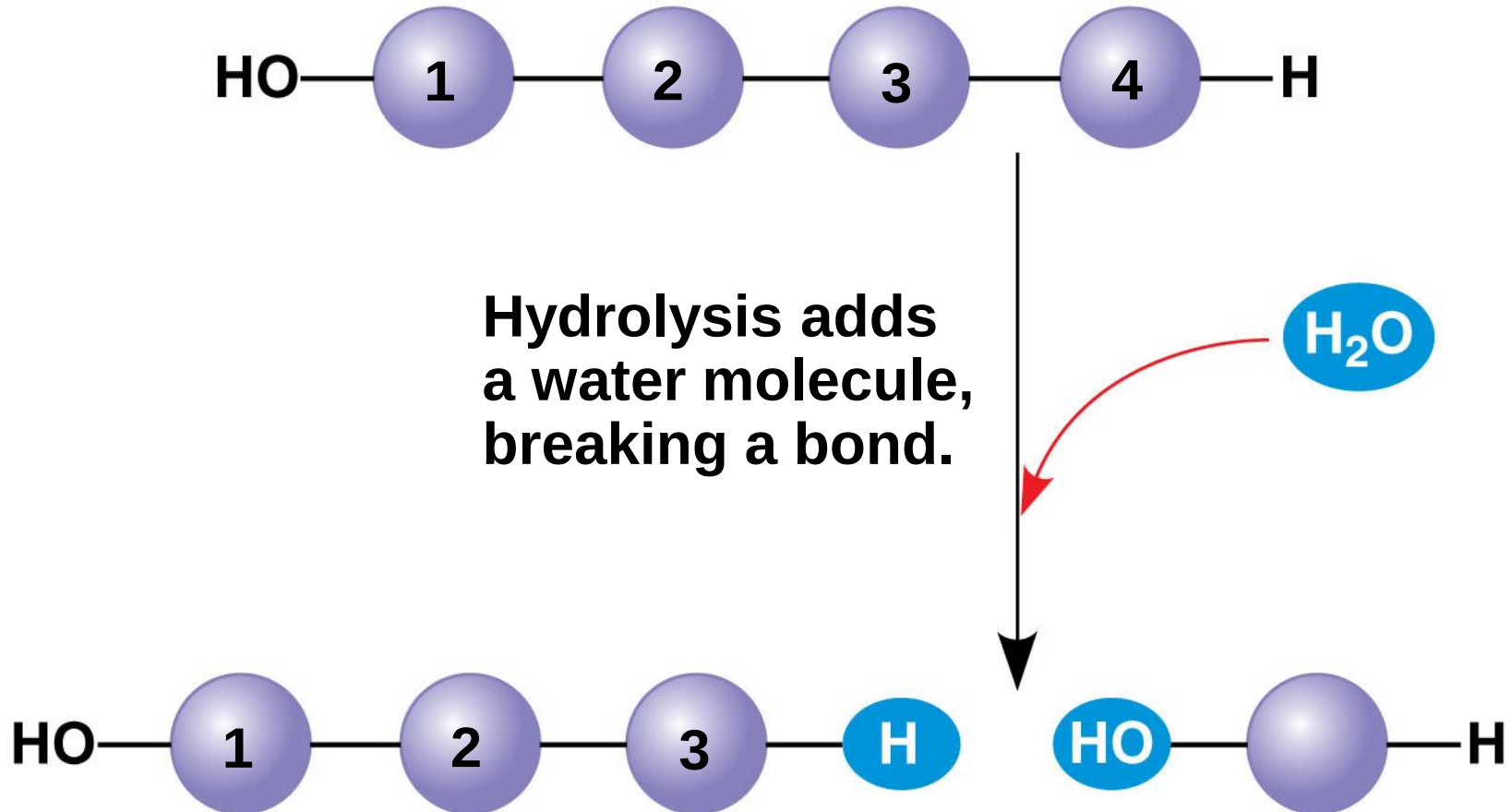
**(b) Hydrolysis: breaking down a polymer**



## (a) Dehydration reaction: synthesizing a polymer



## (b) Hydrolysis: breaking down a polymer



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# 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 5.2: Carbohydrates serve as fuel and building material

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

# Sugars

- **Monosaccharides** have molecular formulas that are usually multiples of  $\text{CH}_2\text{O}$
- Glucose ( $\text{C}_6\text{H}_{12}\text{O}_6$ ) is the most common monosaccharide
- Monosaccharides are classified by
  - The location of the carbonyl group (as aldose or ketose)
  - The number of carbons in the carbon skeleton

Figure 5.3

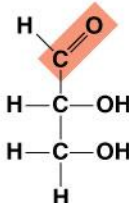
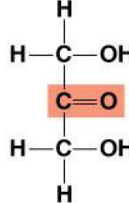
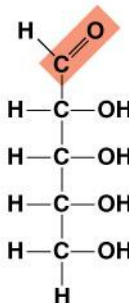
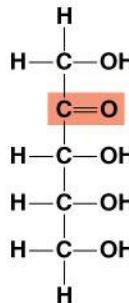
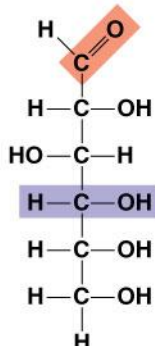
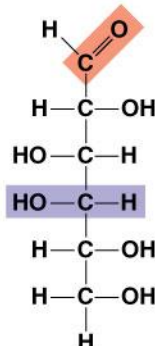
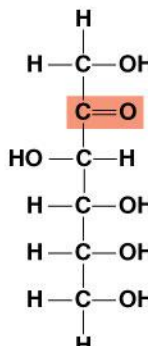
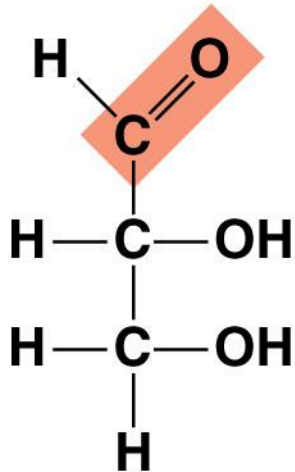
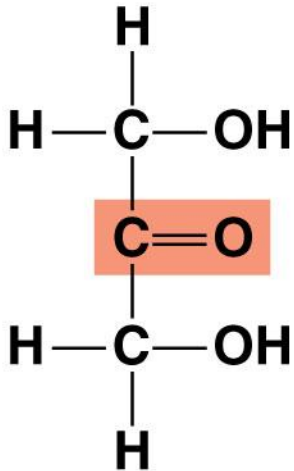
| Aldoses (Aldehyde Sugars)                                                          |                                                                                    | Ketoses (Ketone Sugars)                                                              |  |
|------------------------------------------------------------------------------------|------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------|--|
| Trioses: 3-carbon sugars (C <sub>3</sub> H <sub>6</sub> O <sub>3</sub> )           |                                                                                    |                                                                                      |  |
|   |                                                                                    |   |  |
| Glyceraldehyde                                                                     |                                                                                    | Dihydroxyacetone                                                                     |  |
| Pentoses: 5-carbon sugars (C <sub>5</sub> H <sub>10</sub> O <sub>5</sub> )         |                                                                                    |                                                                                      |  |
|   |                                                                                    |   |  |
| Ribose                                                                             |                                                                                    | Ribulose                                                                             |  |
| Hexoses: 6-carbon sugars (C <sub>6</sub> H <sub>12</sub> O <sub>6</sub> )          |                                                                                    |                                                                                      |  |
|  |  |  |  |
| Glucose                                                                            |                                                                                    | Fructose                                                                             |  |
| Galactose                                                                          |                                                                                    |                                                                                      |  |

Figure 5.3a

| Aldose (Aldehyde Sugar)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               | Ketose (Ketone Sugar)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                |
|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Trioses: 3-carbon sugars ( $C_3H_6O_3$ )                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      |
|  <p>The chemical structure of glyceraldehyde is shown. It consists of a three-carbon chain. The top carbon (C1) is an aldehyde group, with a hydrogen atom (H) to its left and a double-bonded oxygen atom (O) to its right. This C1 is highlighted with an orange diamond. The middle carbon (C2) is bonded to a hydrogen atom (H) on the left and a hydroxyl group (OH) on the right. The bottom carbon (C3) is bonded to a hydrogen atom (H) on the left and a hydroxyl group (OH) on the right, with a hydrogen atom (H) also bonded below it.</p> <p><b>Glyceraldehyde</b></p> |  <p>The chemical structure of dihydroxyacetone is shown. It consists of a three-carbon chain. The top carbon (C1) is bonded to a hydrogen atom (H) above it, a hydrogen atom (H) to its left, and a hydroxyl group (OH) to its right. The middle carbon (C2) is a ketone group, with a double-bonded oxygen atom (O) to its right. This C2 is highlighted with an orange rectangle. The bottom carbon (C3) is bonded to a hydrogen atom (H) to its left and a hydroxyl group (OH) to its right, with a hydrogen atom (H) also bonded below it.</p> <p><b>Dihydroxyacetone</b></p> |

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Figure 5.3b

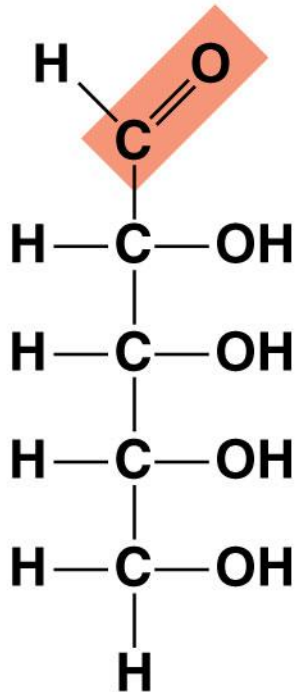
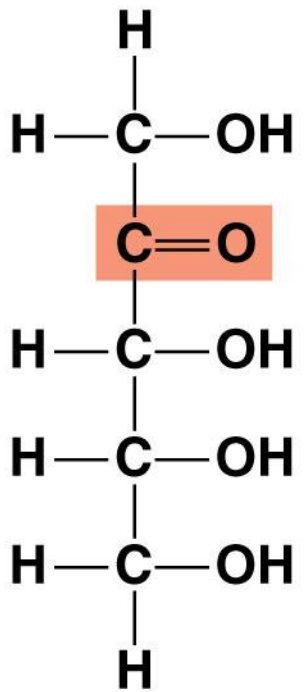
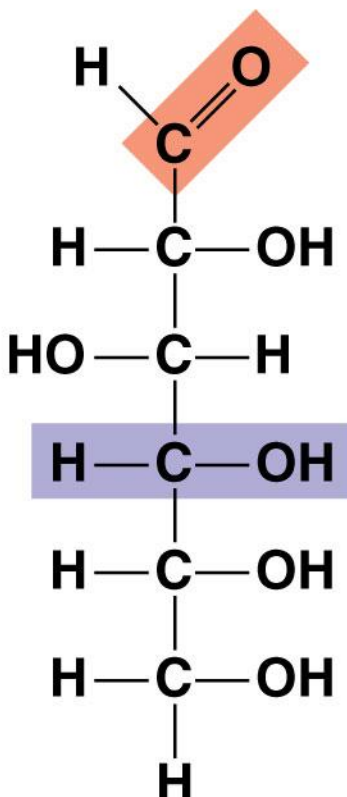
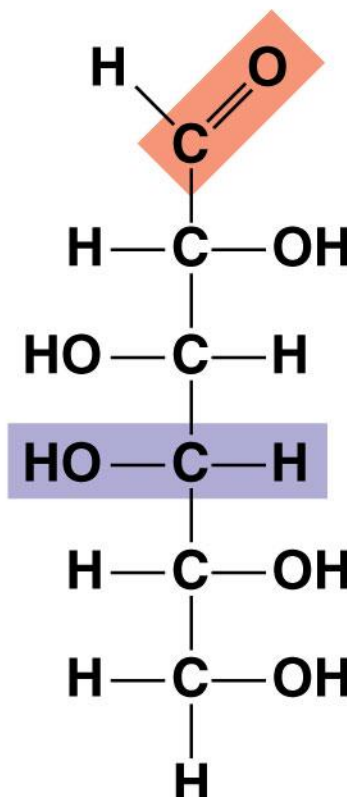
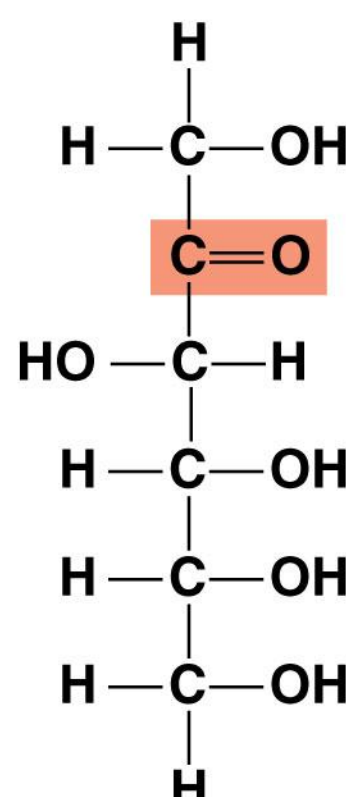
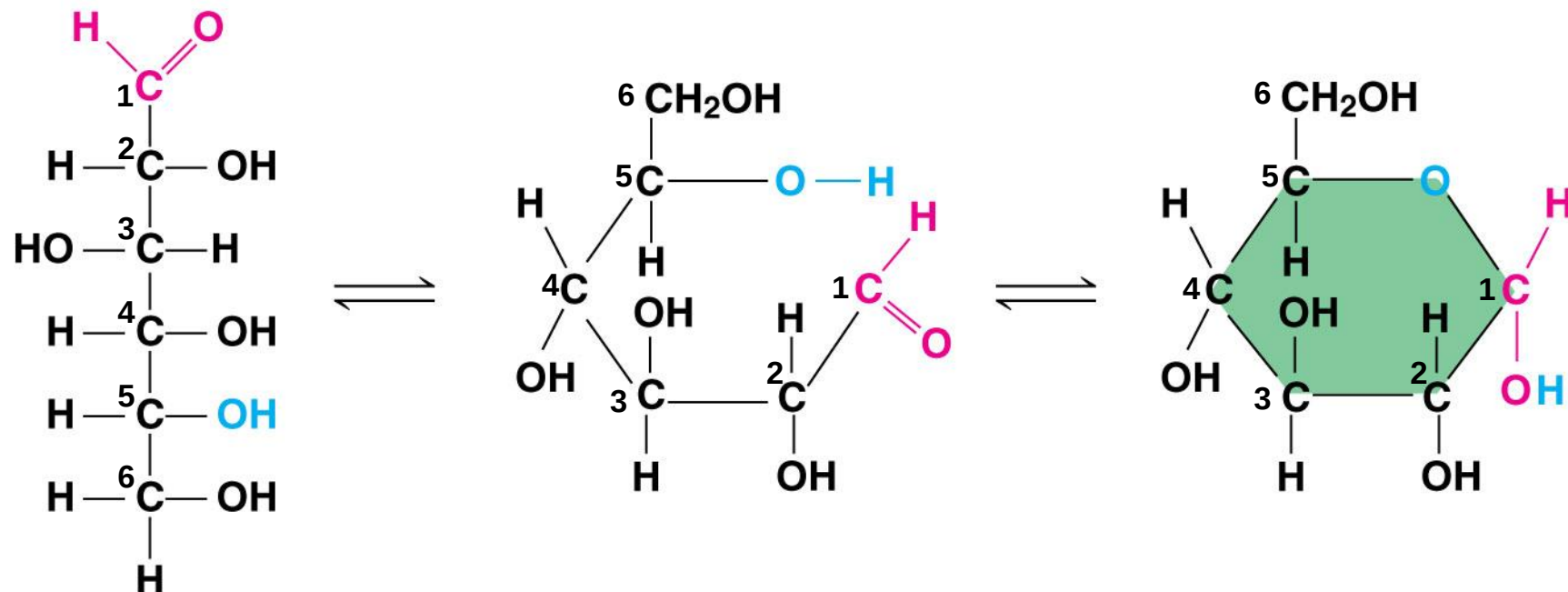
| Aldose (Aldehyde Sugar)                                                                                                               | Ketose (Ketone Sugar)                                                                                                                       |
|---------------------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------|
| Pentoses: 5-carbon sugars ( $C_5H_{10}O_5$ )                                                                                          |                                                                                                                                             |
|  <p data-bbox="425 1156 637 1213"><b>Ribose</b></p> |  <p data-bbox="1275 1156 1545 1213"><b>Ribulose</b></p> |

Figure 5.3c

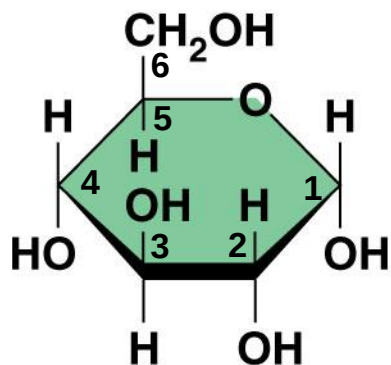
| Aldose (Aldehyde Sugar)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        | Ketose (Ketone Sugar)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                              |
|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Hexoses: 6-carbon sugars (C <sub>6</sub> H <sub>12</sub> O <sub>6</sub> )                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                      |                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                    |
| <div><p>The Fischer projection of glucose shows a vertical chain of six carbon atoms. The top carbon (C1) is an aldehyde group with H on the left and O on the right, highlighted with an orange diamond. C2 has H on the left and OH on the right. C3 has OH on the left and H on the right. C4 has H on the left and OH on the right, highlighted with a purple rectangle. C5 has H on the left and OH on the right. The bottom carbon (C6) is bonded to H on the left and H on the right.</p></div> <p><b>Glucose</b></p> | <div><p>The Fischer projection of galactose shows a vertical chain of six carbon atoms. The top carbon (C1) is an aldehyde group with H on the left and O on the right, highlighted with an orange diamond. C2 has H on the left and OH on the right. C3 has HO on the left and H on the right. C4 has HO on the left and H on the right, highlighted with a purple rectangle. C5 has H on the left and OH on the right. The bottom carbon (C6) is bonded to H on the left and H on the right.</p></div> <p><b>Galactose</b></p> |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                | <div><p>The Fischer projection of fructose shows a vertical chain of six carbon atoms. The top carbon (C1) is bonded to H on the left and OH on the right. C2 has H on the left and OH on the right. C3 is a ketone group with C=O highlighted in an orange rectangle. C4 has HO on the left and H on the right. C5 has H on the left and OH on the right. The bottom carbon (C6) is bonded to H on the left and OH on the right.</p></div> <p><b>Fructose</b></p>                                                             |

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

Figure 5.4



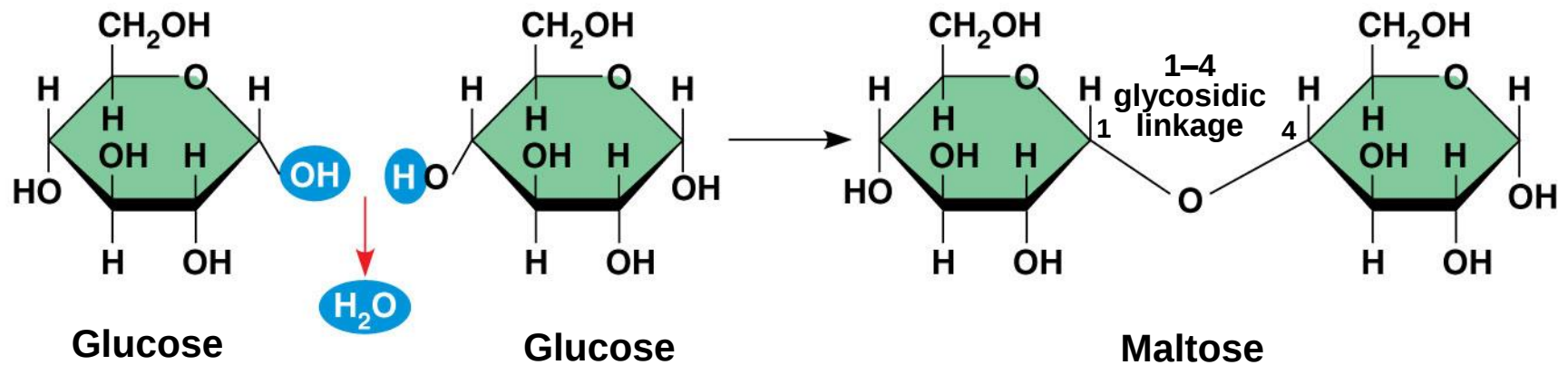
(a) Linear and ring forms



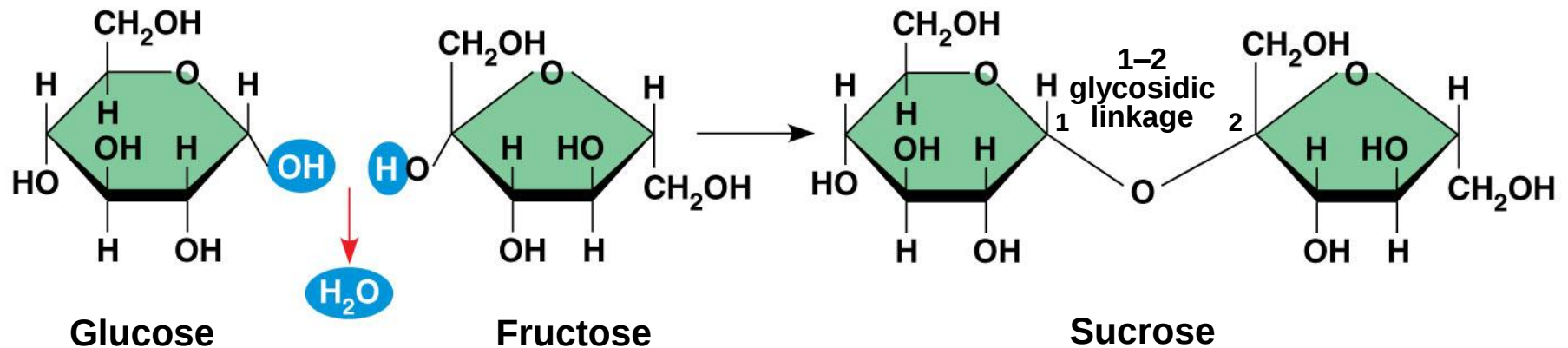
(b) Abbreviated ring structure

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

Figure 5.5



(a) Dehydration reaction in the synthesis of maltose



(b) Dehydration reaction in the synthesis of sucrose

# 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*

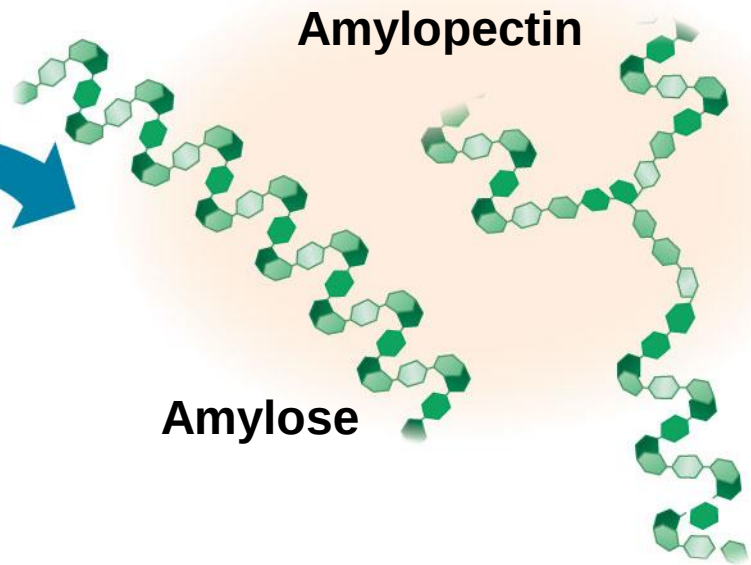
- **Starch**, a storage polysaccharide of plants, consists entirely of glucose monomers
- Plants store surplus starch as granules within chloroplasts and other plastids
- The simplest form of starch is amylose

Figure 5.6

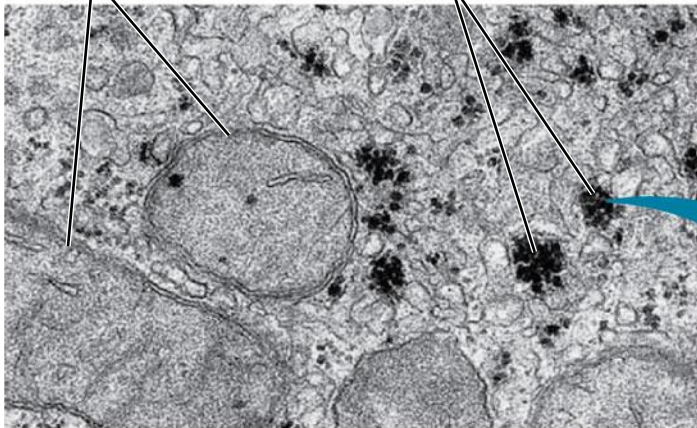
**Chloroplast**      **Starch granules**



**(a) Starch:**  
a plant polysaccharide



**Mitochondria**      **Glycogen granules**



**(b) Glycogen:**  
an animal polysaccharide

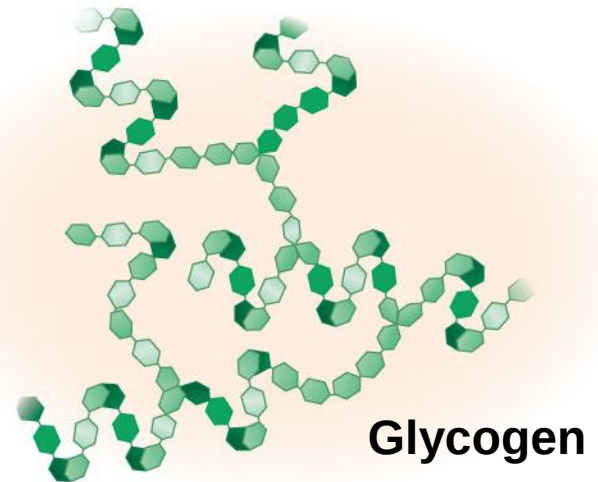
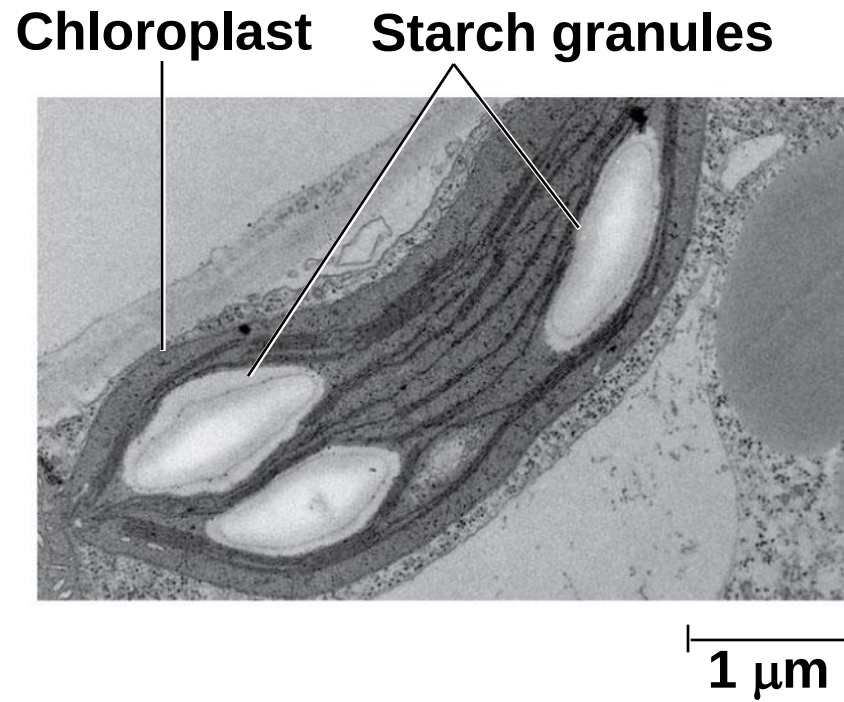


Figure 5.6a

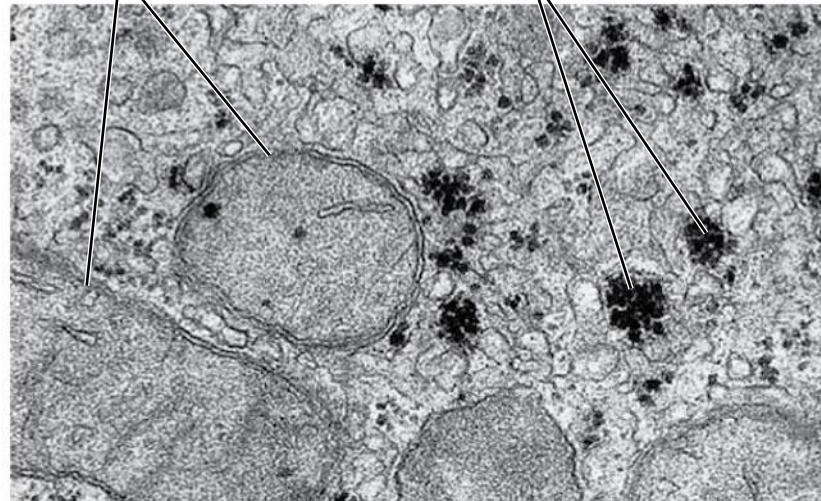


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- **Glycogen** is a storage polysaccharide in animals
- Humans and other vertebrates store glycogen mainly in liver and muscle cells

Figure 5.6b

**Mitochondria**      **Glycogen granules**



0.5  $\mu\text{m}$

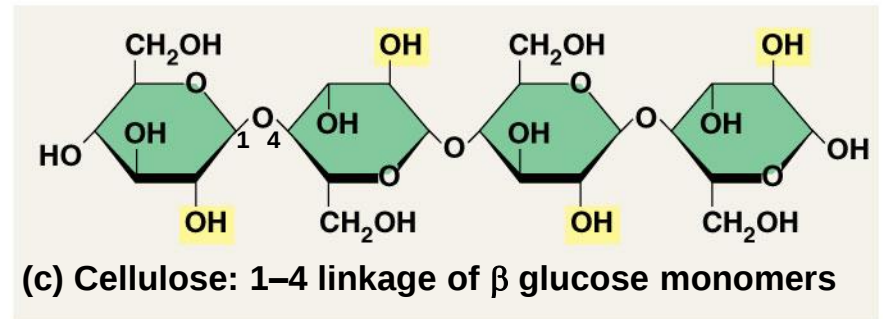
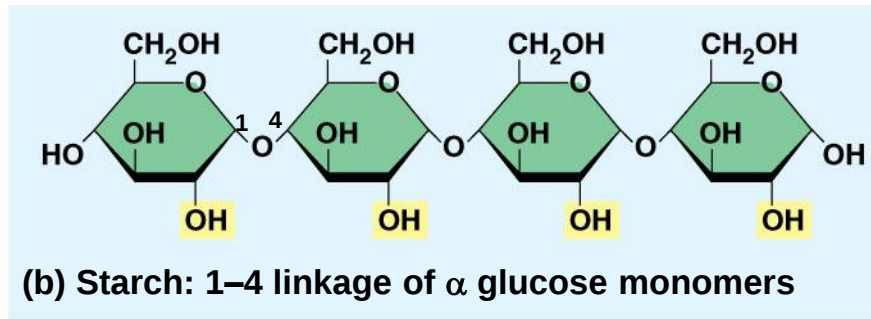
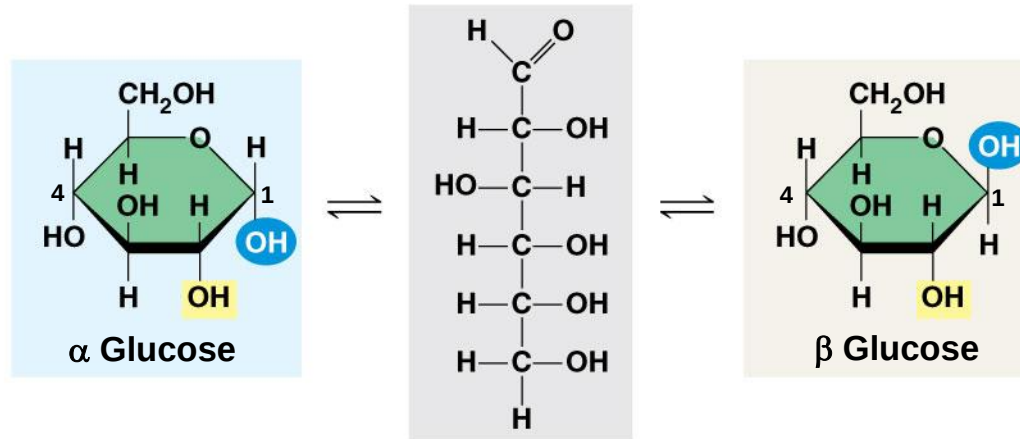
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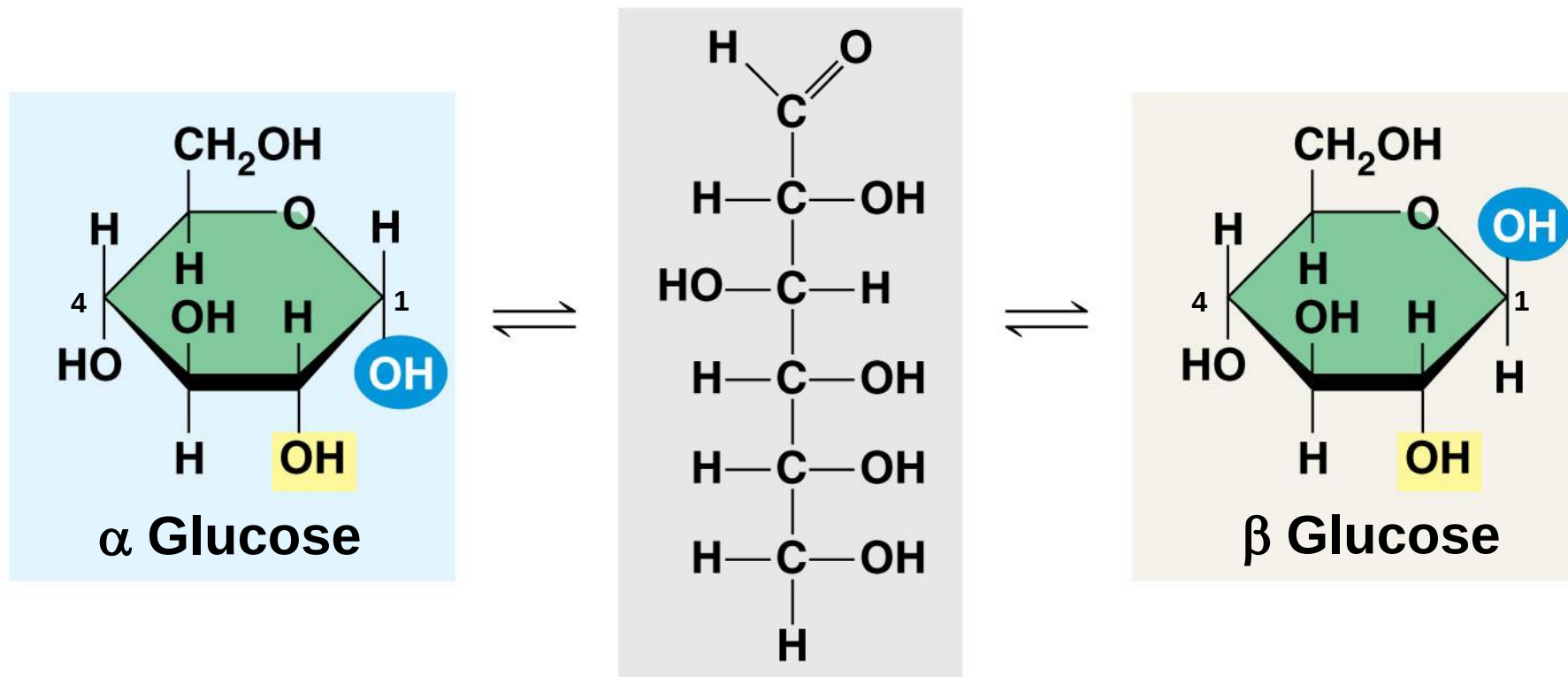
# *Structural Polysaccharides*

- The polysaccharide **cellulose** is a major component of the tough wall of plant cells
- Like starch, cellulose is a polymer of glucose, but the glycosidic linkages differ
- The difference is based on two ring forms for glucose: alpha ( $\alpha$ ) and beta ( $\beta$ )

Figure 5.7

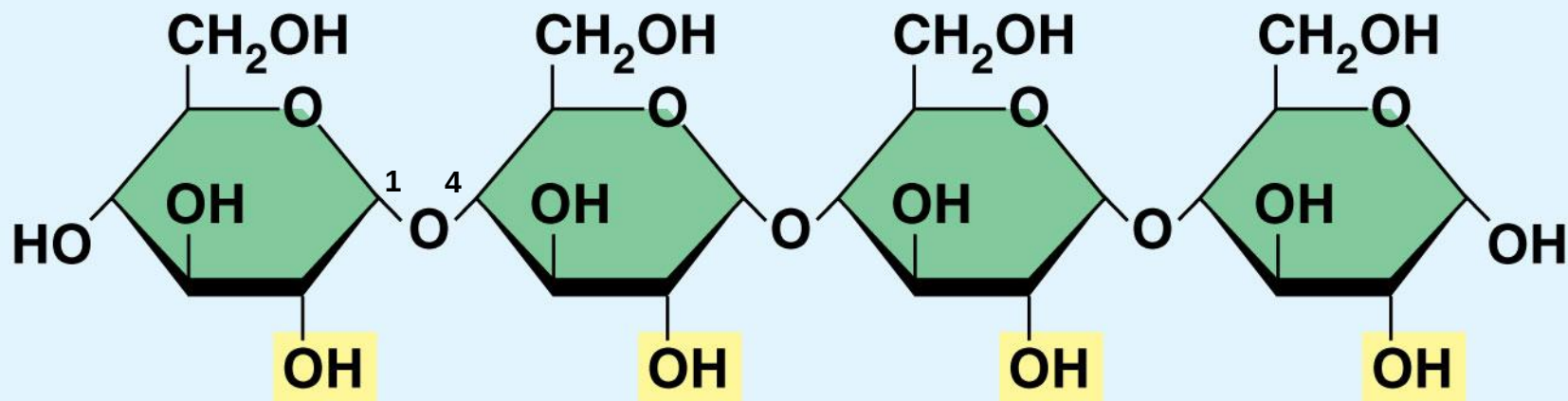
(a)  $\alpha$  and  $\beta$  glucose ring structures



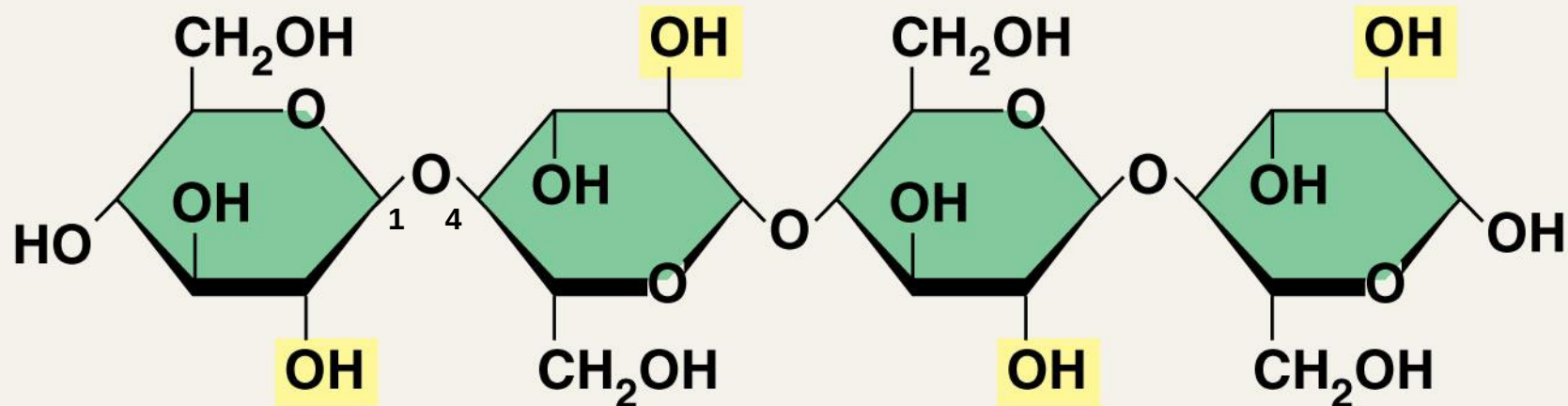


**(a) α and β glucose ring structures**

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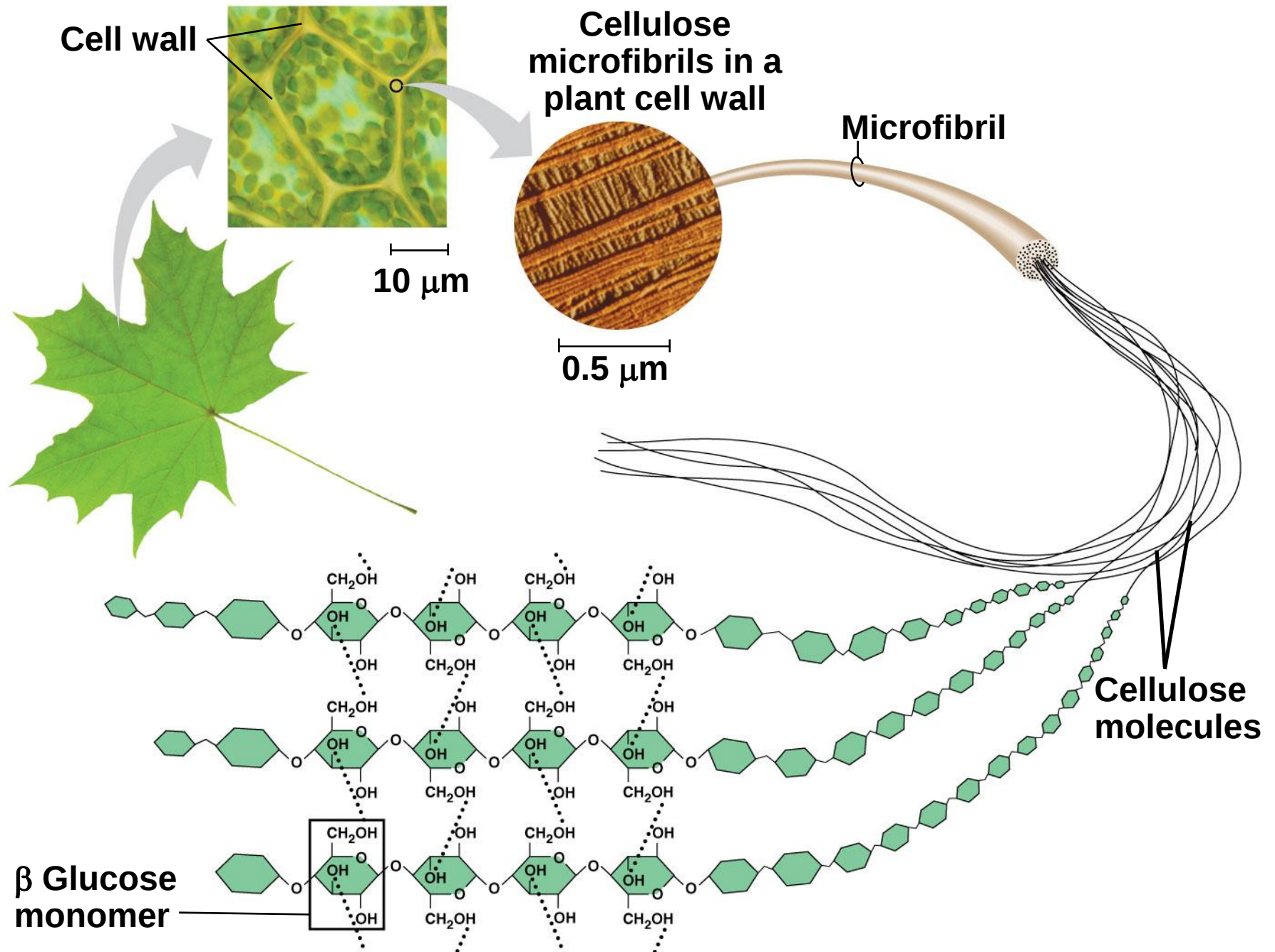
**(b) Starch: 1-4 linkage of  $\alpha$  glucose monomers**



**(c) Cellulose: 1-4 linkage of  $\beta$  glucose monomers**

- Polymers with  $\alpha$  glucose are helical
- Polymers with  $\beta$  glucose are straight
- In straight structures, H atoms on one strand can bond with OH groups on other strands
- Parallel cellulose molecules held together this way are grouped into microfibrils, which form strong building materials for plants

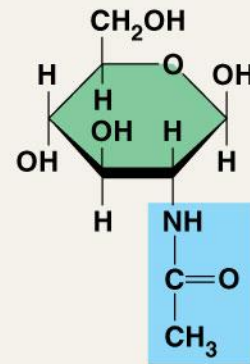
Figure 5.8



- Enzymes that digest starch by hydrolyzing  $\alpha$  linkages can't hydrolyze  $\beta$  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

Figure 5.9



◀ The structure of the chitin monomer

◀ Chitin forms the exoskeleton of arthropods.



▲ Chitin is used to make a strong and flexible surgical thread that decomposes after the wound or incision heals.

Figure 5.9a



▲ Chitin forms the exoskeleton of arthropods.

Figure 5.9b



- ▲ **Chitin is used to make a strong and flexible surgical thread that decomposes after the wound or incision heals.**

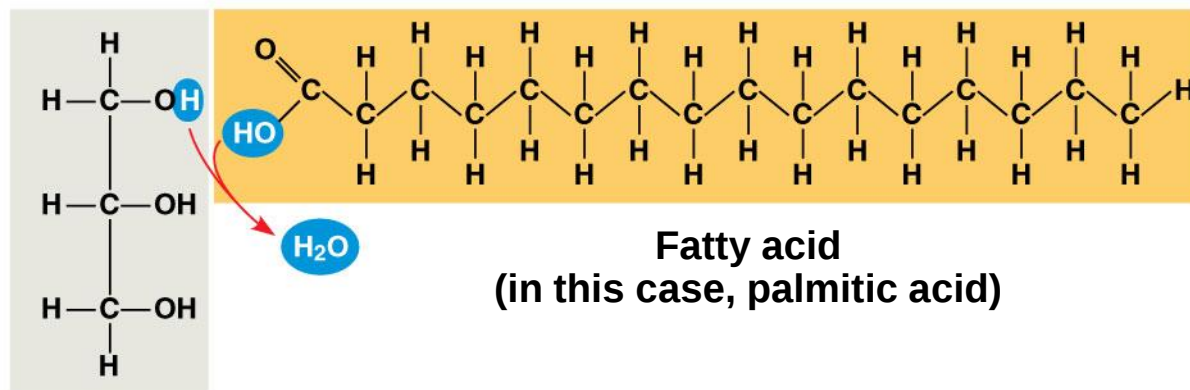
## Concept 5.3: Lipids are a diverse group of hydrophobic molecules

- **Lipids** are the one class of large biological molecules that do not form 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

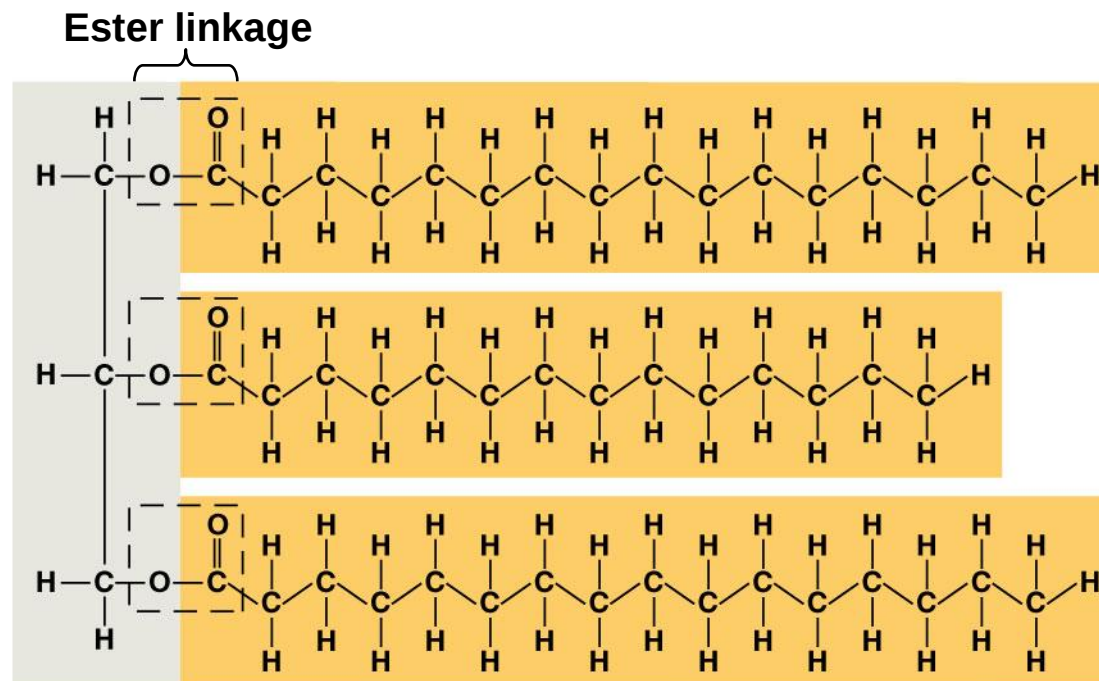
- **Fats** are constructed from two types of smaller molecules: glycerol and fatty acids
- Glycerol is a three-carbon alcohol with a hydroxyl group attached to each carbon
- A **fatty acid** consists of a carboxyl group attached to a long carbon skeleton

Figure 5.10



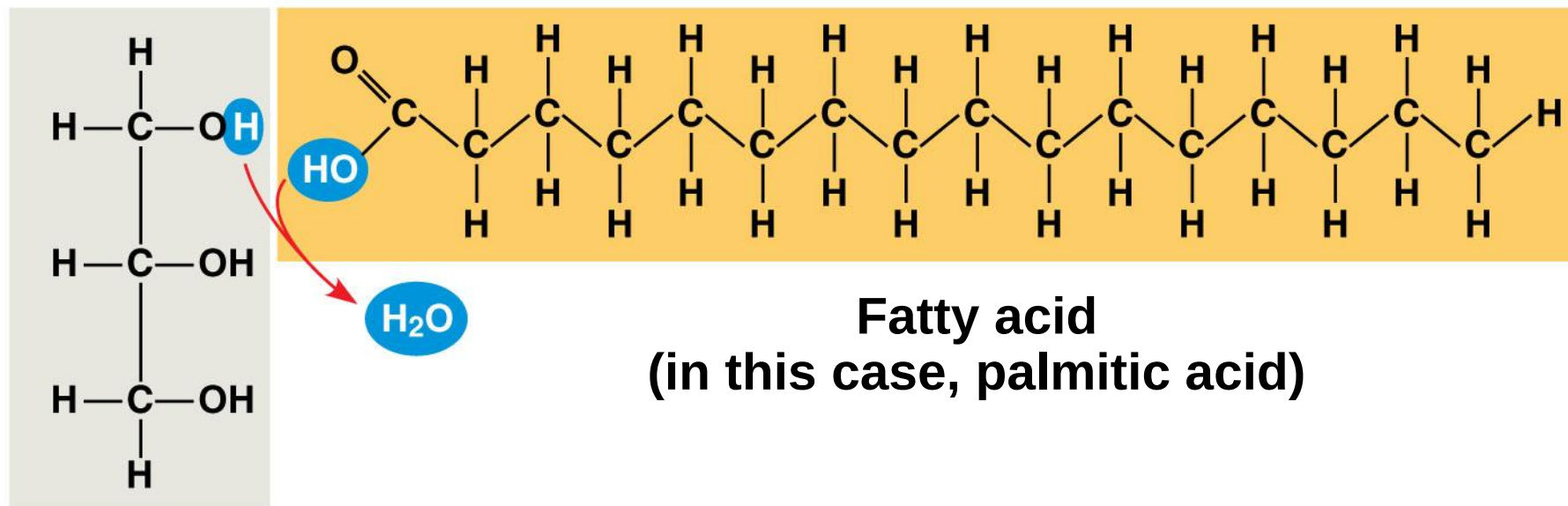
**Glycerol**

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



**(b) Fat molecule (triacylglycerol)**

Figure 5.10a

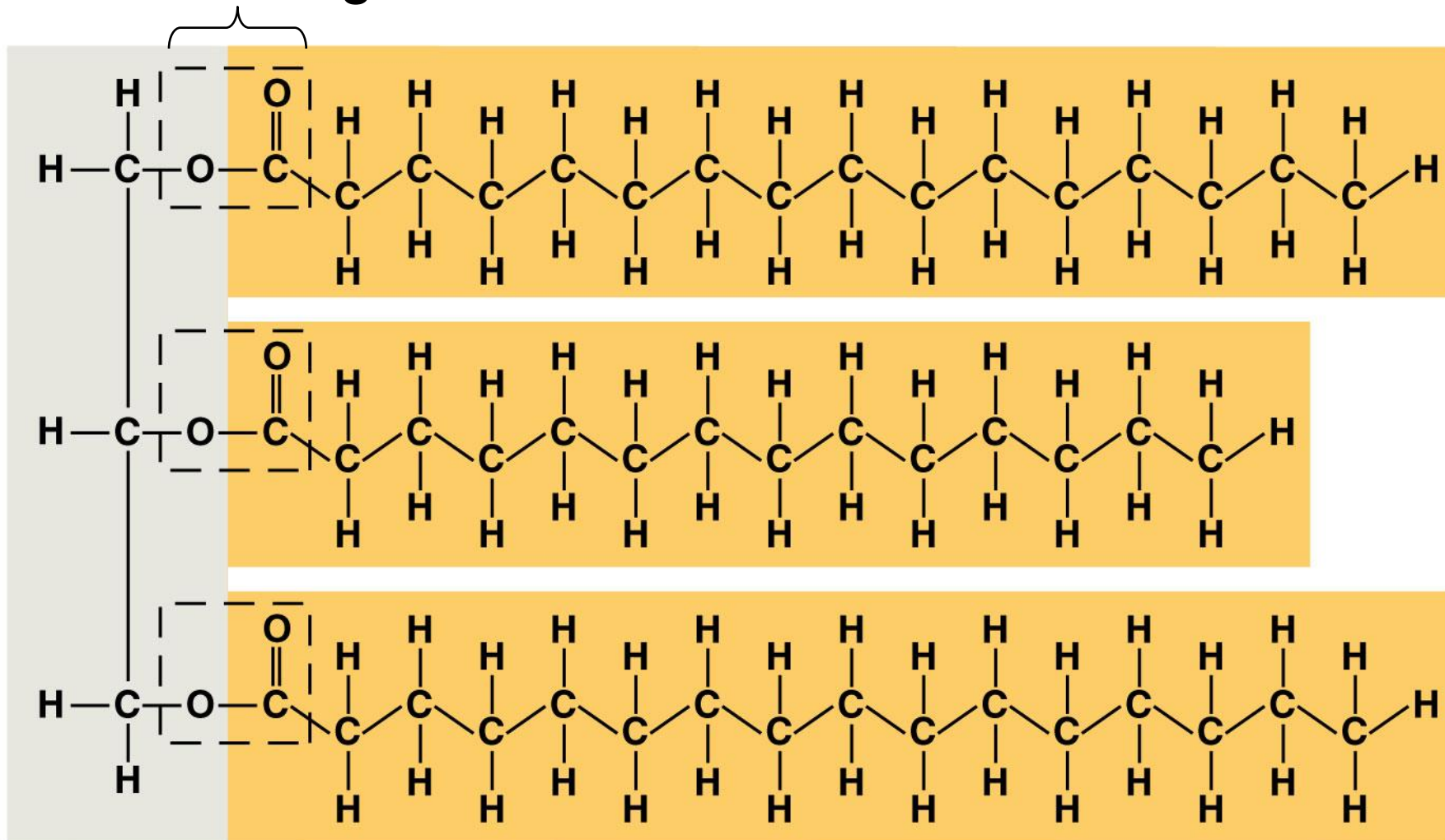


**(a) One of three dehydration reactions in the synthesis of a fat**

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- Fats separate from water because water molecules form hydrogen bonds with 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

## Ester linkage



## (b) Fat molecule (triacylglycerol)

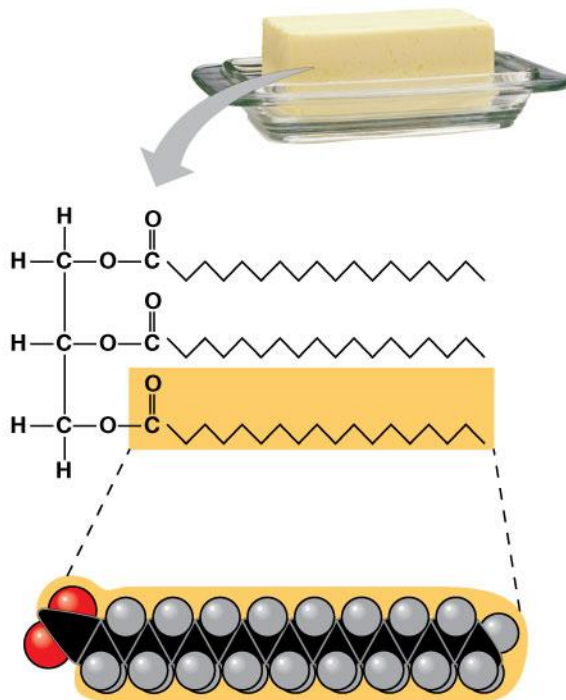
- Fatty acids vary in length (number of carbons) and in the number and locations of double bonds
- **Saturated fatty acids** have the maximum number of hydrogen atoms possible and no double bonds
- **Unsaturated fatty acids** have one or more double bonds



Figure 5.11

### (a) Saturated fat

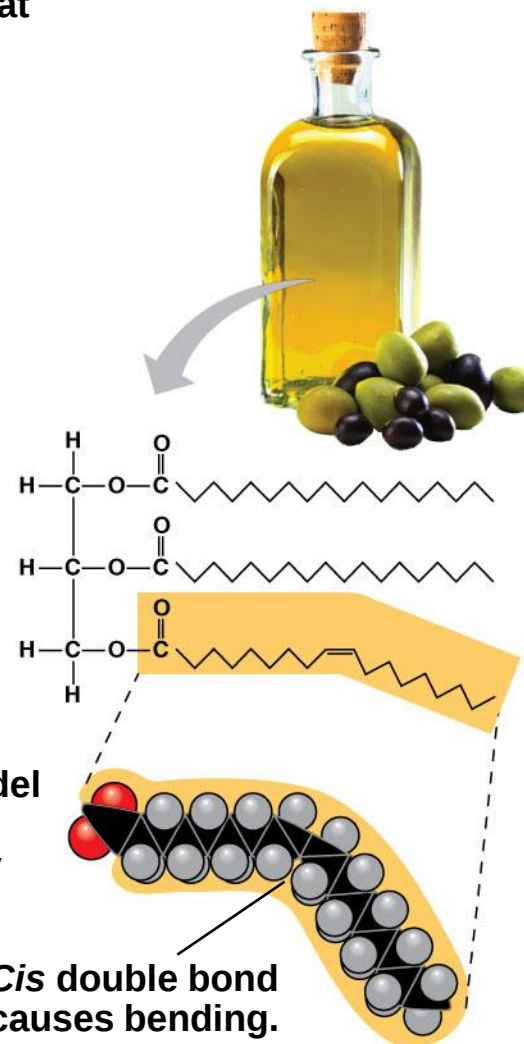
Structural formula of a saturated fat molecule



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

### (b) Unsaturated fat

Structural formula of an unsaturated fat molecule



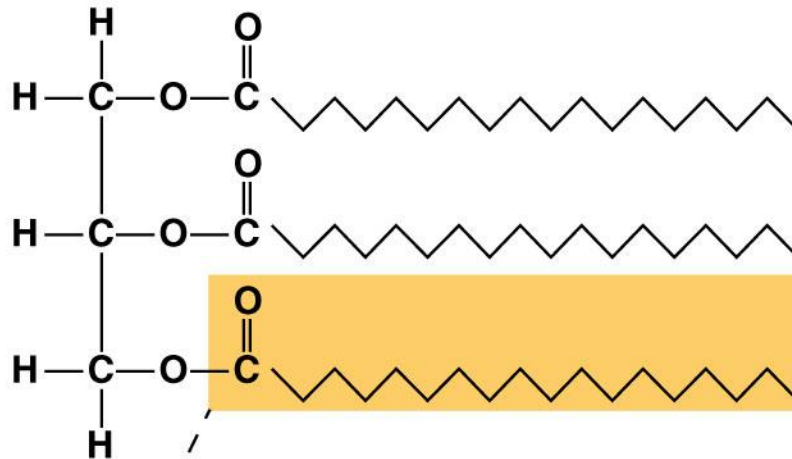
Space-filling model of oleic acid, an unsaturated fatty acid

Cis double bond causes bending.

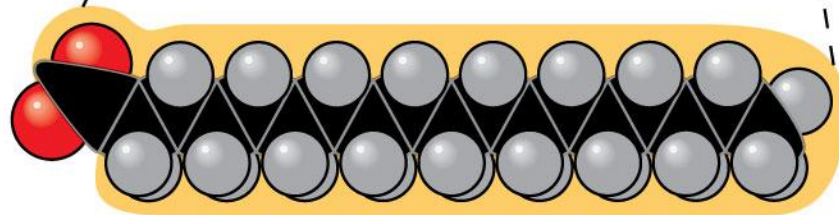
## (a) Saturated fat



**Structural  
formula of a  
saturated fat  
molecule**

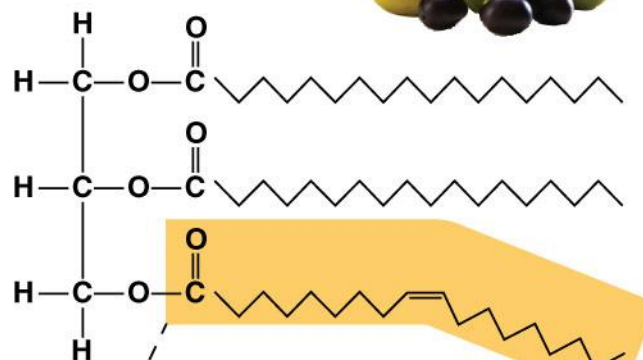


**Space-filling  
model of stearic  
acid, a saturated  
fatty acid**

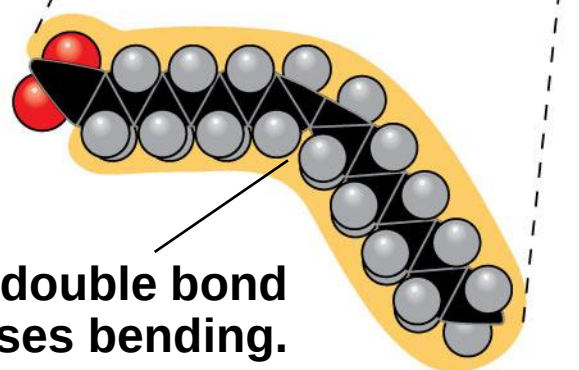


**(b) Unsaturated fat**

**Structural formula of an unsaturated fat molecule**



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



***Cis* double bond causes bending.**



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

- A diet rich in saturated fats may contribute to cardiovascular disease through plaque deposits
- Hydrogenation is the process of converting unsaturated fats to saturated fats by adding hydrogen
- Hydrogenating vegetable oils also creates unsaturated fats with *trans* double bonds
- These ***trans* fats** may contribute more than saturated fats to cardiovascular disease

- Certain unsaturated fatty acids are not synthesized in the human body
- These must be supplied in the diet
- These essential fatty acids include the omega-3 fatty acids, required for normal growth, and thought to provide protection against cardiovascular disease

- The major function of fats is energy storage
- Humans and other mammals store their fat in adipose cells
- Adipose tissue also cushions vital organs and insulates the body

# 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

Figure 5.12

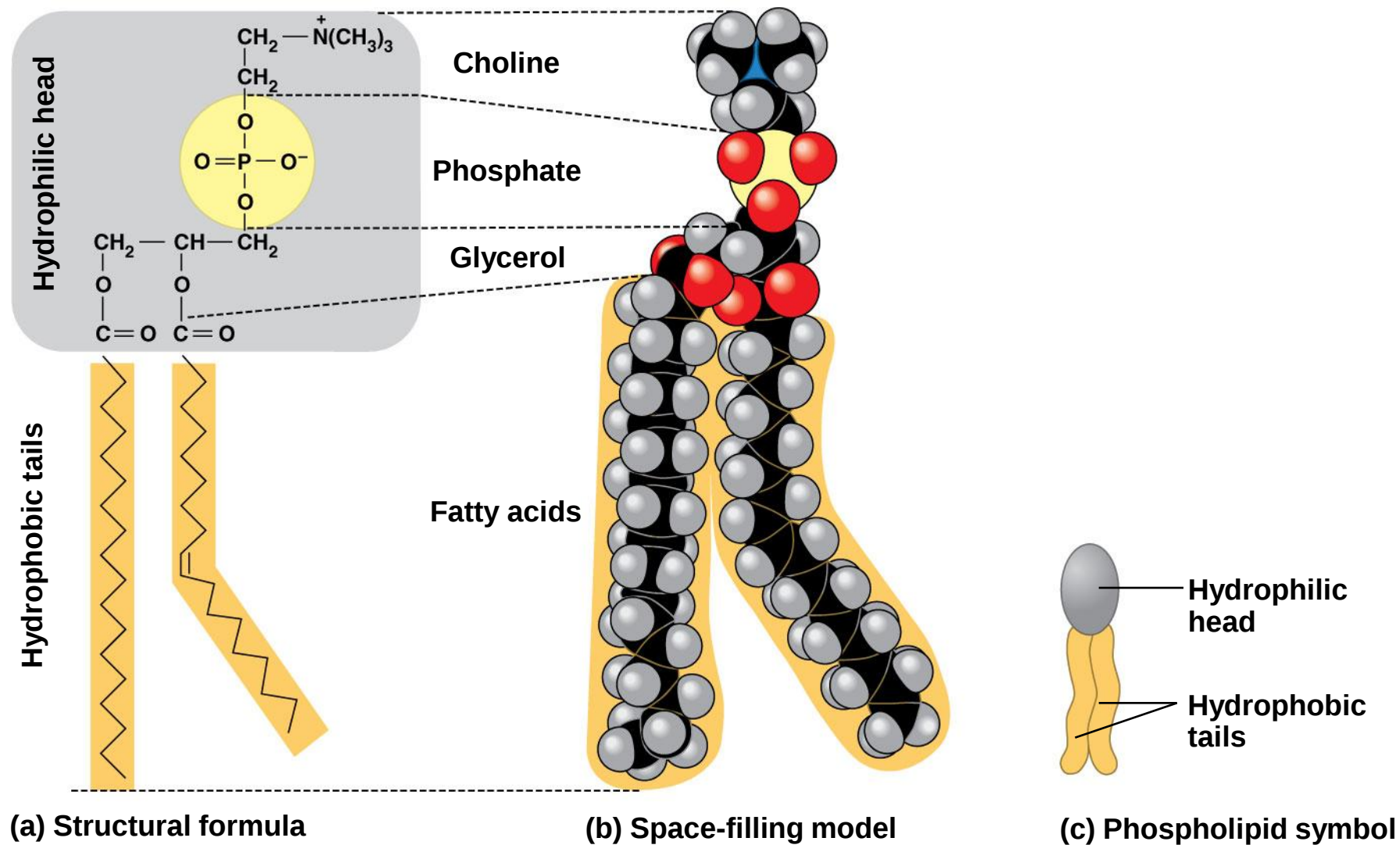
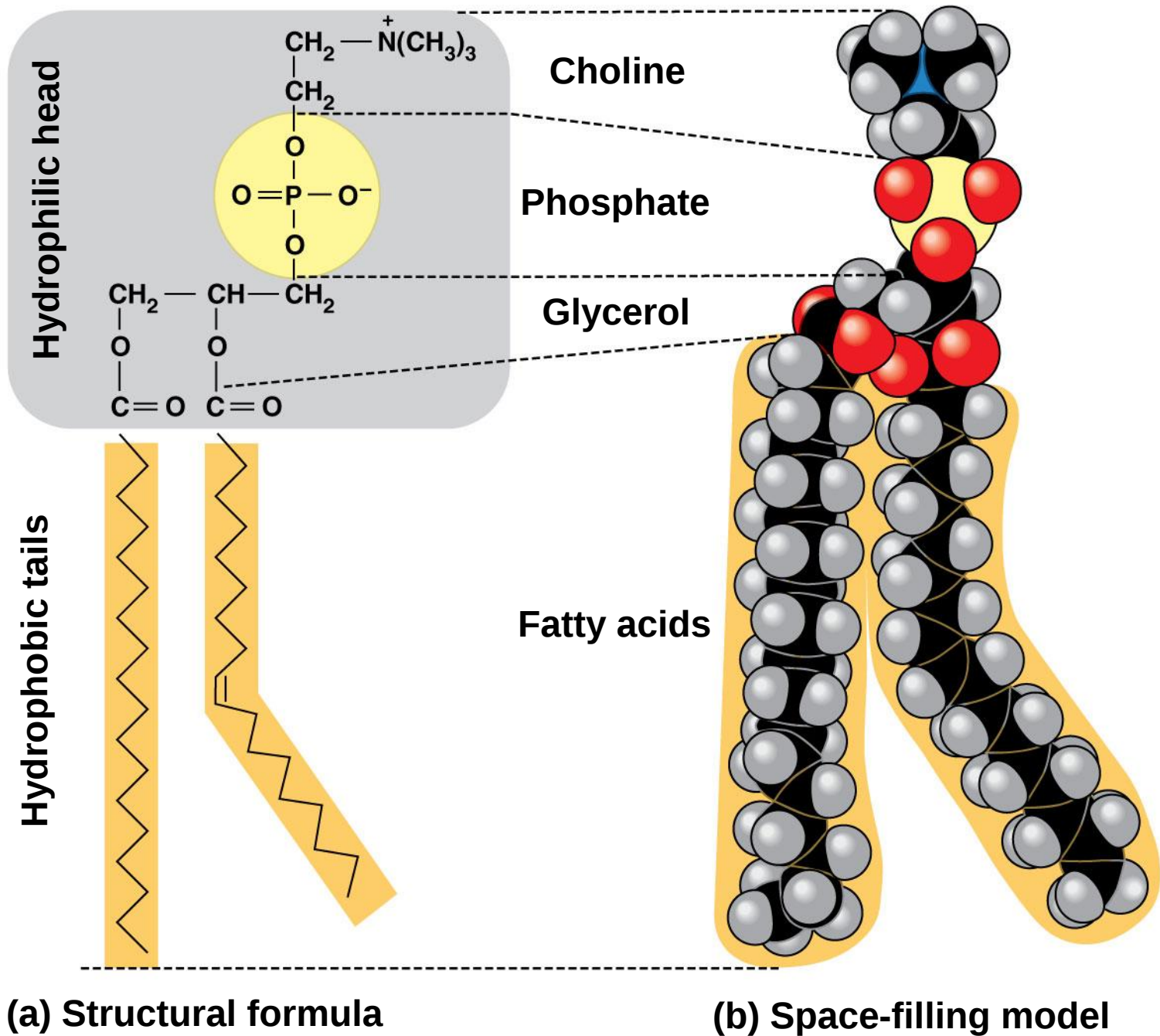


Figure 5.12a

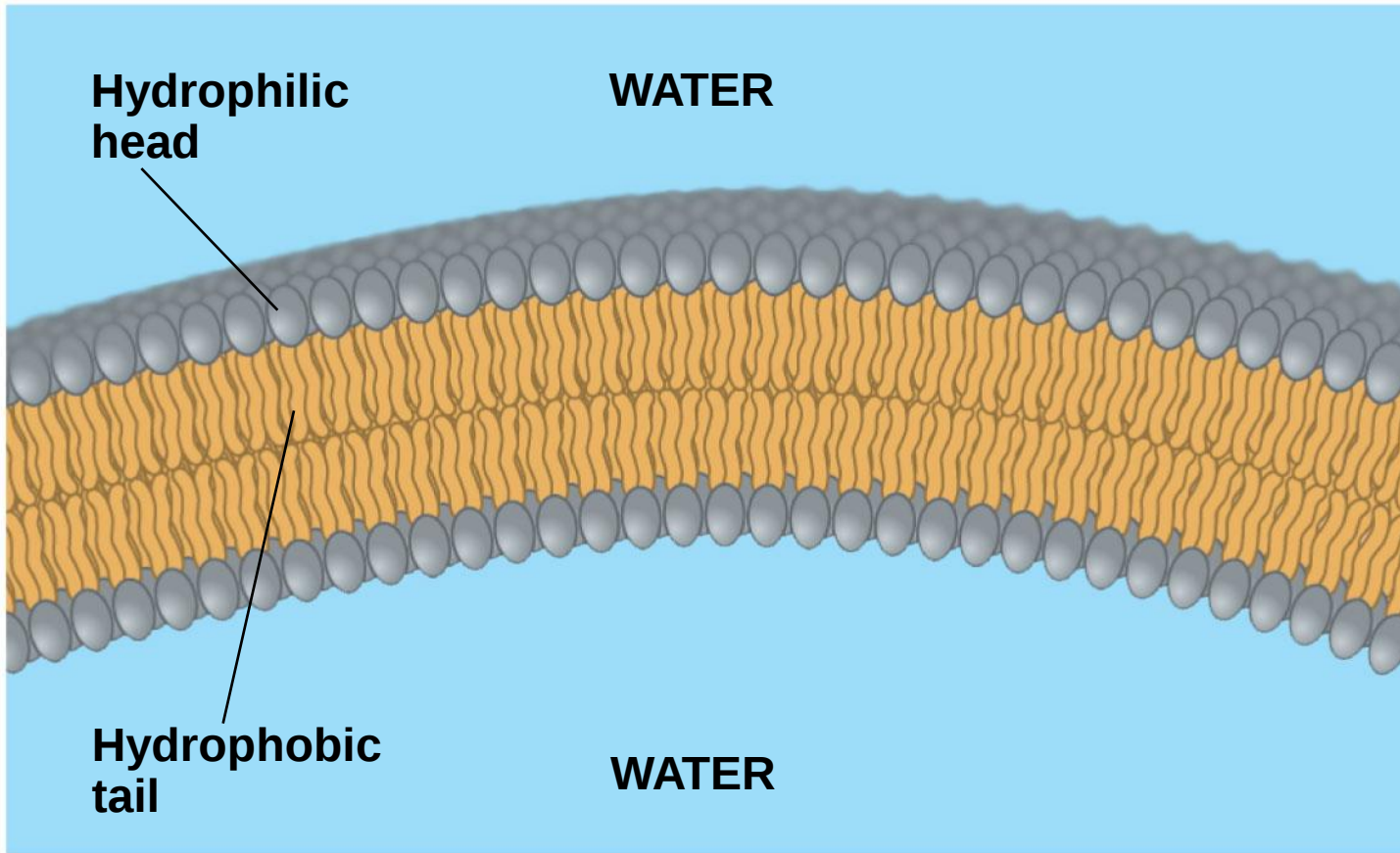


(a) Structural formula

(b) Space-filling model

- When phospholipids are added to water, they self-assemble into a bilayer, with the hydrophobic tails pointing toward the interior
- The structure of phospholipids results in a bilayer arrangement found in cell membranes
- Phospholipids are the major component of all cell membranes

Figure 5.13

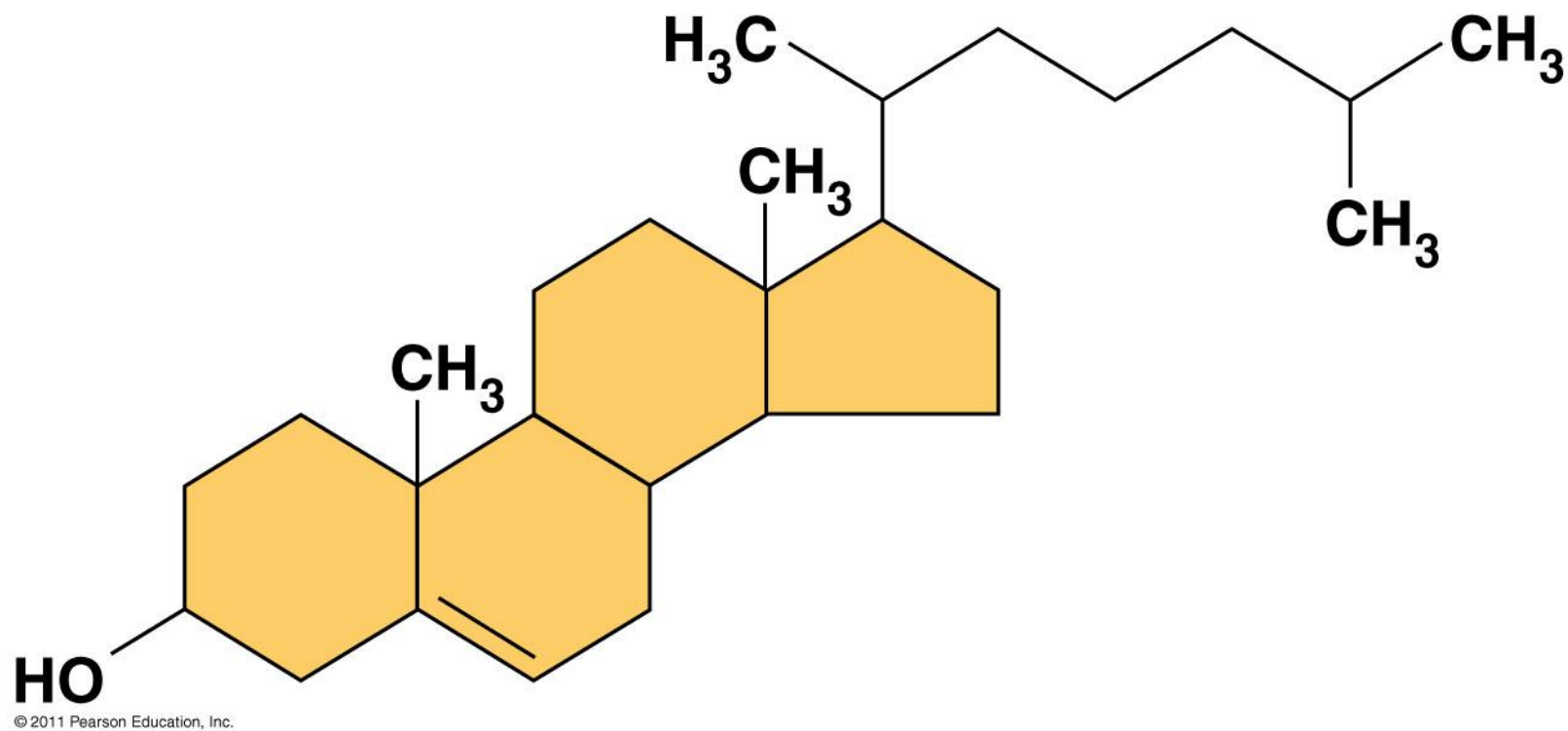


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# Steroids

- **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 cardiovascular disease

Figure 5.14



# **Concept 5.4: Proteins include a diversity of structures, resulting in a wide range of functions**

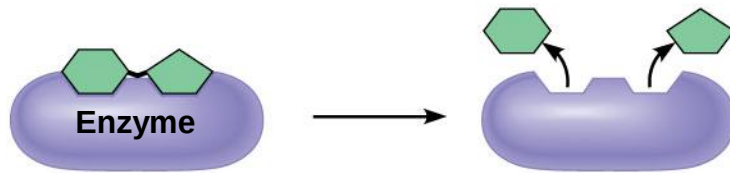
- Proteins account for more than 50% of the dry mass of most cells
- Protein functions include structural support, storage, transport, cellular communications, movement, and defense against foreign substances

Figure 5.15-a

### Enzymatic proteins

**Function:** Selective acceleration of chemical reactions

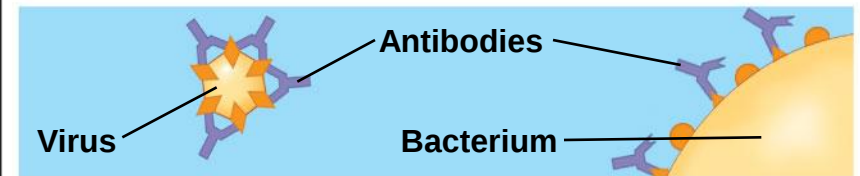
**Example:** Digestive enzymes catalyze the hydrolysis of bonds in food molecules.



### Defensive proteins

**Function:** Protection against disease

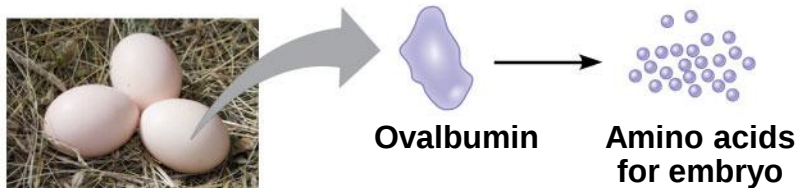
**Example:** Antibodies inactivate and help destroy viruses and bacteria.



### 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 cell membranes.

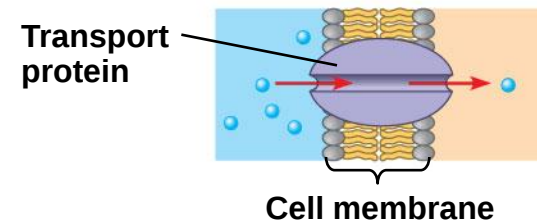
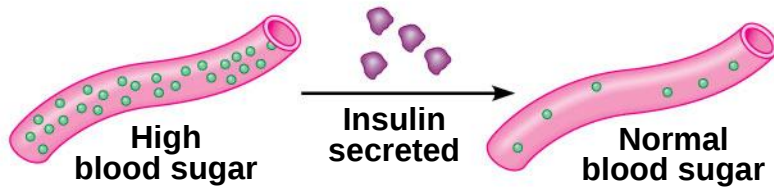


Figure 5.15-b

### Hormonal proteins

**Function:** Coordination of an organism's activities

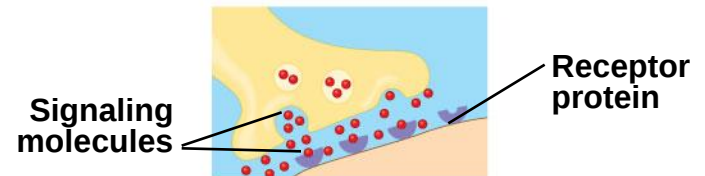
**Example:** Insulin, a hormone secreted by the pancreas, causes other tissues to take up glucose, thus regulating blood sugar concentration



### Receptor proteins

**Function:** Response of cell to chemical stimuli

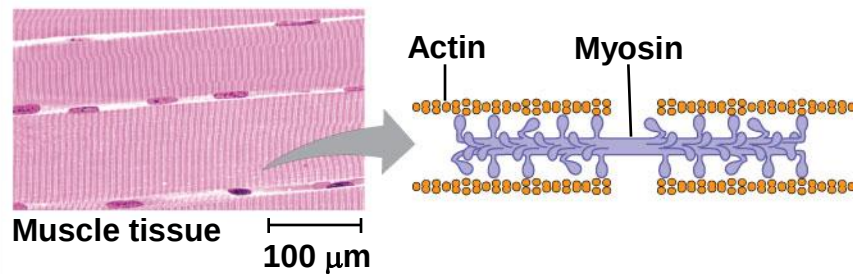
**Example:** Receptors built into the membrane of a nerve cell detect signaling molecules released by other nerve cells.



### Contractile and motor proteins

**Function:** Movement

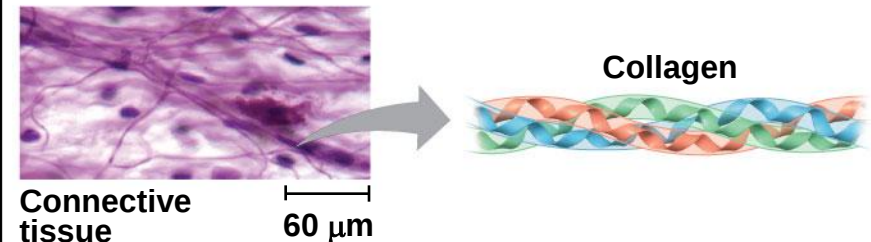
**Examples:** Motor proteins are responsible for the undulations of cilia and flagella. Actin and myosin proteins are responsible for the contraction of muscles.



### Structural proteins

**Function:** Support

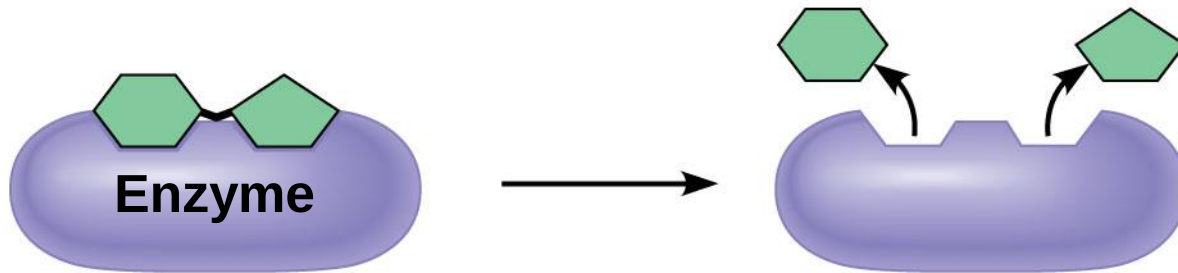
**Examples:** Keratin is the protein of hair, horns, feathers, and other skin appendages. Insects and spiders use silk fibers to make their cocoons and webs, respectively. Collagen and elastin proteins provide a fibrous framework in animal connective tissues.



## Enzymatic proteins

**Function:** Selective acceleration of chemical reactions

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

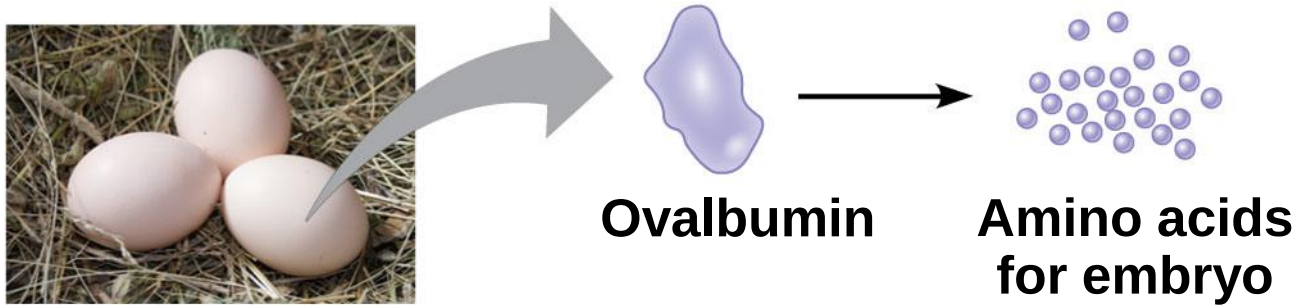


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## Storage proteins

**Function:** Storage of amino acids

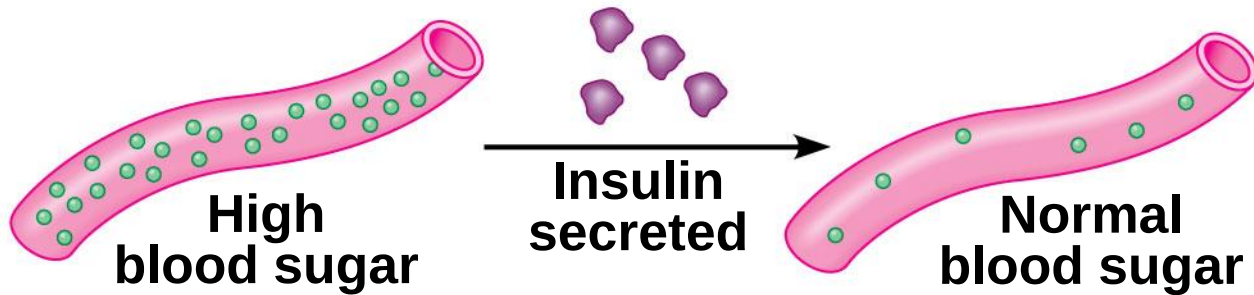
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## Hormonal proteins

**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

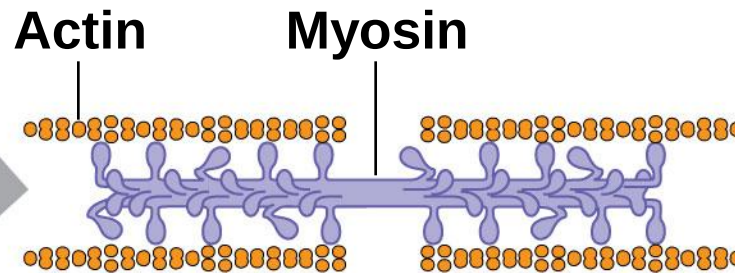
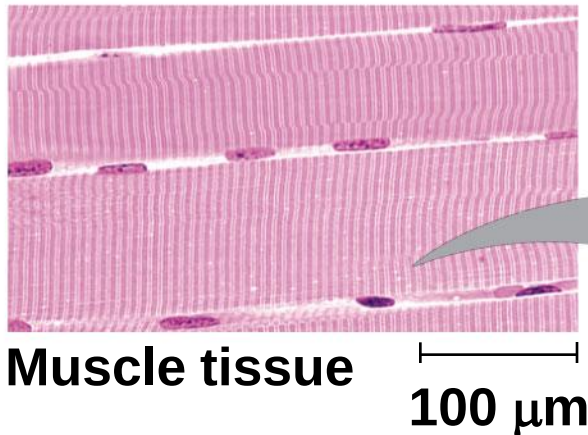


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## Contractile and motor proteins

**Function: Movement**

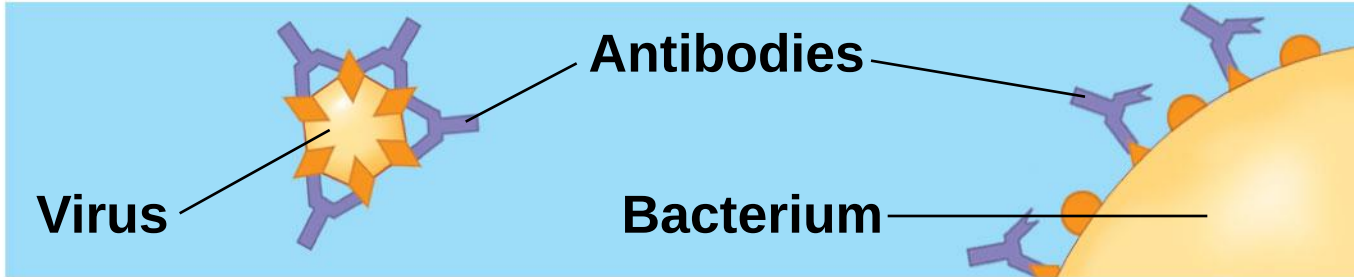
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## Defensive proteins

**Function: Protection against disease**

**Example: Antibodies inactivate and help destroy viruses and bacteria.**

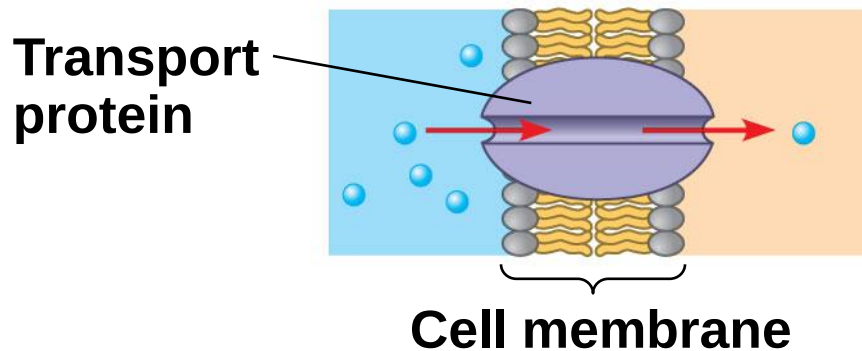


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## Transport proteins

**Function:** Transport of substances

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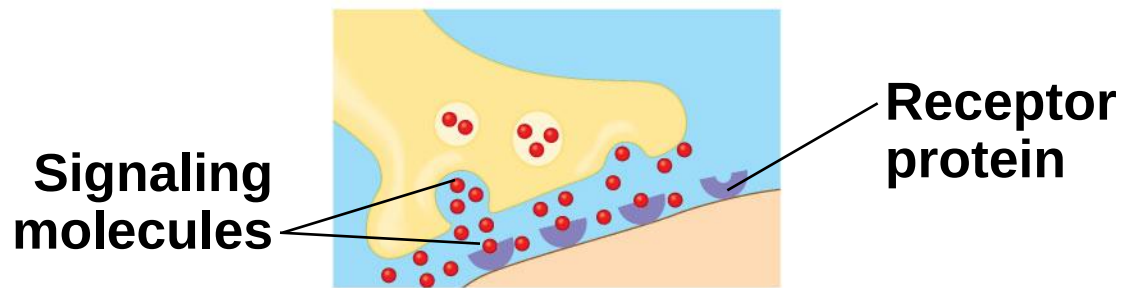


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## Receptor proteins

**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.

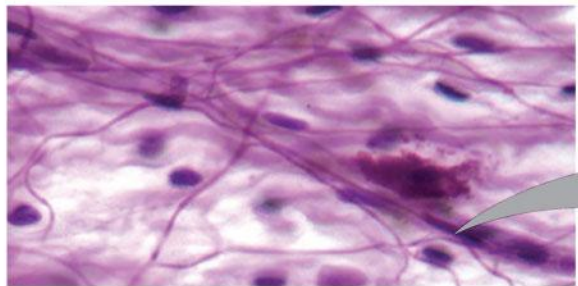


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## Structural proteins

**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.



**Connective  
tissue**

60 μm



- **Enzymes** are a type of protein that acts as a **catalyst** to speed up chemical reactions
- Enzymes can perform their functions repeatedly, functioning as workhorses that carry out the processes of life

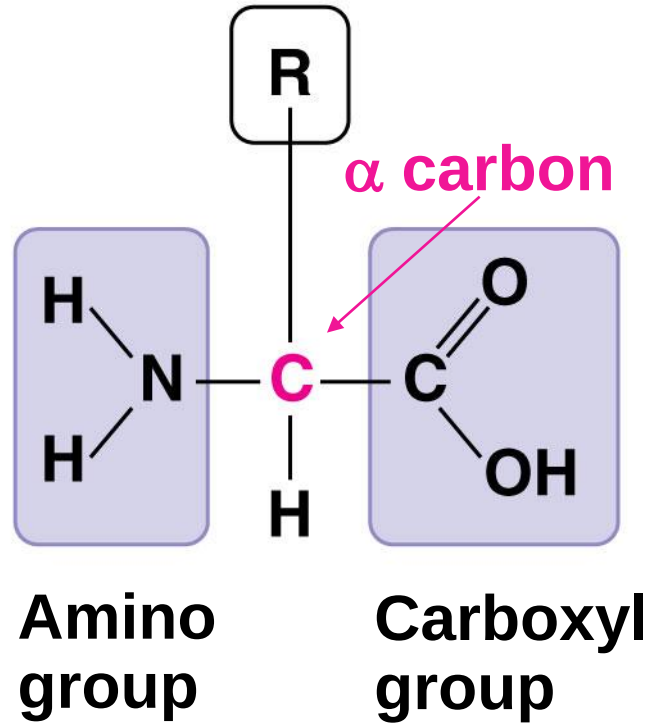
# Polypeptides

- **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

## Side chain (R group)



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Figure 5.16

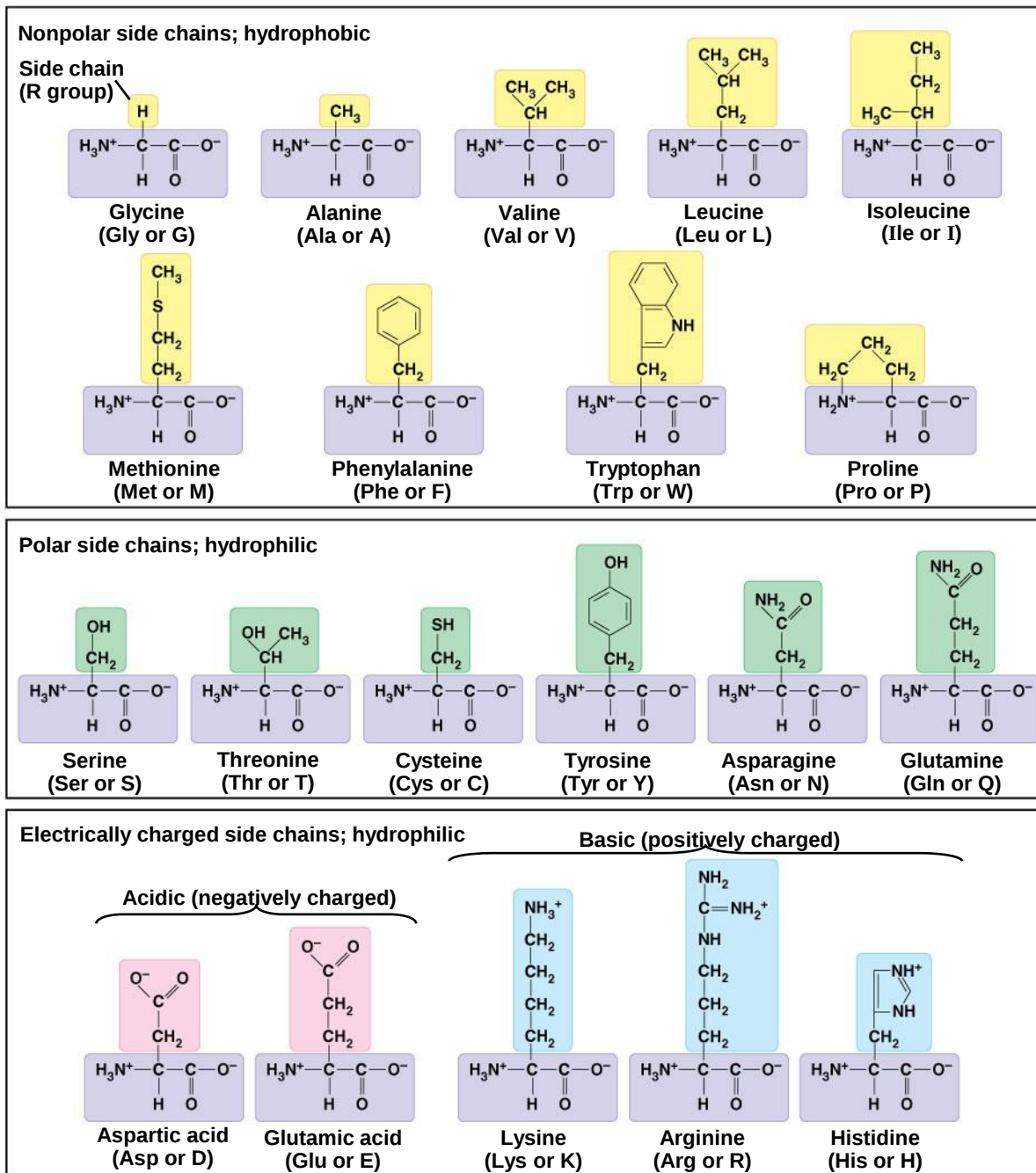
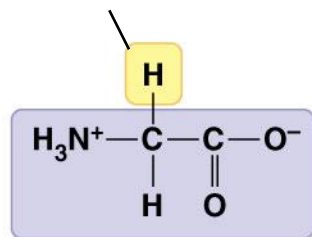


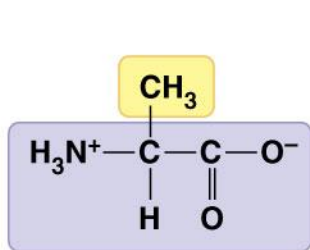
Figure 5.16a

## Nonpolar side chains; hydrophobic

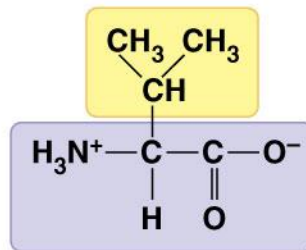
Side chain



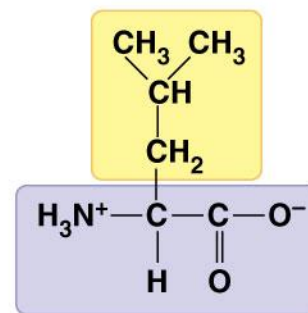
**Glycine**  
(Gly or G)



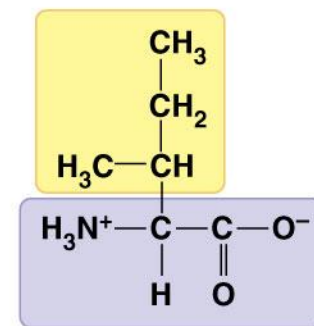
**Alanine**  
(Ala or A)



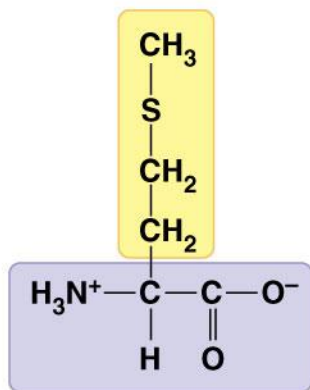
**Valine**  
(Val or V)



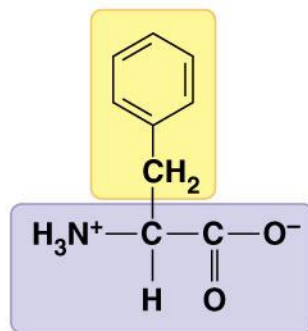
**Leucine**  
(Leu or L)



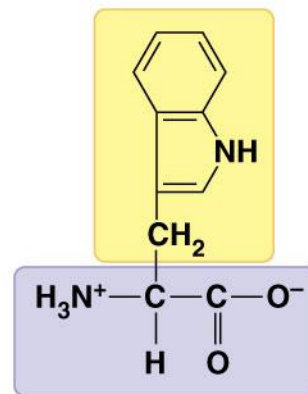
**Isoleucine**  
(Ile or I)



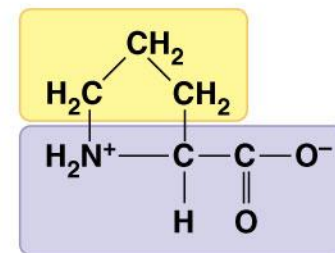
**Methionine**  
(Met or M)



**Phenylalanine**  
(Phe or F)

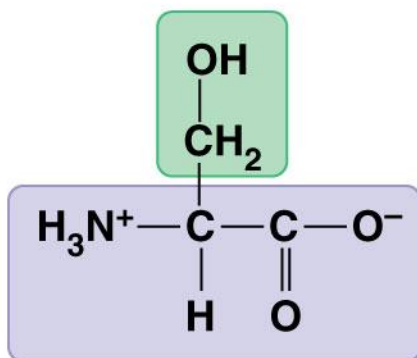


**Tryptophan**  
(Trp or W)

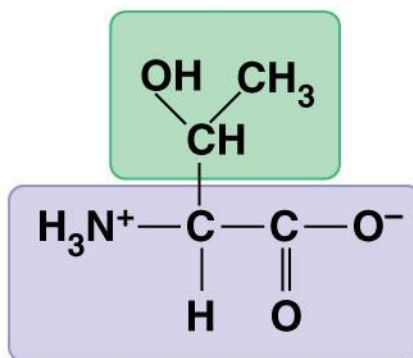


**Proline**  
(Pro or P)

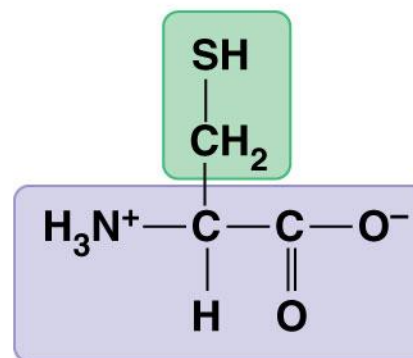
## Polar side chains; hydrophilic



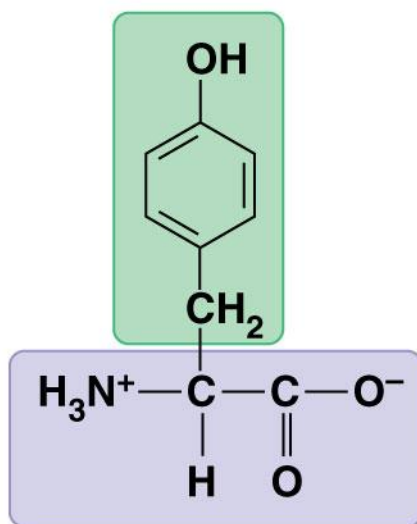
**Serine**  
(Ser or S)



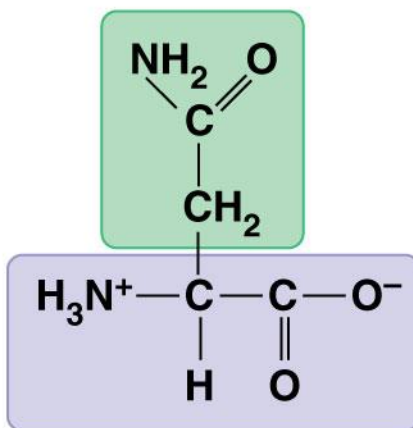
**Threonine**  
(Thr or T)



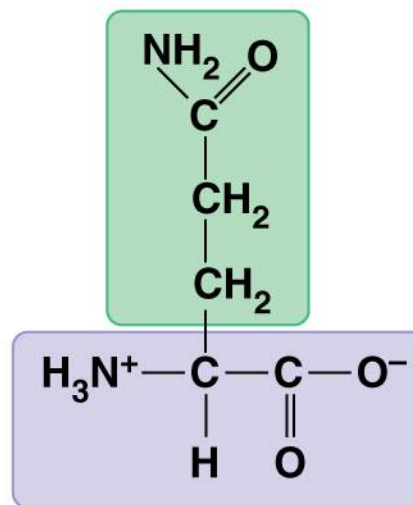
**Cysteine**  
(Cys or C)



**Tyrosine**  
(Tyr or Y)



**Asparagine**  
(Asn or N)

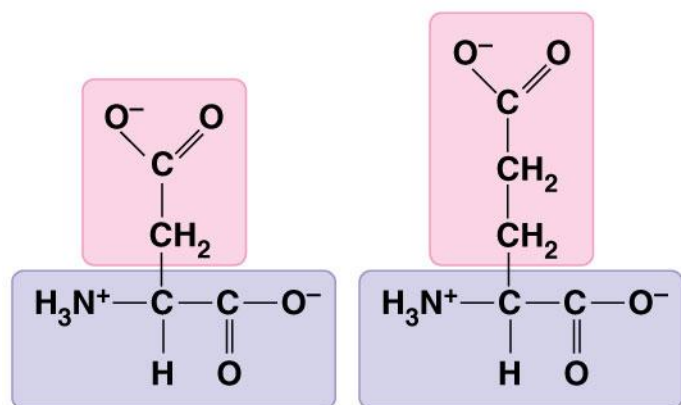
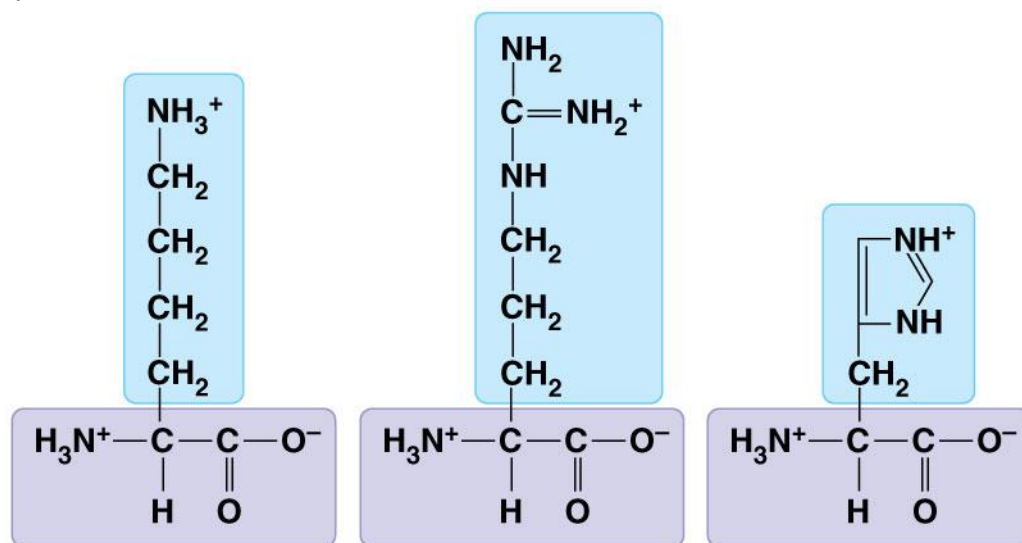


**Glutamine**  
(Gln or Q)

## Electrically charged side chains; hydrophilic

## Basic (positively charged)

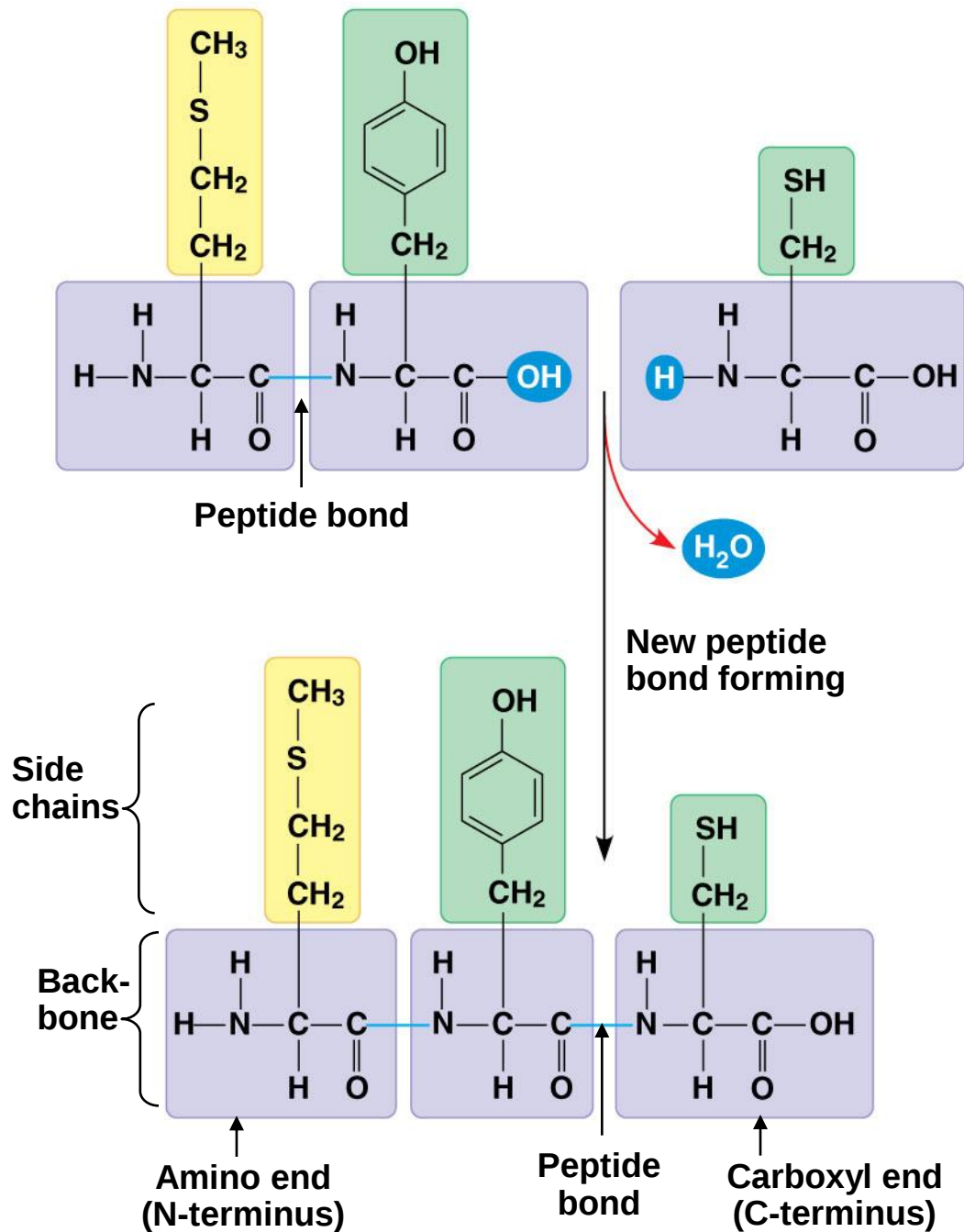
## Acidic (negatively charged)

Aspartic acid  
(Asp or D)Glutamic acid  
(Glu or E)Lysine  
(Lys or K)Arginine  
(Arg or R)Histidine  
(His or H)

# *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 5.17

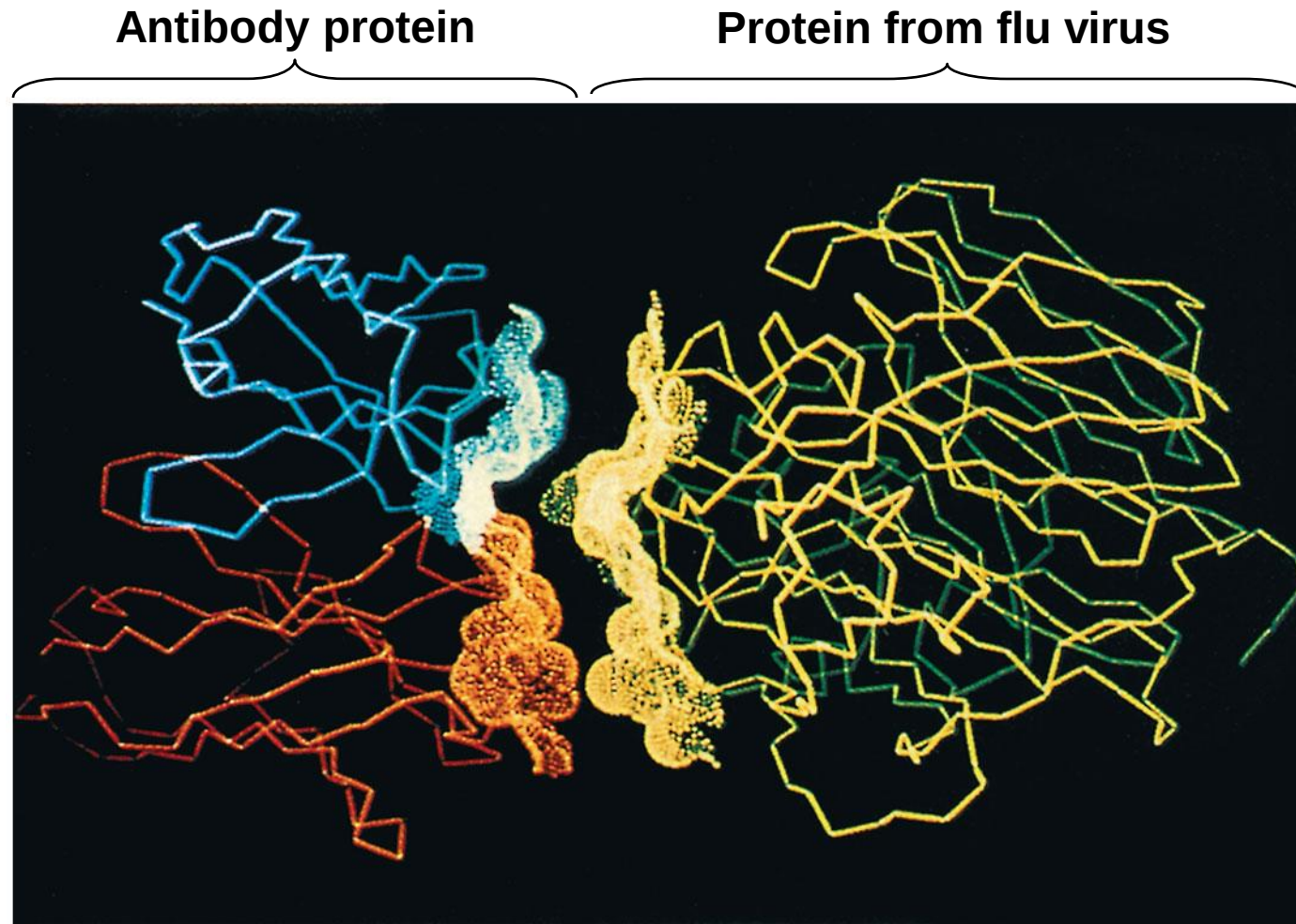


# Protein Structure and Function

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

- The sequence of amino acids determines a protein's three-dimensional structure
- A protein's structure determines its function

Figure 5.19

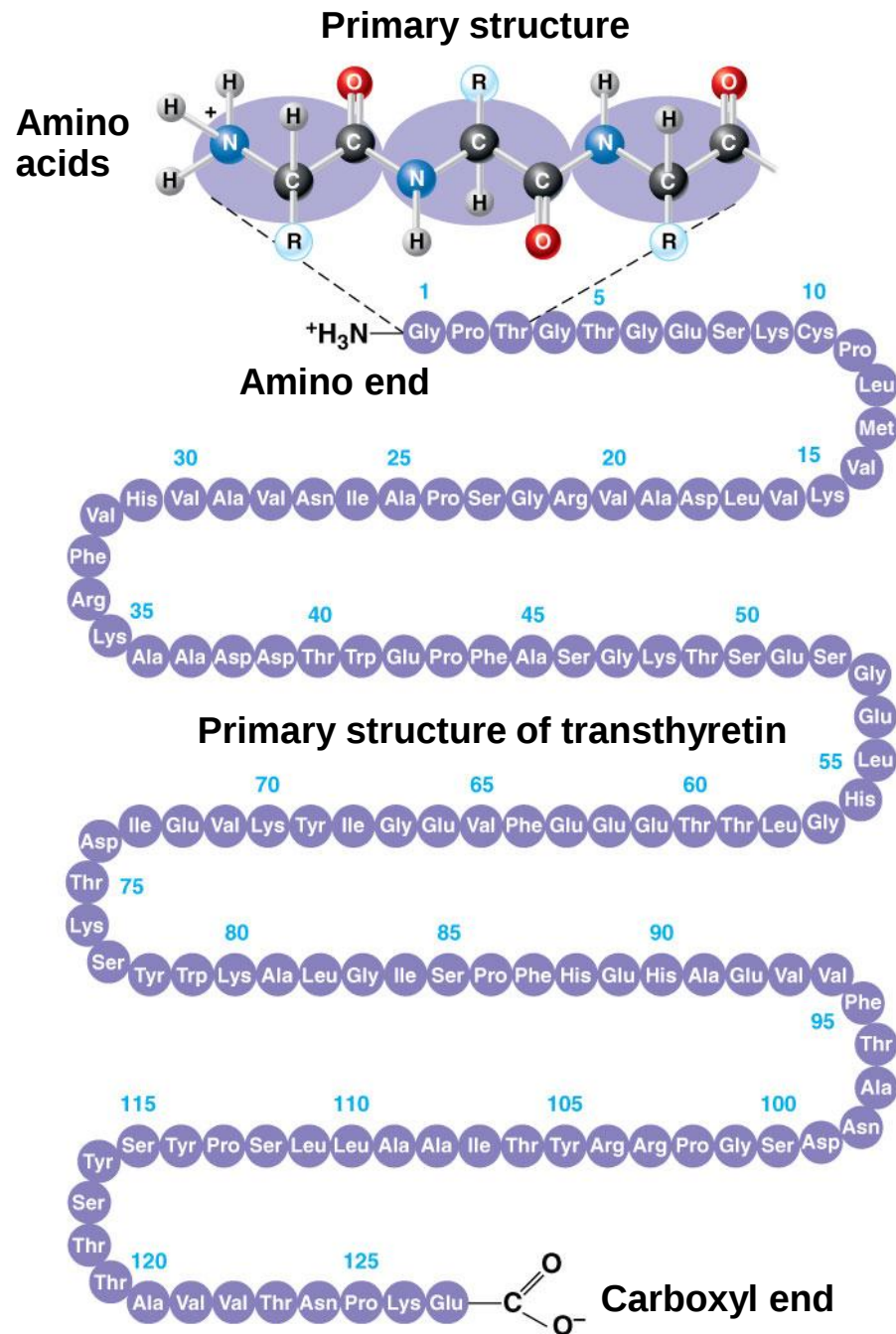


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# *Four Levels of Protein Structure*

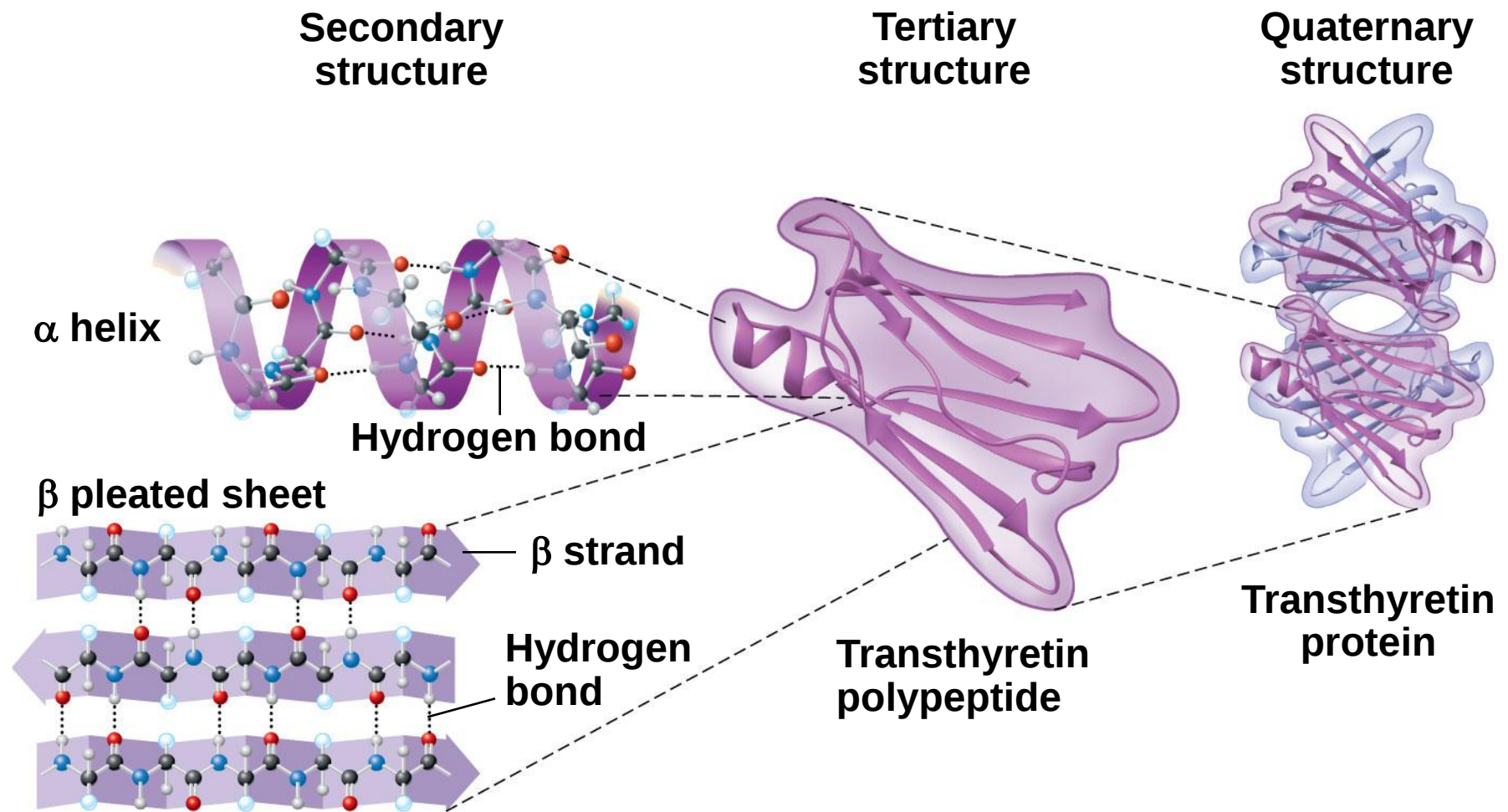
- The primary structure of a protein is its unique sequence of amino acids
- Secondary structure, found in most proteins, consists of coils and folds in the polypeptide chain
- Tertiary structure is determined by interactions among various side chains (R groups)
- Quaternary structure results when a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

Figure 5.20a



- **Primary structure**, the sequence of amino acids in a protein, is like the order of letters in a long word
- Primary structure is determined by inherited genetic information

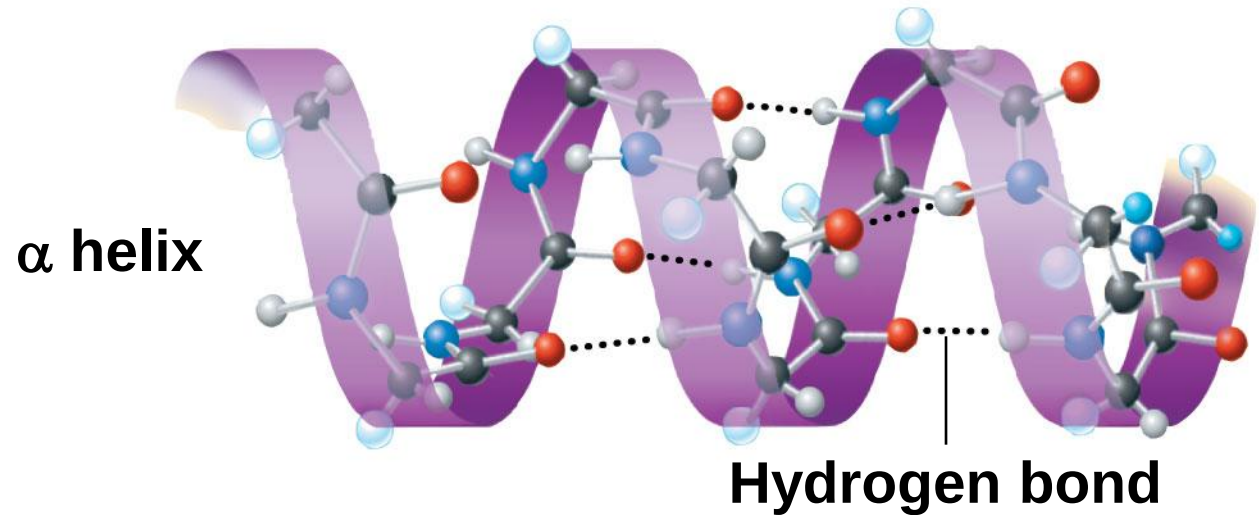
Figure 5.20b



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- The coils and folds of **secondary structure** result from hydrogen bonds between repeating constituents of the polypeptide backbone
- Typical secondary structures are a coil called an  $\alpha$  **helix** and a folded structure called a  $\beta$  **pleated sheet**

## Secondary structure



## $\beta$ pleated sheet

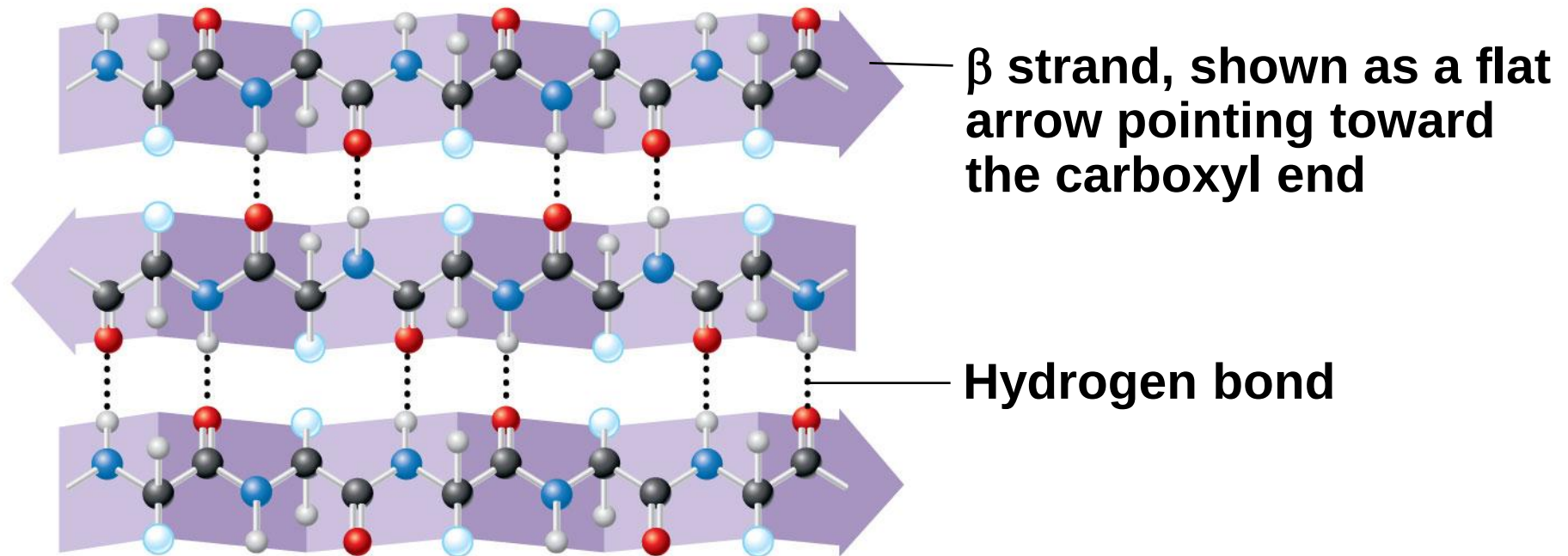


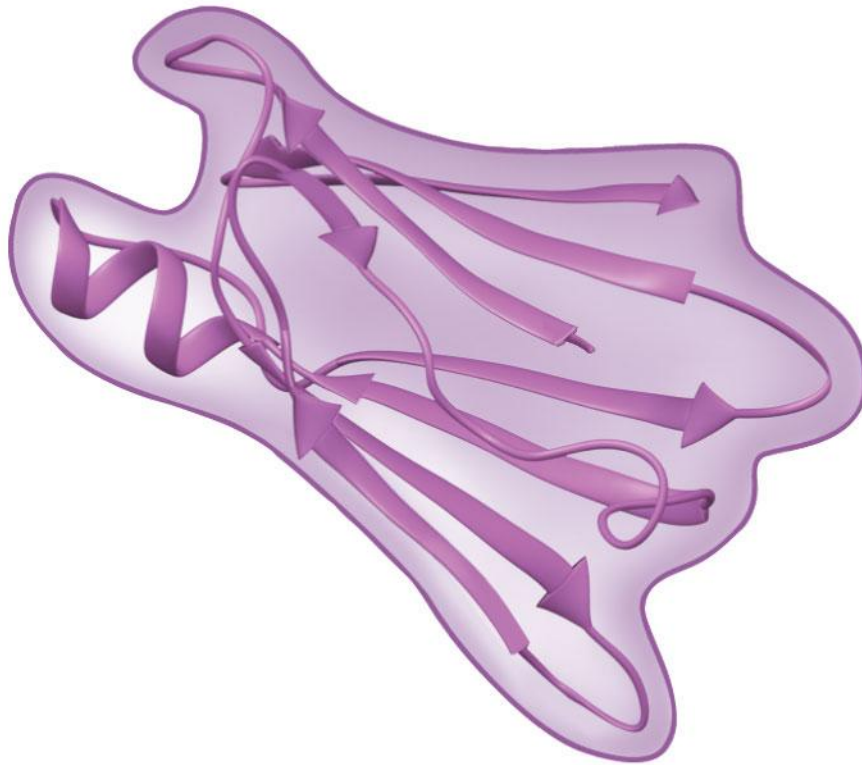
Figure 5.20d



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- **Tertiary structure** is determined by interactions between R groups, rather than interactions between backbone constituents
- These interactions between R groups include hydrogen bonds, ionic bonds, **hydrophobic interactions**, and van der Waals interactions
- Strong covalent bonds called **disulfide bridges** may reinforce the protein's structure

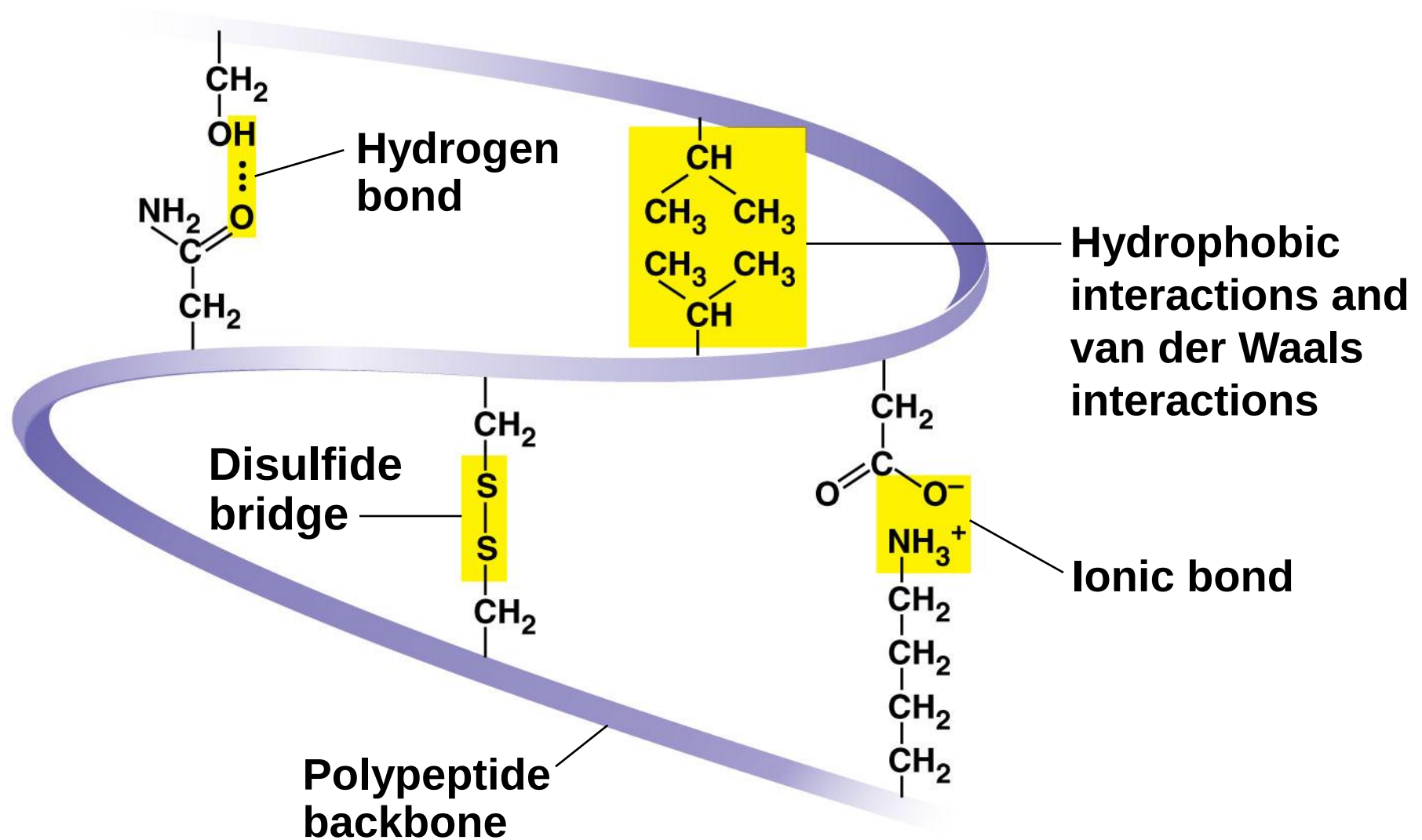
## Tertiary structure



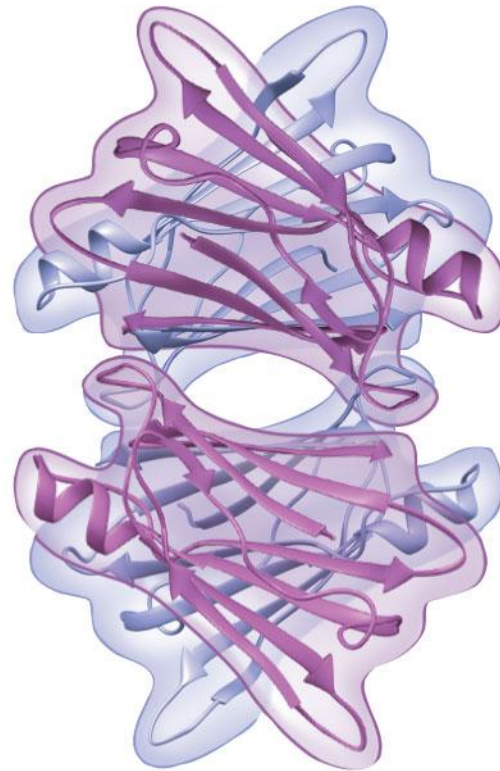
**Transthyretin  
polypeptide**

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Figure 5.20f



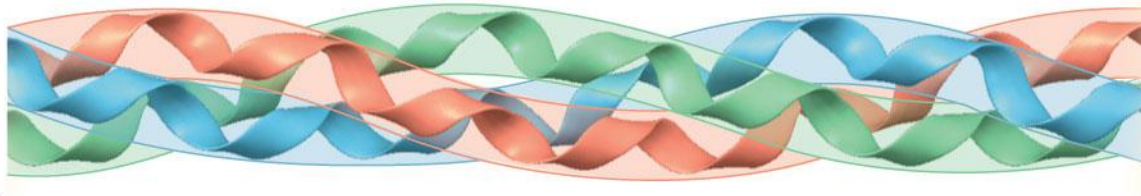
## Quaternary structure



**Transthyretin  
protein  
(four identical  
polypeptides)**

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## Collagen



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Figure 5.20i

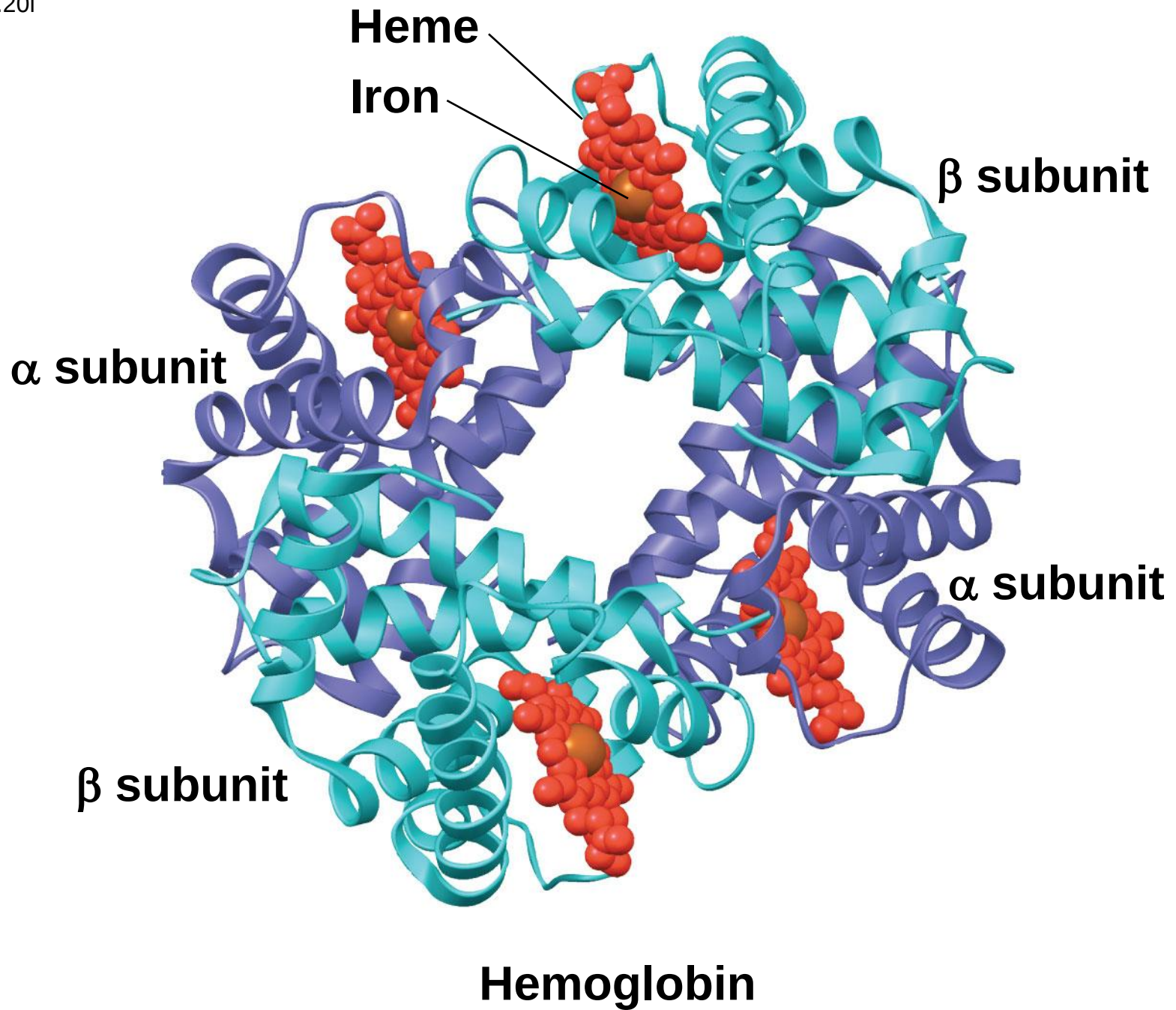


Figure 5.20j



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- **Quaternary structure** results when two or more polypeptide chains form one macromolecule
- Collagen is a fibrous protein consisting of three polypeptides coiled like a rope
- Hemoglobin is a globular protein consisting of four polypeptides: two alpha and two beta chains

# *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 5.21

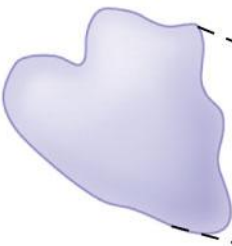
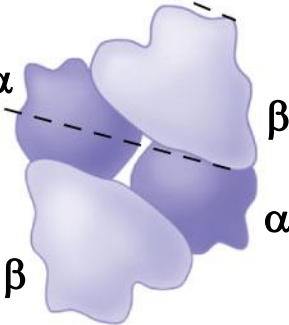
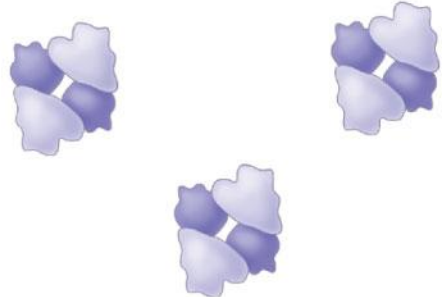
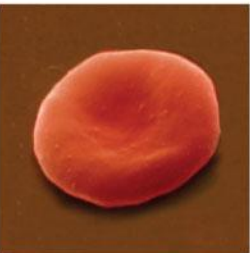
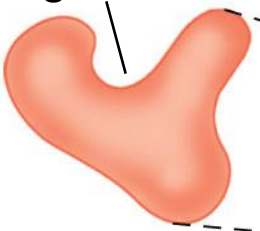
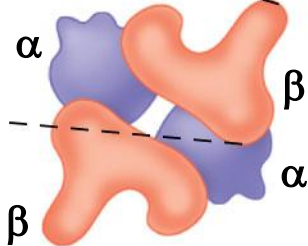
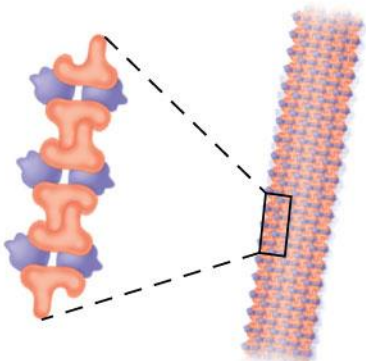
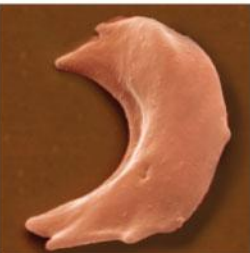
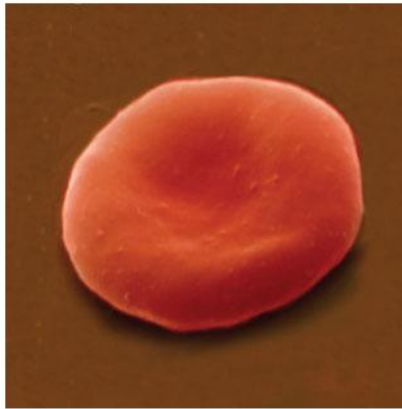
|                        | Primary Structure                                           | Secondary and Tertiary Structures                                                                                                                      | Quaternary Structure                                                                                               | Function                                                                                                                                                              | Red Blood Cell Shape                                                                                                    |
|------------------------|-------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------|
| Normal hemoglobin      | 1 Val<br>2 His<br>3 Leu<br>4 Thr<br>5 Pro<br>6 Glu<br>7 Glu |  <p><math>\beta</math> subunit</p>                                    | <p>Normal hemoglobin</p>         | <p>Molecules do not associate with one another; each carries oxygen.</p>           |  <p>10 <math>\mu\text{m}</math></p>  |
| Sickle-cell hemoglobin | 1 Val<br>2 His<br>3 Leu<br>4 Thr<br>5 Pro<br>6 Val<br>7 Glu | <p>Exposed hydrophobic region</p>  <p><math>\beta</math> subunit</p> | <p>Sickle-cell hemoglobin</p>  | <p>Molecules crystallize into a fiber; capacity to carry oxygen is reduced.</p>  |  <p>10 <math>\mu\text{m}</math></p> |

Figure 5.21a



10  $\mu\text{m}$

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Figure 5.21b



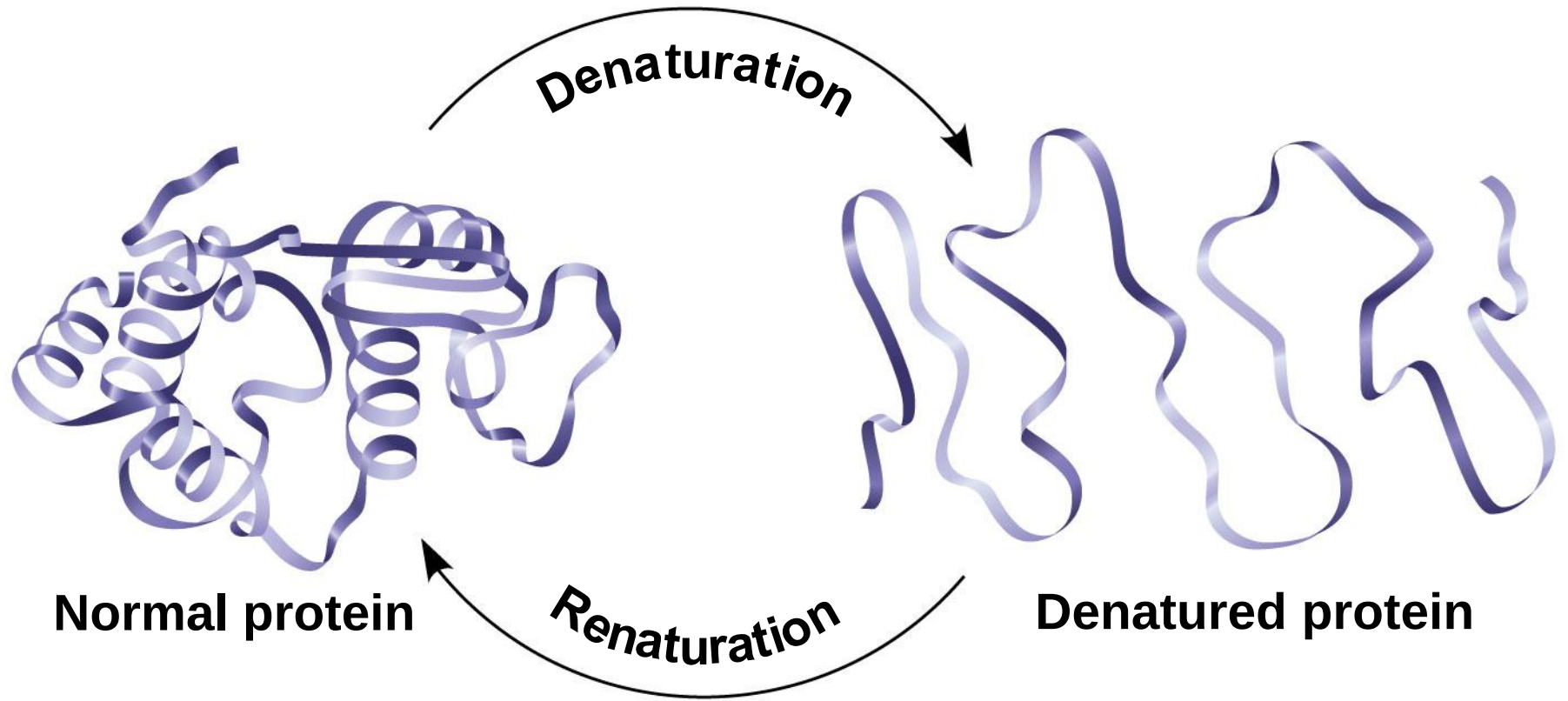
10  $\mu\text{m}$

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# ***What Determines Protein Structure?***

- In addition to primary structure, physical and chemical conditions can affect 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

Figure 5.22

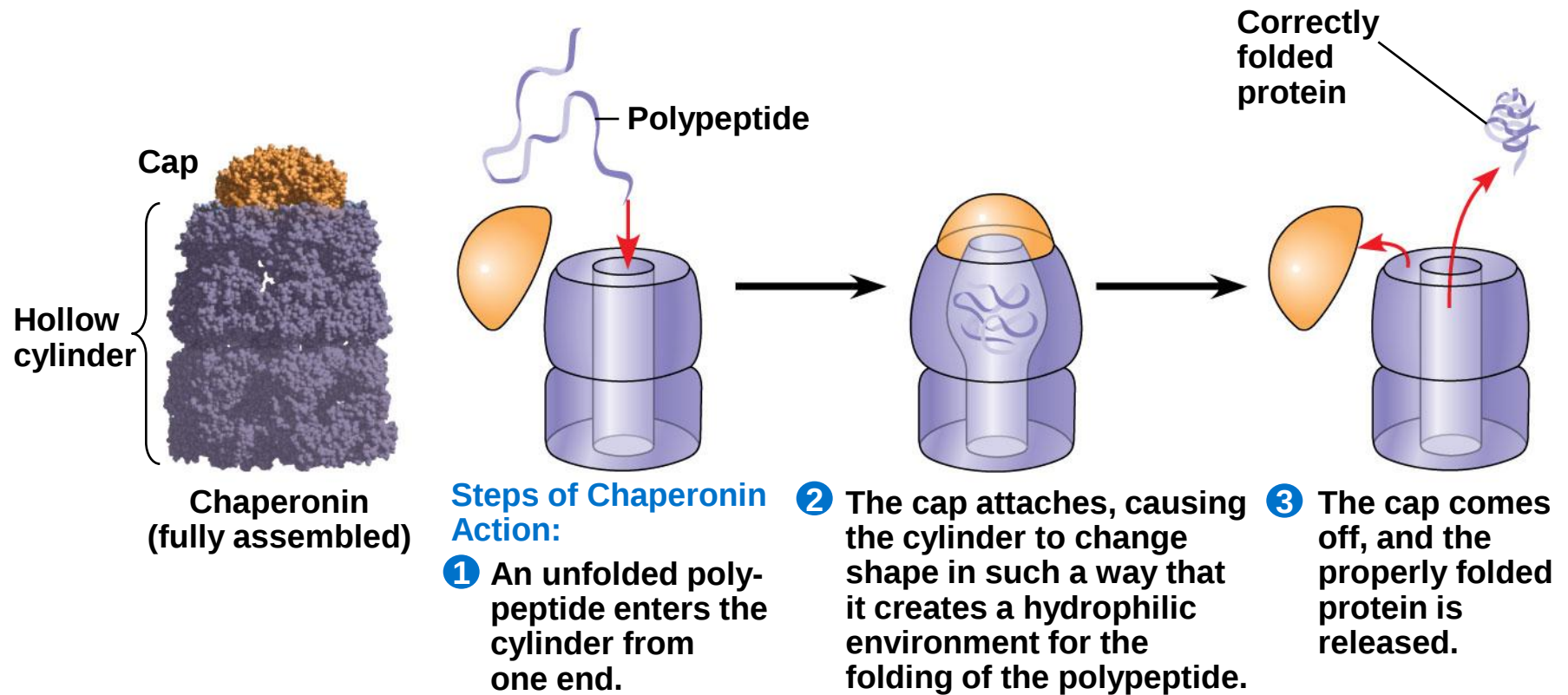


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# *Protein Folding in the Cell*

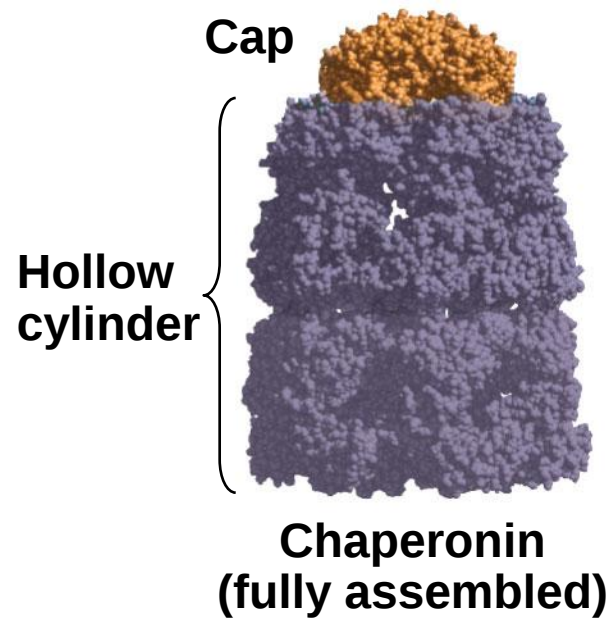
- It is hard to predict a protein's structure from its primary structure
- Most proteins probably go through several stages on their way to a stable structure
- **Chaperonins** are protein molecules that assist the proper folding of other proteins
- Diseases such as Alzheimer's, Parkinson's, and mad cow disease are associated with misfolded proteins

Figure 5.23

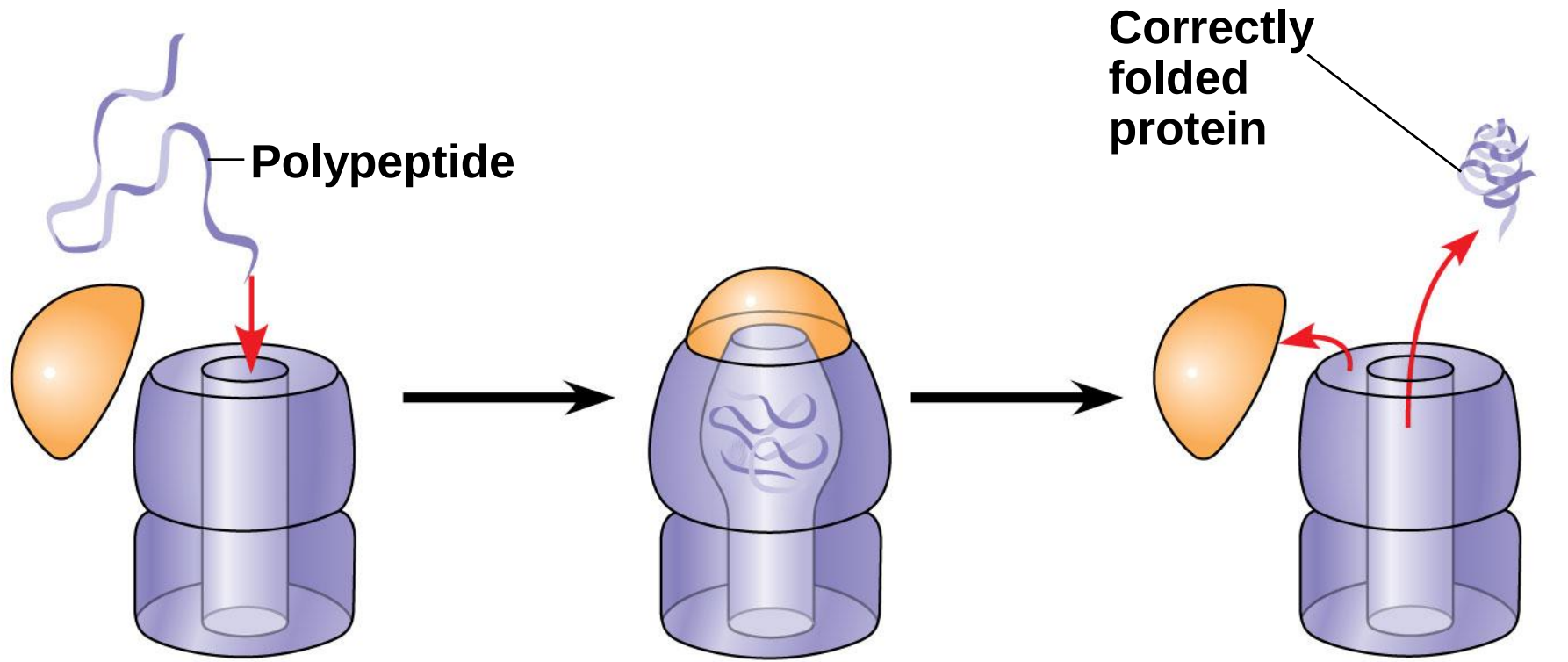


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Figure 5.23a



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### Steps of Chaperonin Action:

**1** An unfolded polypeptide enters the cylinder from one end.

**2** The cap attaches, causing the cylinder to change shape in such a way that it creates a hydrophilic environment for the folding of the polypeptide.

**3** The cap comes off, and the properly folded protein is released.

# Concept 5.5: 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 directs synthesis of messenger RNA (mRNA) and, through mRNA, controls protein synthesis
- Protein synthesis occurs on ribosomes

Figure 5.25-1

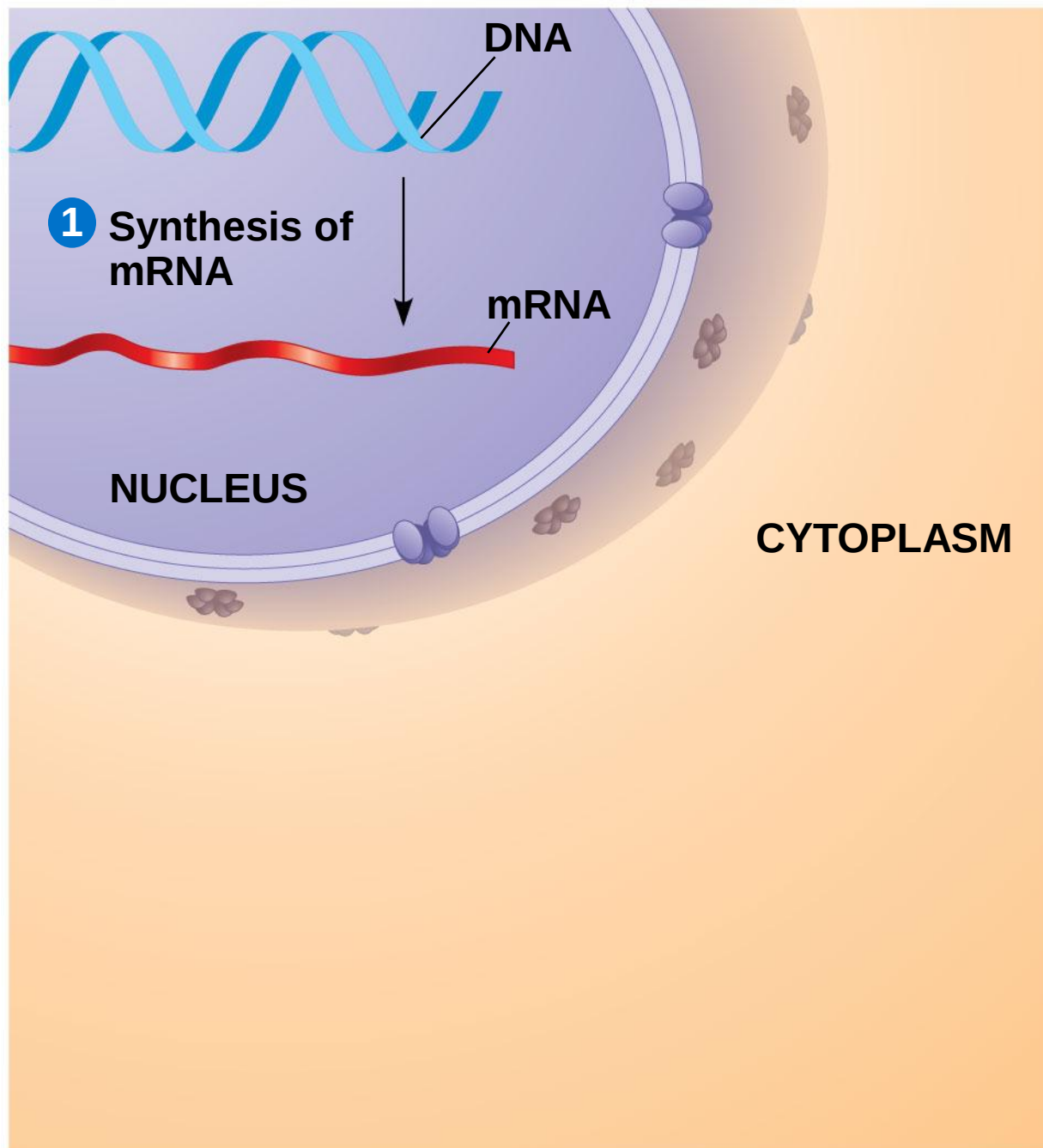


Figure 5.25-2

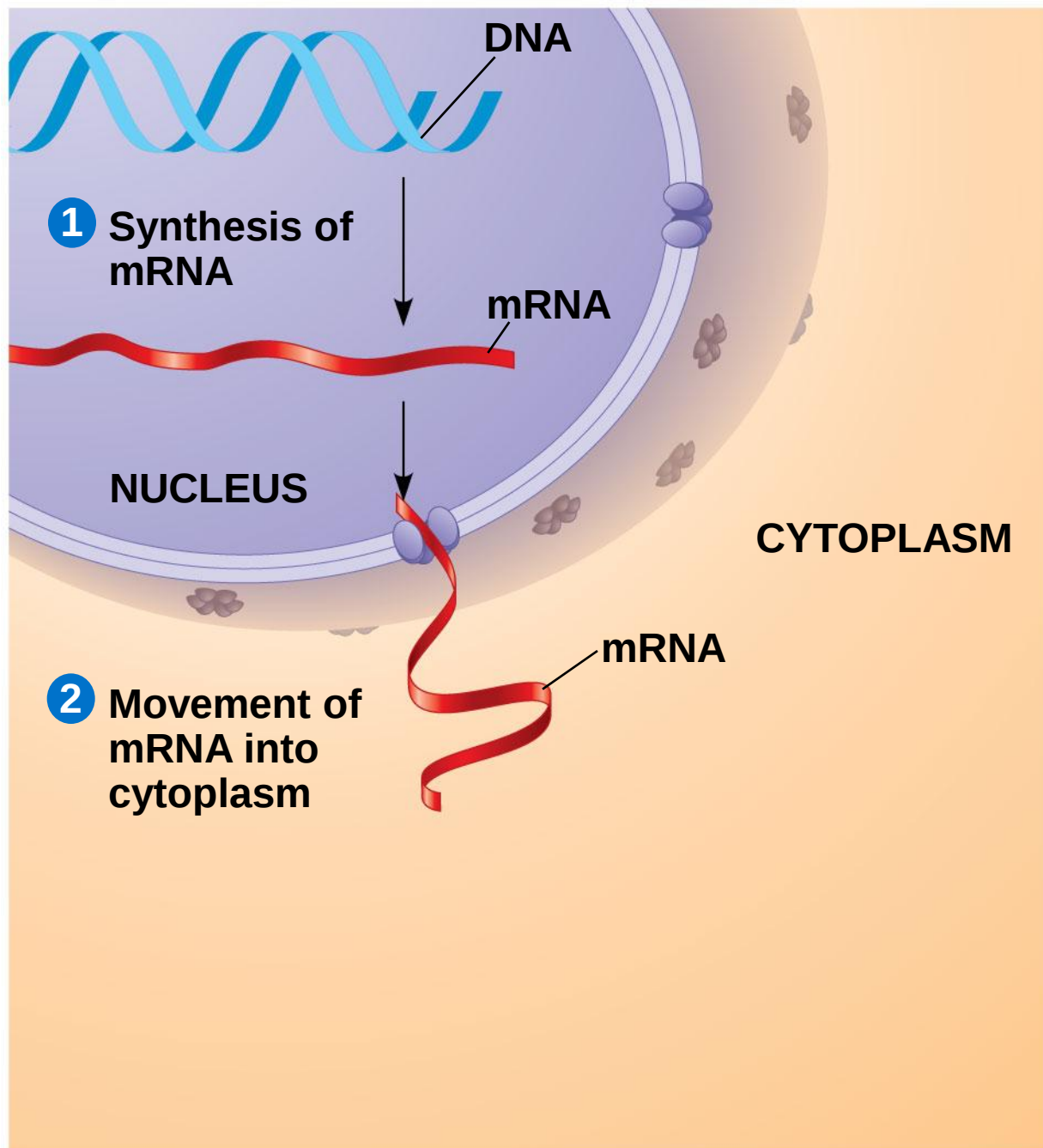
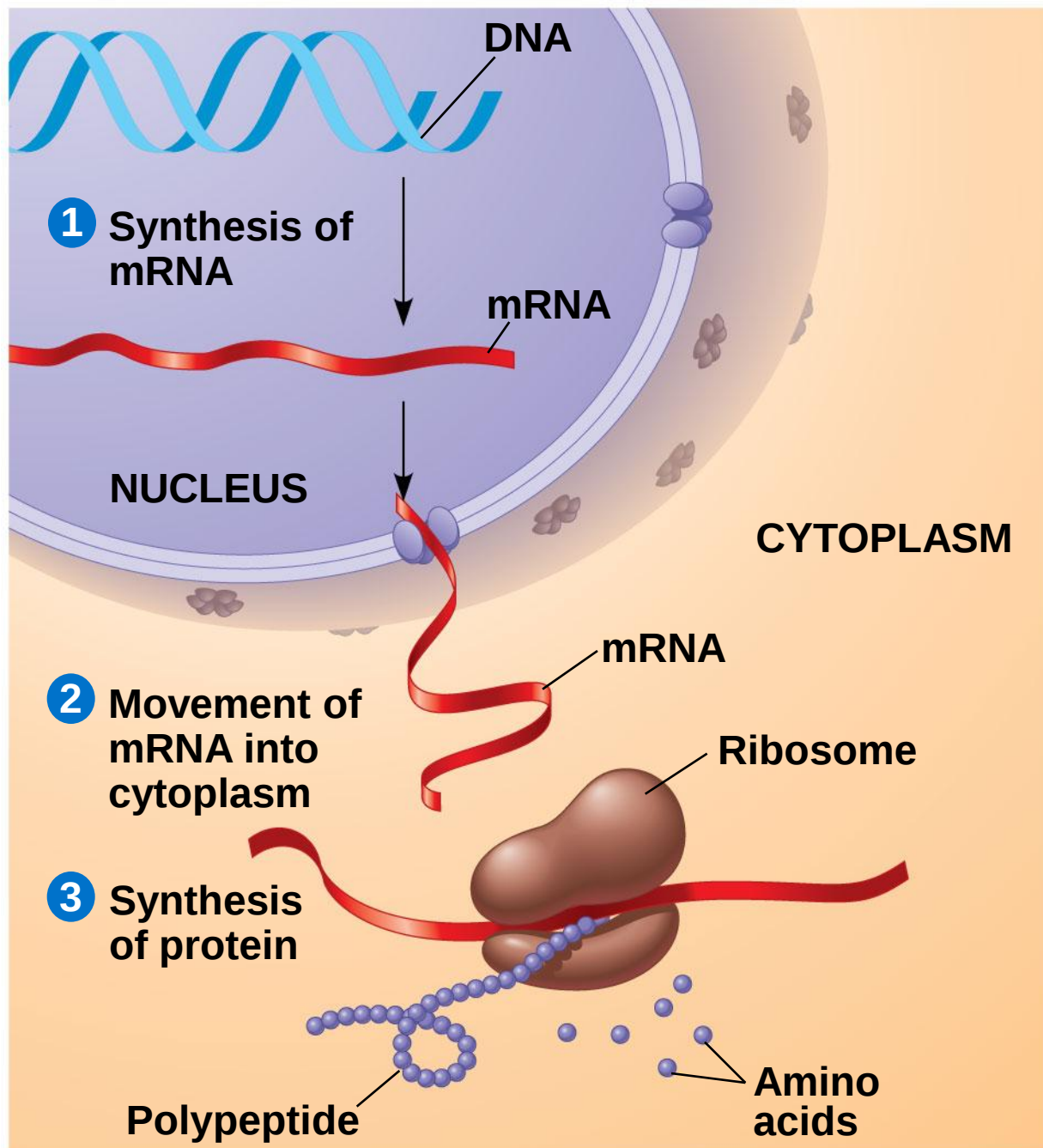


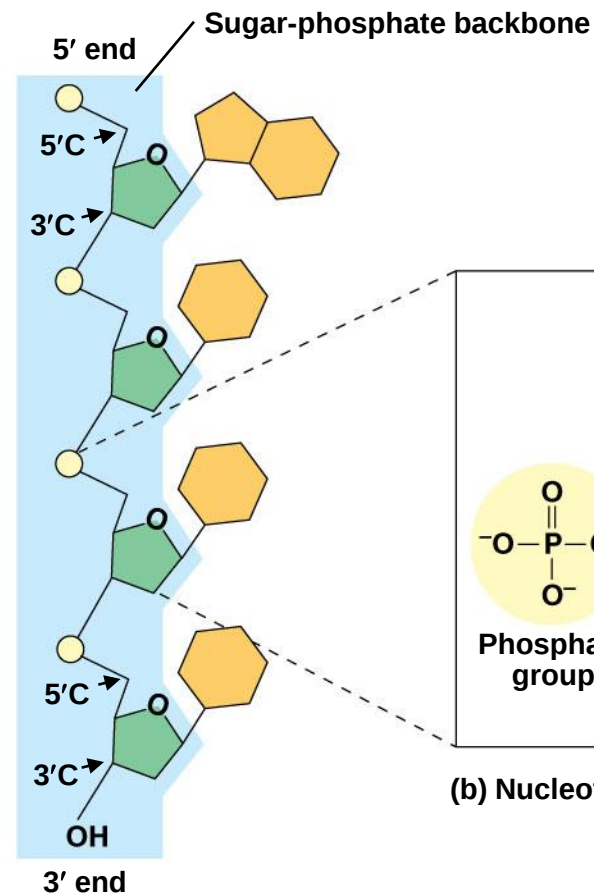
Figure 5.25-3



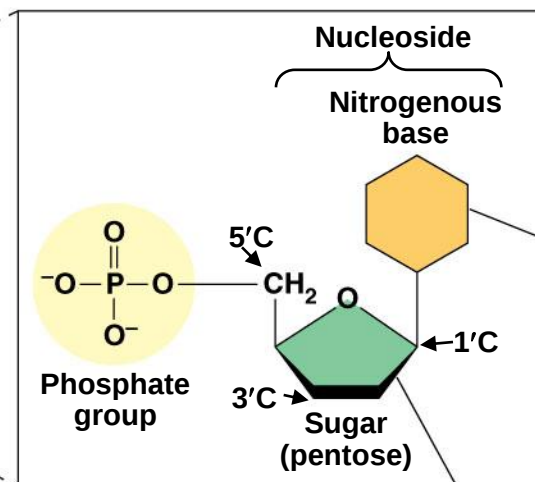
# The Components of Nucleic Acids

- 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

Figure 5.26



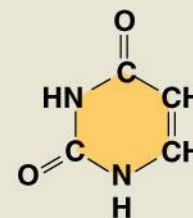
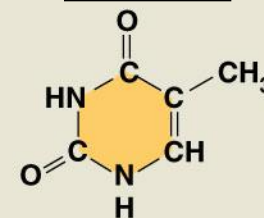
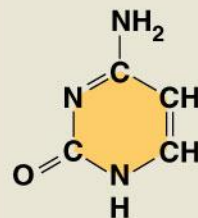
(a) Polynucleotide, or nucleic acid



(b) Nucleotide

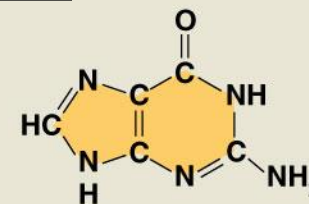
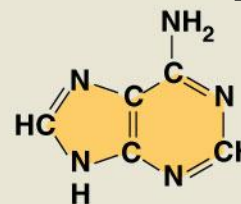
### Nitrogenous bases

#### Pyrimidines



Cytosine (C) Thymine (T, in DNA) Uracil (U, in RNA)

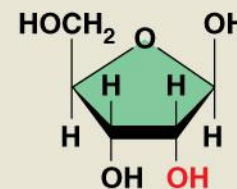
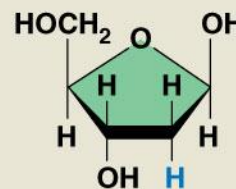
#### Purines



Adenine (A)

Guanine (G)

### Sugars

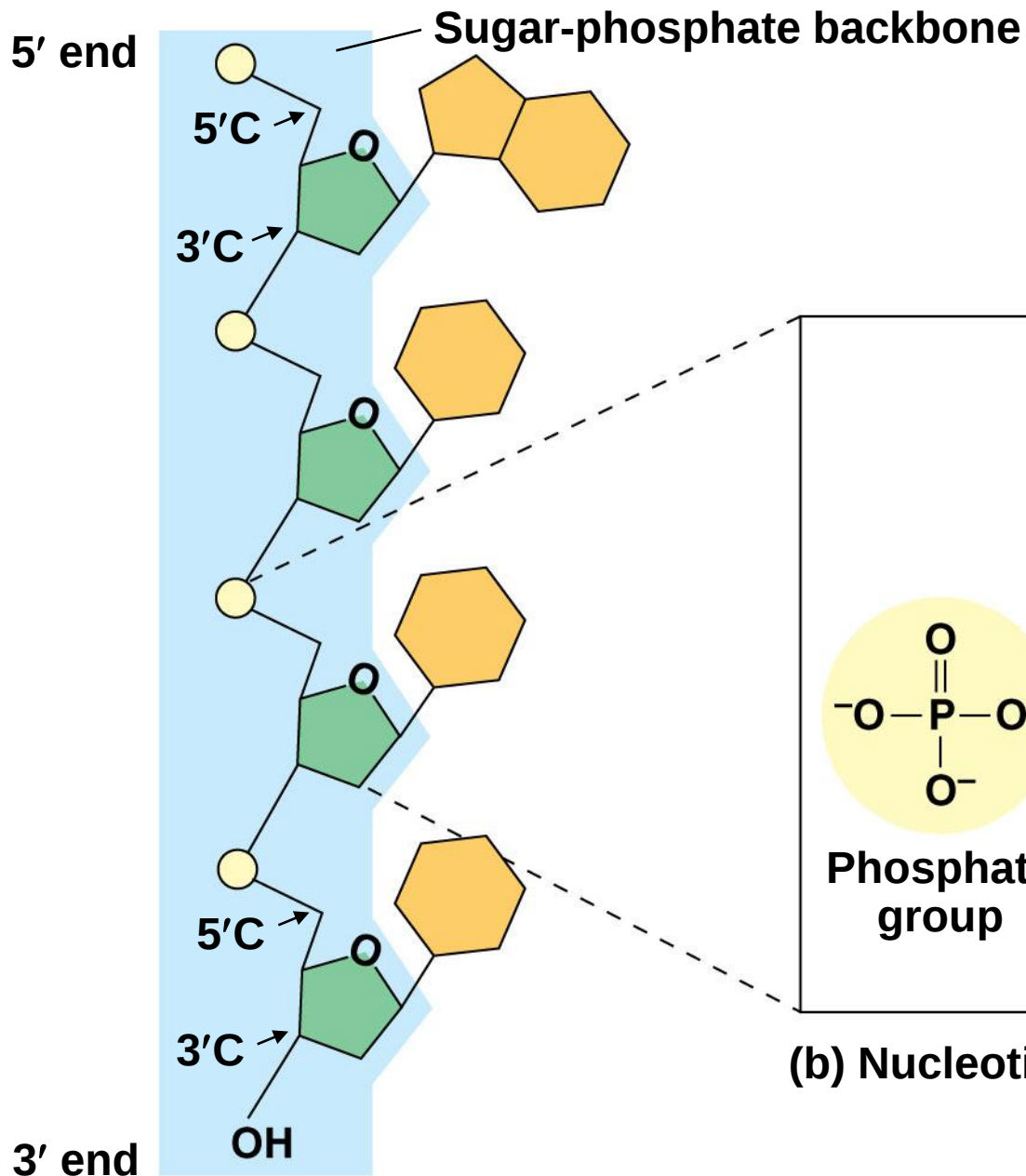


Deoxyribose (in DNA)

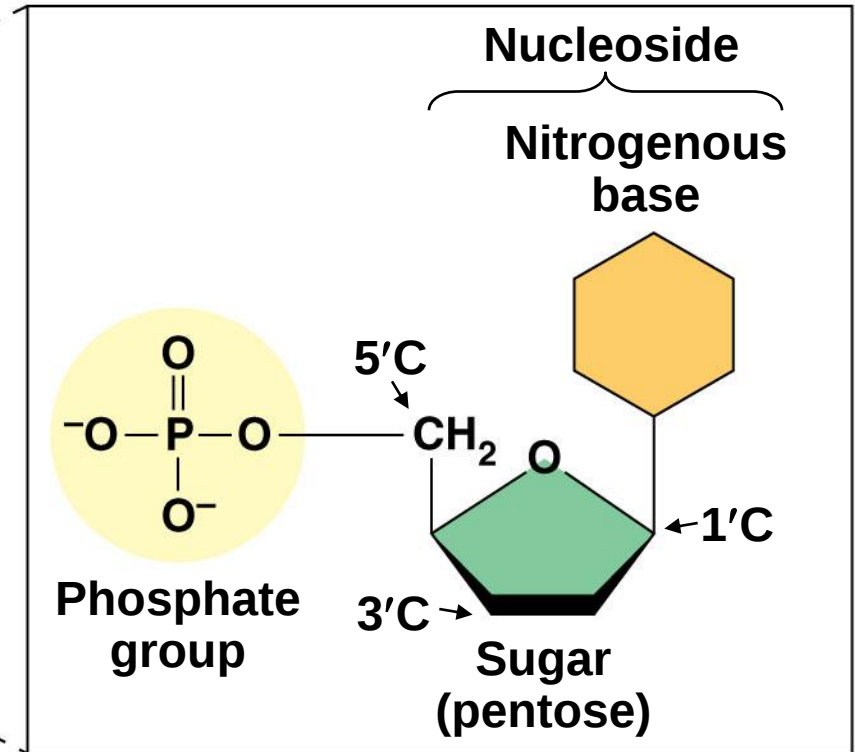
Ribose (in RNA)

(c) Nucleoside components

Figure 5.26ab



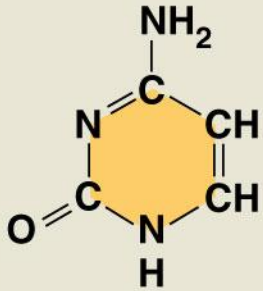
**(a) Polynucleotide, or nucleic acid**



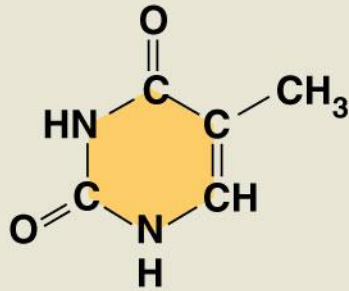
**(b) Nucleotide**

## Nitrogenous bases

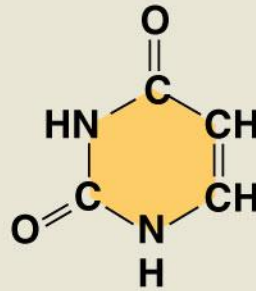
### Pyrimidines



**Cytosine (C)**

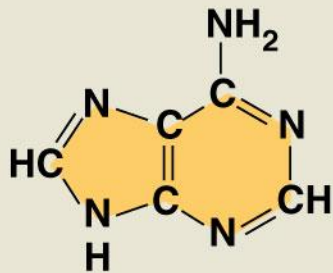


**Thymine (T, in DNA)**

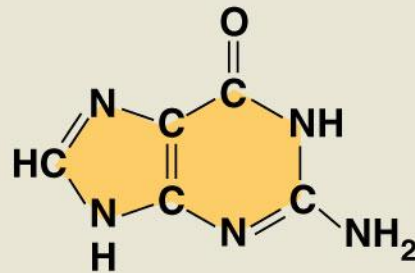


**Uracil (U, in RNA)**

### Purines

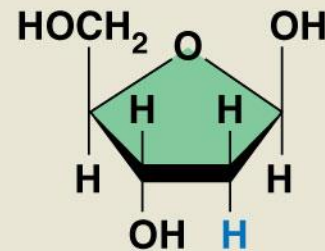


**Adenine (A)**

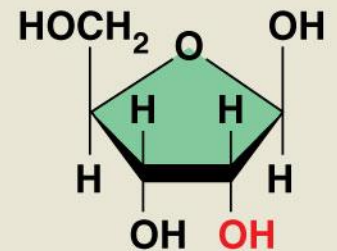


**Guanine (G)**

## Sugars



**Deoxyribose (in DNA)**



**Ribose (in RNA)**

## (c) Nucleoside components

- Nucleoside = nitrogenous base + sugar
- There are two families of nitrogenous bases
  - **Pyrimidines** (cytosine, thymine, and uracil) have a single six-membered ring
  - **Purines** (adenine and guanine) have a six-membered ring fused to a five-membered ring
- In DNA, the sugar is **deoxyribose**; in RNA, the sugar is **ribose**
- Nucleotide = nucleoside + phosphate group

# Nucleotide Polymers

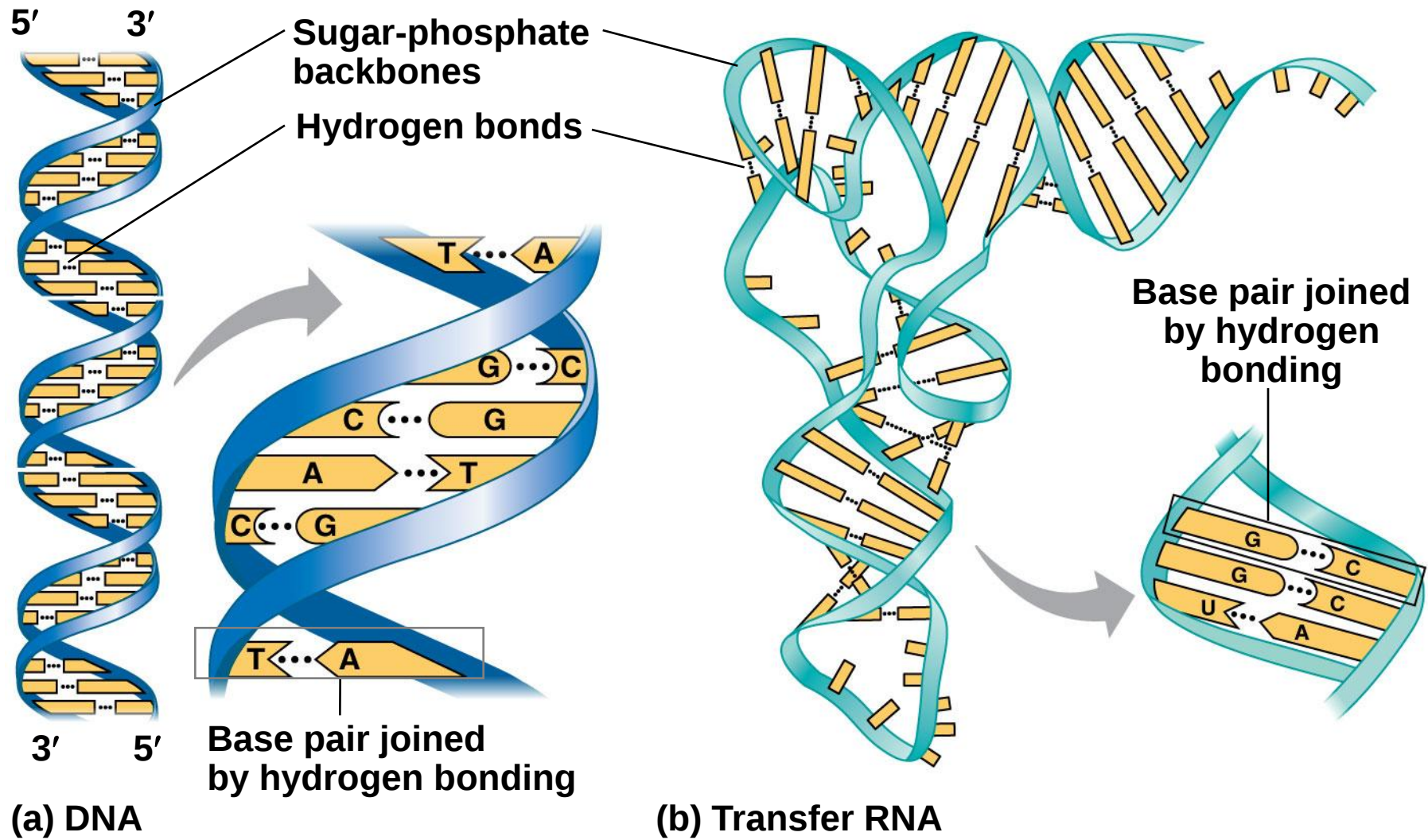
- Nucleotide polymers are linked together to build a polynucleotide
- Adjacent nucleotides are joined by covalent bonds that form between the —OH group on the 3' carbon of one nucleotide and the phosphate on the 5' carbon on the next
- These links create a backbone of sugar-phosphate units with nitrogenous 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'→3' directions from each other, an arrangement referred to as **antiparallel**
- One DNA molecule includes many genes

- The nitrogenous bases in DNA pair up and form hydrogen bonds: adenine (A) always with thymine (T), and guanine (G) always with cytosine (C)
- 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

Figure 5.27



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# The Theme of Emergent Properties in the Chemistry of Life: *A Review*

- Higher levels of organization result in the emergence of new properties
- Organization is the key to the chemistry of life

Figure 5.UN02

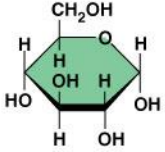
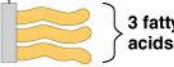
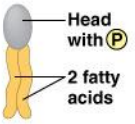
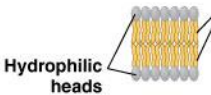
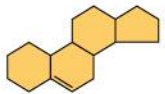
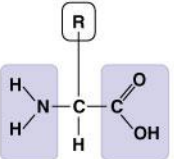
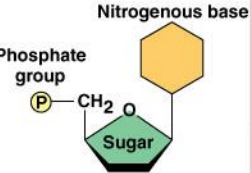
| Large Biological Molecules                                                                               | Components                                                                                                                                                | Examples                                                                                                                                                                                                                                           | Functions                                                                                                                                                                                                                                                                                                                          |
|----------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <b>CONCEPT 5.2</b><br>Carbohydrates serve as fuel and building material                                  | <br>Monosaccharide monomer                                               | <b>Monosaccharides:</b> glucose, fructose                                                                                                                                                                                                          | Fuel; carbon sources that can be converted to other molecules or combined into polymers                                                                                                                                                                                                                                            |
|                                                                                                          |                                                                                                                                                           | <b>Disaccharides:</b> lactose, sucrose<br><br><b>Polysaccharides:</b> <ul style="list-style-type: none"> <li>Cellulose (plants)</li> <li>Starch (plants)</li> <li>Glycogen (animals)</li> <li>Chitin (animals and fungi)</li> </ul>                | <ul style="list-style-type: none"> <li>Strengthens plant cell walls</li> <li>Stores glucose for energy</li> <li>Stores glucose for energy</li> <li>Strengthens exoskeletons and fungal cell walls</li> </ul>                                                                                                                       |
| <b>CONCEPT 5.3</b><br>Lipids are a diverse group of hydrophobic molecules                                | Glycerol<br><br>3 fatty acids                                            | <b>Triacylglycerols</b> (fats or oils):<br>glycerol + 3 fatty acids                                                                                                                                                                                | Important energy source<br>                                                                                                                                                                                                                     |
|                                                                                                          | <br>Head with P<br>2 fatty acids                                         | <b>Phospholipids:</b> phosphate group + 2 fatty acids                                                                                                                                                                                              | Lipid bilayers of membranes<br><br>Hydrophilic heads<br>Hydrophobic tails                                                                                                                                                                       |
|                                                                                                          | <br>Steroid backbone                                                     | <b>Steroids:</b> four fused rings with attached chemical groups                                                                                                                                                                                    | <ul style="list-style-type: none"> <li>Component of cell membranes (cholesterol)</li> <li>Signaling molecules that travel through the body (hormones)</li> </ul>                                                                                                                                                                   |
| <b>CONCEPT 5.4</b><br>Proteins include a diversity of structures, resulting in a wide range of functions | <br>Amino acid monomer (20 types)                                       | <ul style="list-style-type: none"> <li>Enzymes</li> <li>Structural proteins</li> <li>Storage proteins</li> <li>Transport proteins</li> <li>Hormones</li> <li>Receptor proteins</li> <li>Motor proteins</li> <li>Defensive proteins</li> </ul>      | <ul style="list-style-type: none"> <li>Catalyze chemical reactions</li> <li>Provide structural support</li> <li>Store amino acids</li> <li>Transport substances</li> <li>Coordinate organismal responses</li> <li>Receive signals from outside cell</li> <li>Function in cell movement</li> <li>Protect against disease</li> </ul> |
| <b>CONCEPT 5.5</b><br>Nucleic acids store, transmit, and help express hereditary information             | <br>Nitrogenous base<br>Phosphate group<br>Sugar<br>Nucleotide monomer | <b>DNA:</b> <br><ul style="list-style-type: none"> <li>Sugar = deoxyribose</li> <li>Nitrogenous bases = C, G, A, T</li> <li>Usually double-stranded</li> </ul> | Stores hereditary information                                                                                                                                                                                                                                                                                                      |
|                                                                                                          |                                                                                                                                                           | <b>RNA:</b> <br><ul style="list-style-type: none"> <li>Sugar = ribose</li> <li>Nitrogenous bases = C, G, A, U</li> <li>Usually single-stranded</li> </ul>      | Various functions during gene expression, including carrying instructions from DNA to ribosomes                                                                                                                                                                                                                                    |

Figure 5.UN02a

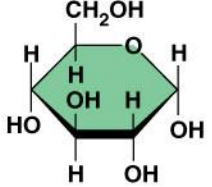
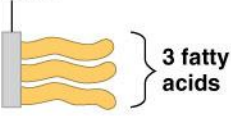
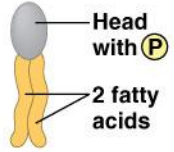
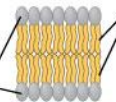
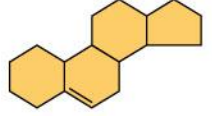
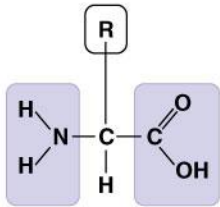
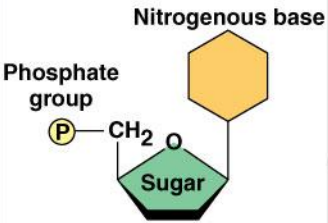
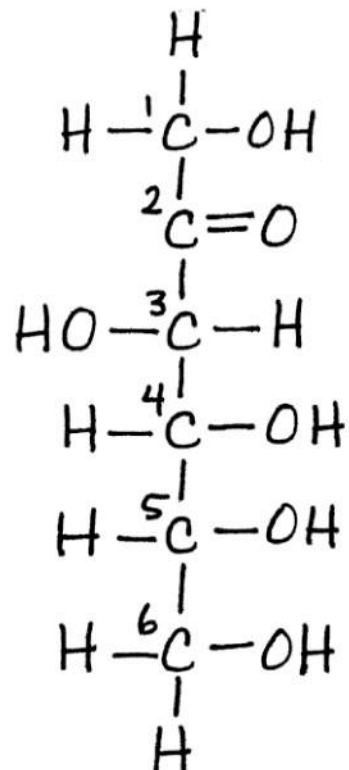
| Large Biological Molecules                                                | Components                                                                                                  | Examples                                                                                                                                                                                                                                    | Functions                                                                                                                                                            |
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| <b>CONCEPT 5.2</b><br>Carbohydrates serve as fuel and building material   | <br>Monosaccharide monomer | <b>Monosaccharides:</b> glucose, fructose                                                                                                                                                                                                   | Fuel; carbon sources that can be converted to other molecules or combined into polymers                                                                              |
|                                                                           |                                                                                                             | <b>Disaccharides:</b> lactose, sucrose<br><br><b>Polysaccharides:</b> <ul style="list-style-type: none"> <li>• Cellulose (plants)</li> <li>• Starch (plants)</li> <li>• Glycogen (animals)</li> <li>• Chitin (animals and fungi)</li> </ul> |                                                                                                                                                                      |
| <b>CONCEPT 5.3</b><br>Lipids are a diverse group of hydrophobic molecules | Glycerol<br>               | <b>Triacylglycerols</b> (fats or oils): glycerol + 3 fatty acids                                                                                                                                                                            | Important energy source<br>                                                       |
|                                                                           |                           | <b>Phospholipids:</b> phosphate group + 2 fatty acids                                                                                                                                                                                       | Lipid bilayers of membranes<br>                                                  |
|                                                                           | <br>Steroid backbone     | <b>Steroids:</b> four fused rings with attached chemical groups                                                                                                                                                                             | <ul style="list-style-type: none"> <li>• Component of cell membranes (cholesterol)</li> <li>• Signaling molecules that travel through the body (hormones)</li> </ul> |

Figure 5.UN02b

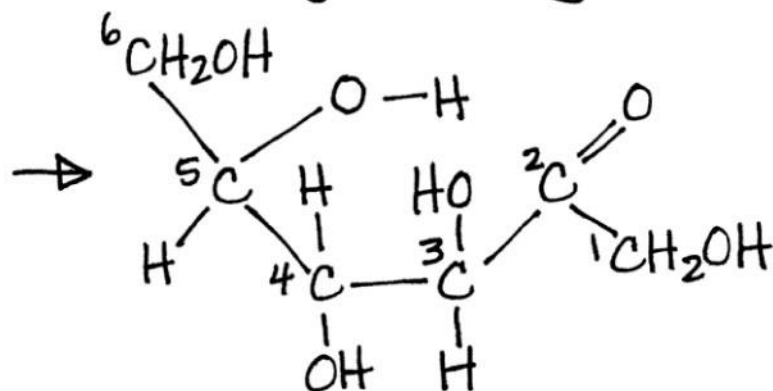
| Large Biological Molecules                                                                                          | Components                                                                                                                 | Examples                                                                                                                                                                                                                                                      | Functions                                                                                                                                                                                                                                                                                                                                          |
|---------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------|---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <p><b>CONCEPT 5.4</b></p> <p>Proteins include a diversity of structures, resulting in a wide range of functions</p> |  <p>Amino acid monomer<br/>(20 types)</p> | <ul style="list-style-type: none"> <li>• Enzymes</li> <li>• Structural proteins</li> <li>• Storage proteins</li> <li>• Transport proteins</li> <li>• Hormones</li> <li>• Receptor proteins</li> <li>• Motor proteins</li> <li>• Defensive proteins</li> </ul> | <ul style="list-style-type: none"> <li>• Catalyze chemical reactions</li> <li>• Provide structural support</li> <li>• Store amino acids</li> <li>• Transport substances</li> <li>• Coordinate organismal responses</li> <li>• Receive signals from outside cell</li> <li>• Function in cell movement</li> <li>• Protect against disease</li> </ul> |
| <p><b>CONCEPT 5.5</b></p> <p>Nucleic acids store, transmit, and help express hereditary information</p>             |  <p>Nucleotide monomer</p>                | <p><b>DNA:</b> </p> <ul style="list-style-type: none"> <li>• Sugar = deoxyribose</li> <li>• Nitrogenous bases = C, G, A, T</li> <li>• Usually double-stranded</li> </ul>    | Stores hereditary information                                                                                                                                                                                                                                                                                                                      |
|                                                                                                                     |                                                                                                                            | <p><b>RNA:</b> </p> <ul style="list-style-type: none"> <li>• Sugar = ribose</li> <li>• Nitrogenous bases = C, G, A, U</li> <li>• Usually single-stranded</li> </ul>         | Various functions during gene expression, including carrying instructions from DNA to ribosomes                                                                                                                                                                                                                                                    |

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Linear form



→ Ring forming



→ Ring form

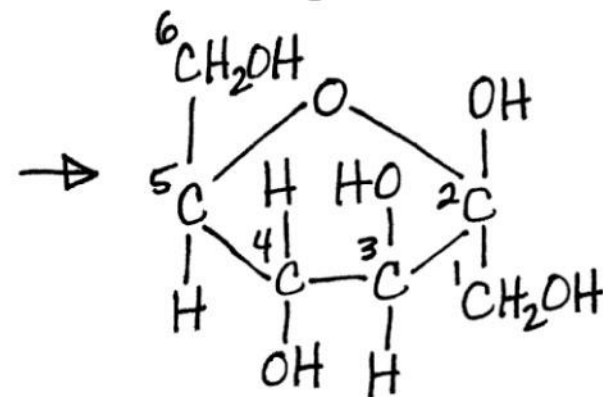
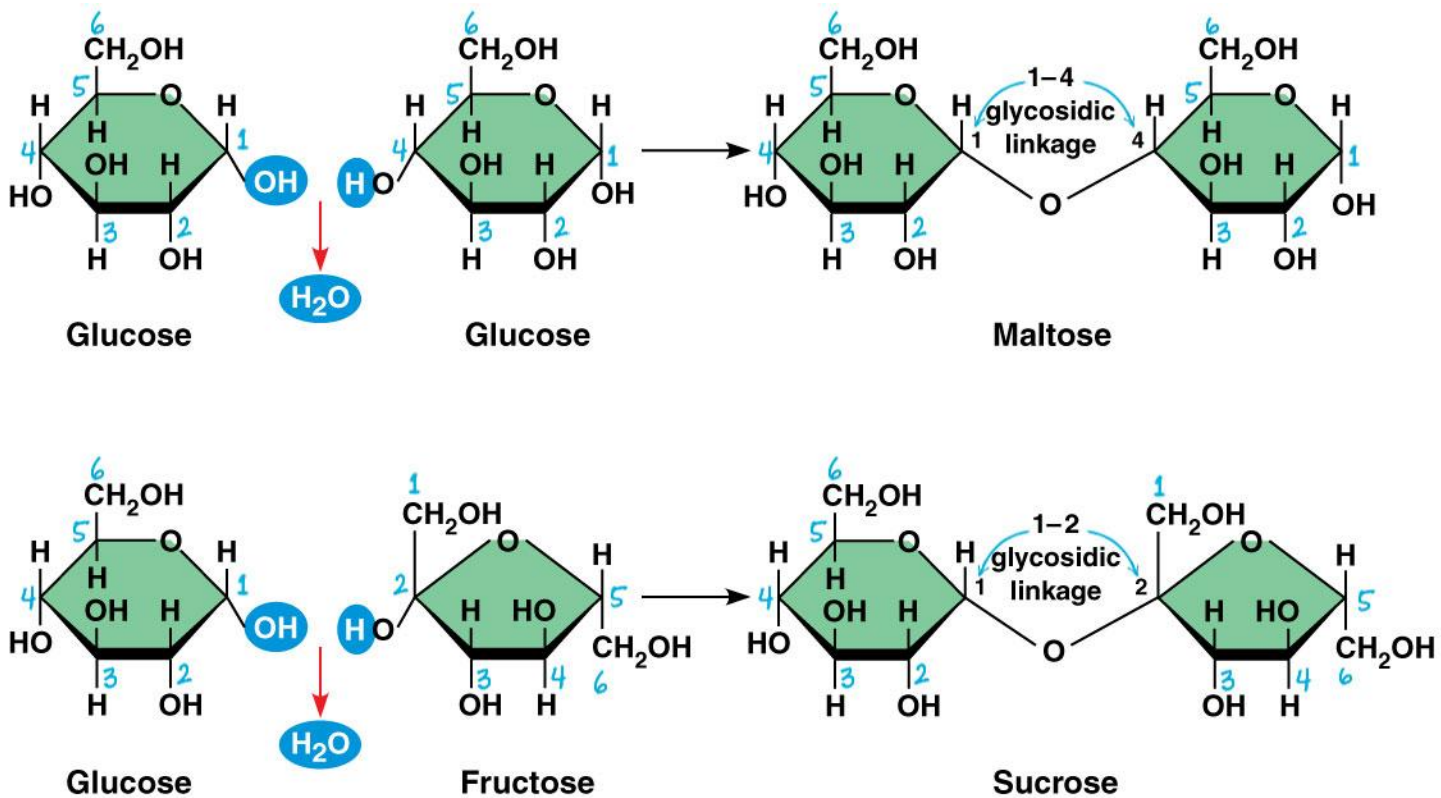


Figure 5. UN04



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Figure 5. UN05

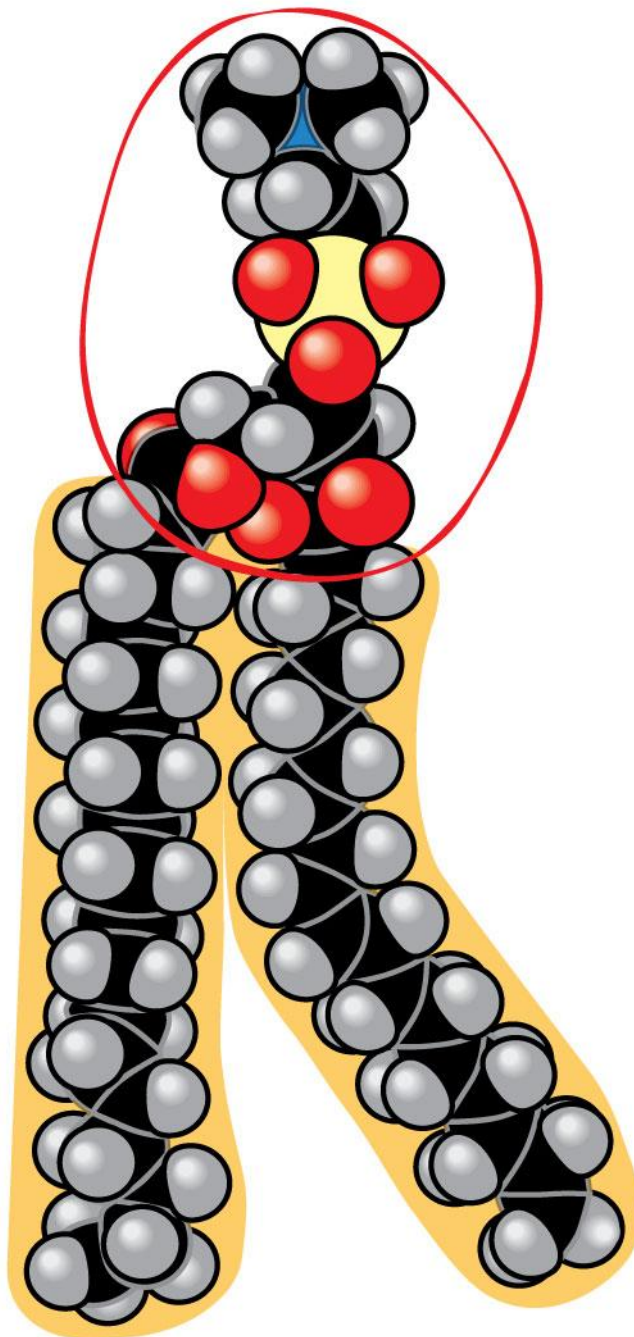
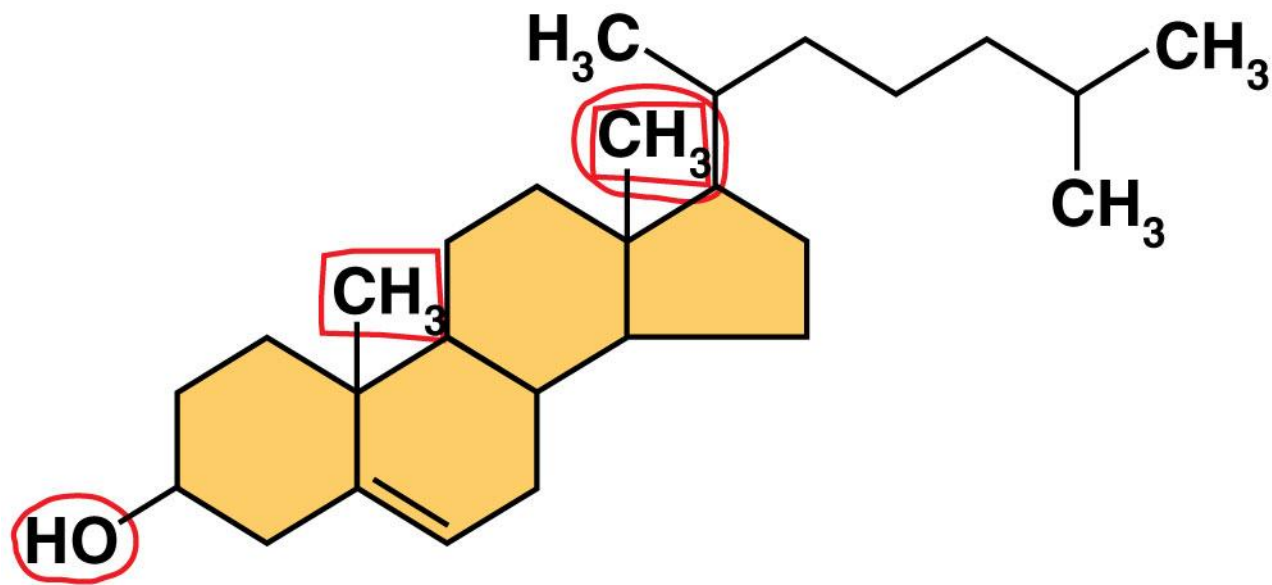
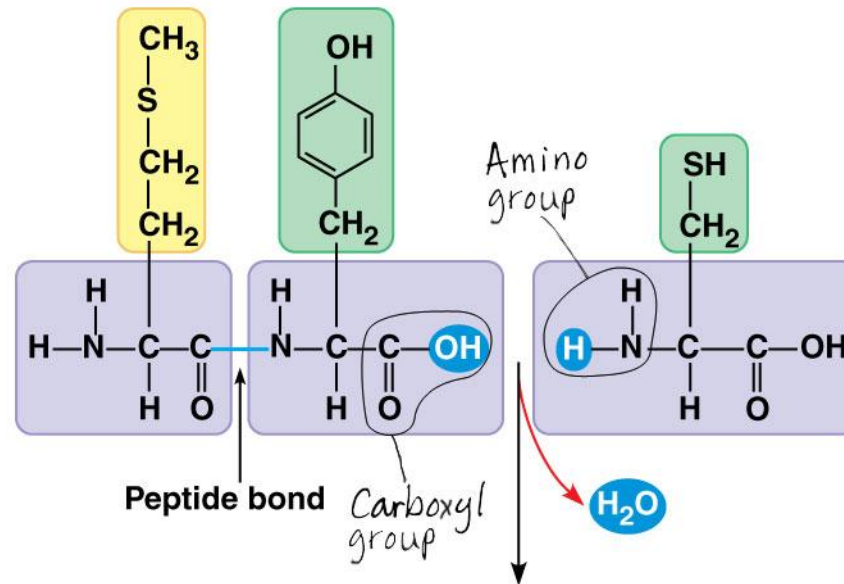


Figure 5. UN06



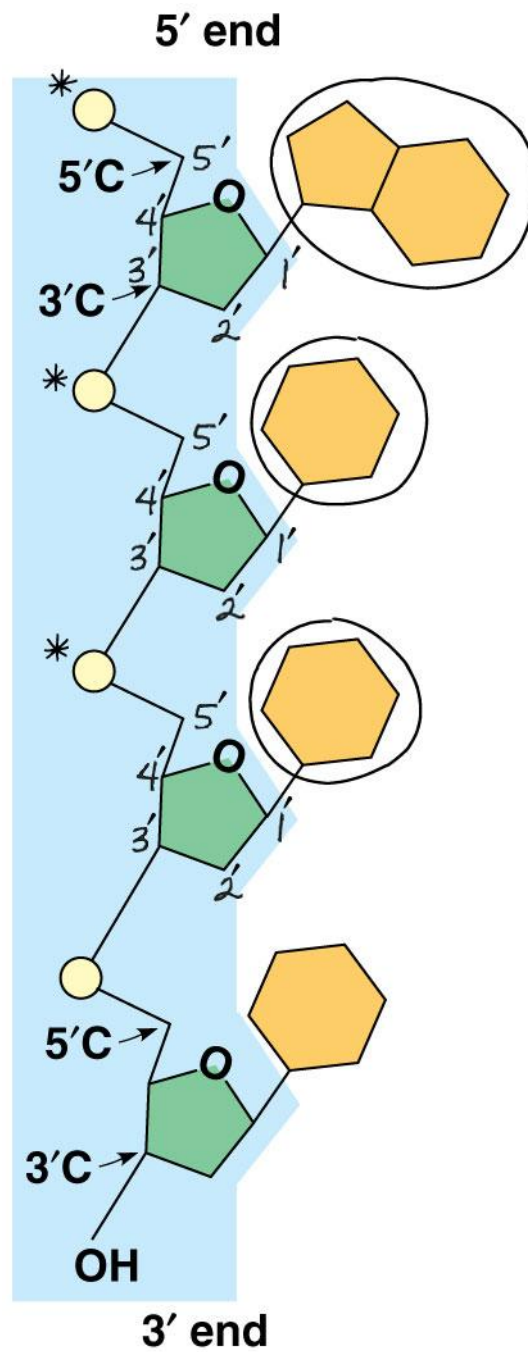
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Figure 5. UN07



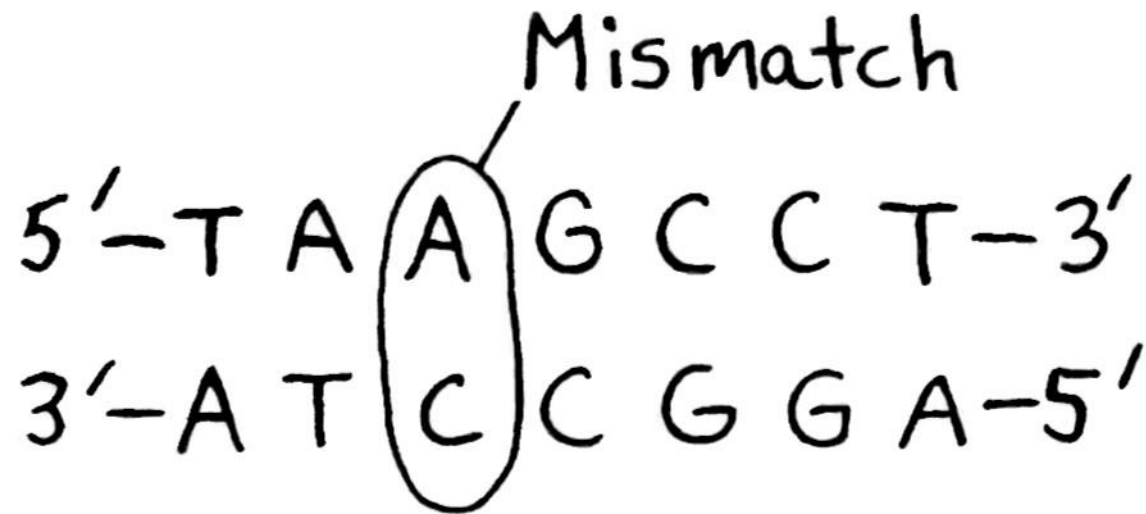
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Figure 5. UN08



5'-T A G G C C T-3'  
3'-A T C C G G A-5'

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3'-A T T C G G A-5'

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Figure 5. UN12

|                  | Monomers<br>or Components | Polymer or<br>larger molecule | Type of linkage         |
|------------------|---------------------------|-------------------------------|-------------------------|
| Carbohydrates    | Monosaccharides           | Polysaccharides               | Glycosidic linkages     |
| Lipids           | Fatty acids               | Triacylglycerols              | Ester linkages          |
| Proteins         | Amino acids               | Polypeptides                  | Peptide bonds           |
| Nucleic<br>acids | Nucleotides               | Polynucleotides               | Phosphodiester linkages |

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Figure 5. UN13

